STATE OF OREGON
DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES
1069 STATE OFFICE BUILDING
PORTLAND, OREGON 97201

PROCEEDINGS OF THE ANDESITE CONFERENCE

A. R. McBirney, Editor

BULLETIN 65

1969

STATE GOVERNING BOARD

Fayette I. Bristol, Chairman	Rogue River
Harold Banta	Baker
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FOREWORD

Fifty-two geologists, geophysicists, and geochemists came together in the Central Oregon Cascades during the first week of July 1968 to discuss a wide range of subjects related to andesitic volcanism. This volume is a compilation of a representative selection of the topics and views discussed.

Any printed summary of this kind, however complete it may be, inevitably falls short of an adequate presentation of the personal exchange of ideas that takes place in an informal meeting such as this one was. It is impossible to include the extended discussions that are by for the most valuable part of the sessions and field trips. It will, however, convey the considered thoughts of some of the participants an certain basic aspects of andesites, and it will demonstrate the range of views on certain topics. No attempt has been made to present a consensus even if it were possible to reach one.

The Andesite Conference was organized through the joint efforts of the Upper Mantle Committee, the Center for Volcanology, and the State of Oregon Department of Geology and Mineral Industries. It was mode possible by the generous support of many individuals and organizations. Chief among these ore:

The people of Bend and their Lunar & Planetary Bose Research, Inc.
The staff of Crater Lake National Pork
The staff of Deschutes and Willamette National Forests
The Eugene Water and Electric Board
Central Oregon Community College
Pacific Northwest Bell Telephone Co.
Pacific Power & Light Co.
Pacific Trailways

This volume is a companion to the Andesite Conference Guidebook (Scientific Report 16-S), which provides information of areas in the Oregon Cascades which were visited on field trips during the conference.

We wish to express our gratitude for all the persons who helped to make the meeting an unqualified success and a memorable experience for all who participated.

Hollis M. Dole
State of Oregon Department of
Geology and Mineral Industries

Hisashi Kuno
Upper Mantle Committee

Alexander R. McBirney
Center for Volcanology

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THE CHEMICAL COMPOSITION OF CENOZOIC ANDESITE

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Abstract

Average values and sample frequency distributions are presented for the essential oxides and certain normative parameters of Cenozoic andesite.

The rock name andesite has been in common use all over the world since its revival by Roth in 1861*. By a curious irony, even now, 130 years after their discovery, very little is known of the andesites of the "type" locality, the Andes Mountains. It has long been known, however, that they are remarkably abundant in other similar mountain chains which mark the continental margins of the Pacific Ocean, in the island arcs which elsewhere rim that ocean, in the Indonesian archipelago which forms the northeastern boundary of the Indian Ocean, in the Dodecanese and Cycladean archipelagoes, which separate the eastern Mediterranean from the Aegean and the Asian mainland, and in the Antilles, which lie between the Caribbean and the Atlantic. They are also exeedingly common in certain tectonic environments remote from or only incidentally associated with the margins of the present oceans, as in Mexico or the inner volcanic arch of the Carpathians, extending from Slovakia across Hungary to Romania. Andesites are commonly closely associated, geographically and chronologically, with subalkaline** basalt and rhyolite, and a number of the contributions to this volume are concerned with the significance of this association. The purpose of this note is to set the stage far the later discussion; it is concerned not with how or why andesite is thought to have formed, but with what, in one sense, it is.

In describing andesites, petrographers have always relied heavily on chemical analyses, and in the course of time a considerable body of data concerning the bulk composition of Cenozoic rocks called andesite has accumulated in the journal and reference literature. No exhaustive summary of this infomotion appears to have been attempted since that of Washington (1917), and it is difficult to estimate its present extent with any accuracy. The incomplete collection which provides the data for this note now contains over 1800 "complete"*** analyses of Cenozoic rocks called andesite in the source references, and it is with this body of data that we shall be concerned. The literature sampling is surely extensive enough to provide a reliable indication of what remains in the unexamined literature. That the rocks so far studied and reported upon also provide an adequate sample of those that remain unstudied is something we must assume as a working hypothesis, for otherwise there would be nothing to talk about, in this or any other natural science. It is, however, a hypothesis concerning whose propriety only the foolhardy will enjoy dogmatic convictions.

The data are drawn from a file of analyses of Cenozoic volcanics maintained at the Geophysical Laboratory largely to permit experimentation in electronic data storage and retrieval. The clerical and bibliographic labor have to be carried along as time permits. This, combined with language difficulty, has led to frequent reliance on summary publications. From repeated brief checks I am persuaded that the incidence of numerical errors attributable to the use of secondary sources is not large. The names applied to the analyses by the compilers of secondary references may sometimes differ from those used in the original publications, though this is on the whole not common. It would be preferable, in every respect, to obtain all information from original sources. This, however, would involve an investment of time and money not now ovoiloble.

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* The history of the term is carefully reviewed by Johannsen (1937).

** A term used here as previously suggested in Choyes (1966).

*** i.e., containing results for FeO, Fe_2O_3, H_2O, and nearly always for at least two of the minor oxides MnO, TiO_2, P_2O_5, as well as, of course, those for SiO_2, Al_2O_3, MgO, CaO, Na_2O, and K_2O.

Table 1. Three averages for andesite.

	Cenozoic Andesite	Daly's Andesite	Cenozoic Andesite of U.S.
SiO_2	58.17	59.59	59.78
Al_2O_3	17.26	17.31	17.19
Fe_2O_3	3.07	3.33	2.45
FeO	4.17	3.13	3.65
MgO	3.23	2.75	3.17
CaO	6.93	5.80	6.06
Na_2O	3.21	3.58	3.96
K_2O	1.61	2.04	1.67
TiO_2	0.80	0.77	0.85
P_2O_5	0.20	0.26	0.23
$H_2O^{\pm}$	1.24		0.87
No. of anal.	1775	87	90

What Is Andesite?

The definitions of andesite proposed in various widely accepted petrographic classifications are something less than consistent. The word is very commonly used, however, and, given suitable facilities for data reduction, we could readily discover what properties are common to objects denoted by it. That is what we shall attempt to do with regard to its chemical composition. Accordingly, for the purpose of this note we accept as andesite the universe of almost all objects called andesite by professional petrographers, the petrographers' interest being sufficient to prompt publication of a "full" chemical analysis for each object so denoted. With one minor exception noted below, we shall make no attempt to second-guess the author of the publication from which any analysis was obtained; only in this way can we hope to discover properties common to objects given the same name when the name itself is widely used but has no universally accepted connotation with regard to those properties.

A sample chosen in this fashion will of course not include analyses of specimens that "ought" to have been called andesite according to one or other petrographic system or set of naming conventions but were in fact called something else in the source references. Conversely, analyses of specimens that would not be classified as andesite according to certain of these systems or conventions will nevertheless be included if the name was applied to them in the references from which the analyses were obtained.

The exception noted above is to this last rule. Interesting in principle, it turns out to be of trifling practical importance. The name andesite has rarely been applied to rocks containing modal feldspathoid in more than trace amount, but it does occur in certain instances in which the analyses are nepheline normative. In most such occurrences so far noted, the rocks in question are intimately associated with feldspathoidal lavas, and "andesite" often seems to be serving as an abbreviation for "trachyandesite." Because extreme values -- in this case, of alkalis -- can seriously bias estimates of variance even in large samples, ne-normative analyses were excluded from the sample. The number of rejects is very small; there are seven from central France, fourteen from Etna, three from other Mediterranean localities, one from the Greek islands, one from central Europe, and twenty from the western Pacific*. Of 1821 analyses of rocks called andesites, 46 have thus been rejected because they are ne-normative. No other knowing exception has been made to the rule that the rock name used is in each instance the one attached to the analysis in the source reference.

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* Although the name andesite is applied without modification in the publication from which the Etna analyses were taken, the textual analogy is with hawaiite, and in earlier publications the same rocks are given names other than andesite. In the current file, the name andesite is also attached to nineteen analyses of Hawaiian rocks of the sort for which Macdonald (1960) suggested the name hawaiite. Hawaiite in the sense proposed by Iddings -- i.e., andesine basalt -- is surely a more appropriate name for these specimens. All are rich in alkalis, in all normative plagioclase is more sodic than labradorite, all but two are ne-normative, and only three carry more than 50 percent of SiO_2. The overwhelming international preference seems to be to refrain from characterizing as andesite rocks which are either modally or normatively feldspathoidal.

Table 2. Means, standard deviations, and frequency distributions for essential oxides of Cenozoic ondesite.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CoO	Na_2O	K_2O	TiO_2	P_2O_5
Average	58.17	17.26	3.07	4.18	3.24	6.93	3.21	1.61	0.8	0.21
Standard deviation	4.06	1.56	1.38	1.62	1.24	1.63	0.72	0.75	0.35	0.15
Origin	44.00	9.00	0	0	0	0	0.80	0	0	0
Class interval	1.00	0.50	0.50	0.333	0.333	0.50	0.20	0.20	0.10	0.05
Class No.										
1	0	0	25	15	13	1	0	3	10	89
2	0	1	44	21	13	2	0	29	18	201
3	2	0	110	20	23	1	1	83	34	286
4	1	2	205	27	50	3	7	97	61	282
5	6	2	277	36	71	8	16	158	122	277
6	8	2	284	36	111	13	23	200	141	141
7	23	2	241	60	144	19	72	171	271	89
8	44	2	202	98	140	37	109	191	351	54
9	86	7	140	90	204	48	146	217	249	33
10	99	17	96	118	199	61	128	171	180	17
11	111	37	55	144	180	102	161	125	91	22
12	166	60	34	134	172	158	221	79	77	12
13	155	81	21	148	152	217	224	81	50	12
14	184	123	22	157	86	243	166	43	18	6
15	183	190	6	123	65	245	162	41	20	5
16	164	240	6	135	51	184	108	24	13	2
17	138	229	1	102	44	173	81	17	8	5
18	122	238	3	83	26	91	57	16	5	3
19	68	205	0	69	13	82	25	10	6	2
20	64	139	1	44	2	40	25	7	3	1
21	61	78	1	40	8	23	13	3	4	1
22	30	57	0	25	2	11	11	3	5	0
23	27	28		16	1	5	6	0	4	1
24	9	13		13	1	4	5	3	2	0
25	5	11		6	2	3	3	2	4	0
26	4	6		6	0	1	4	1	4	0
27	3	2		4	0	0	0	0	4	1
28	5	0		1	0		1		0	0
29	1	2		2	1		0		3	
30	3	1		0	0				0	
31	0	0								

The Average Composition of Andesite

In Table 1 the average of 1775 analyses of Cenozoic rocks called andesite is compared with the well-known and often cited average presented by Daly (1933). The over-all similarity is very striking, but certain of the differences--e.g. those for SiO_2, FeO, MgO, CaO, Na_2O, and K_2O--would be clearly significant as between random samples of this size. Most of the data contributing to the new average were not available to Daly, and except for the rejection of "distinctly 'inferior' analyses," it is not known how he selected the analyses he did actually use. An average for the continental United States, generated in this study and shown in column 3 of Table 1, suggests that some of the larger differences--e.g. those for SiO_2, CaO, Na_2O--between Daly's average and the new one could result from heavy reliance on U.S. data in the former, but for other oxides this does not seem to be the case.

Turning to information of a type not previously available, Table 2 contains frequency distributions for each of the essential oxides; from these, readers who wish to do so can readily compile histograms or cumulative frequency diagrams. To some extent the rather sizable standard deviations and broad ranges shown in Table 2 must reflect loose usage based upon the almost traditional prior conviction that petrographic classification is either impossible or trivial. How else can one account for "andesites" containing, for instance, less than 50 or more than 70 percent of SiO_2? Some errors of transcription have no doubt escaped detection, but many of the more strikingly extreme variants shown in Table 2 have been rechecked in the source references.

Even by petrographers, rock names are evidently often used stratigraphically or geologically rather than petrographically. Foiling satisfactory criteria for detecting their occurrence, a sampling procedure of the sort used here is at the mercy of such misapplications. In samples of the size used in this study, even extreme variants con scarcely influence mean values; they may, however, seriously inflate sample variances, and it is notable that, in each of the distributions of Table 2 that shows a central tendency, the concentration of data in the central region markedly exceeds normal expectation. This would be of considerable substantive interest if the possibility that it was a consequence of sloppy, non-petrographic use of petrographic terms could be excluded. But it is precisely this possibility that cannot be excluded.

Some Normative and Molar Properties of Cenozoic Andesite

(a) Oxidation state. The first column of Table 3 contains the sample frequency distribution of the ratio

$$\underline{Ox} = \text{molar } Fe_2O_3 / (\text{molar FeO} + \text{molar } Fe_2O_3).$$

This quantity is readily converted into almost any of the numerous statistics used by petrographers to characterize oxidation. If, for instance, $\underline{Ox} = k$ in a particular analysis, the ratio of the weight of ferric oxide to the sum of the weights of ferric and ferrous oxide in the analysis is $2.22k/(1 + 1.22k)$, the ratio of the molar amount of ferric oxide to the molar amount of ferrous oxide is $k/(1 - k)$, the ratio of the weights of the two oxides is $2.22k/(1 - k)$, and the molar amount of FeO available for normative allocation to silicates connot exceed $(1 - 2k)/k$ times the molar amount of Fe_2O_3.

The average value of $\underline{Ox}$, as shown in Table 3, is 0.267, so that the average weight ratio of ferric to ferrous oxide is 0.808, i.e. there is on the average a 1.24-fold excess of ferrous over ferric oxide. This is in marked contrast to the ratio of the two weights in the Daly average, in which there is actually a small excess of ferric over ferrous oxide.

Variable surficial oxidation would generate positive skewness in an initially symmetrical distribution of $\underline{Ox}$, and this would appear to be a reasonable explanation of the striking histogram shown in Figure 1. As might be expected under the circumstances, the sample distribution is again notably dense in the central region, the interval $\bar{x} \pm s$ including over 80 percent of the sample points. One might also expect that extensive surficial oxidation would be strongly associated with extensive hydration, but this is not so. The distribution of $\underline{Ox}$ in the 1293 analyses that contain less than 2 percent of H_2O is very similar to its distribution in the full sample; in particular, positive skewness is quite as pronounced.

(b) The sample distribution of normative corundum. In subalkaline rocks as a group, the first inequality in the molar relation

$$Na_2O + K_2O < Al_2O_3 < Na_2O + K_2O + CaO \qquad (1)$$

holds as a matter of definition. The second is also nearly always true; $\underline{di}$ cannot otherwise appear in the norm, but $\underline{di}$ is nearly always present in the norms of subalkaline rocks. The norms of 1520 of the 1775 andesite analyses on which this note is based contain less $\underline{di}$ than $\underline{hy}$, however, and the average value of the ratio $\underline{hy}/(\underline{di} + \underline{hy})$ is nearly 0.75. Andesites, in fact, not infrequently contain an excess of Al_2O_3 over ($Na_2O + K_2O + CaO$) so that their norms contain $\underline{c}$ but no $\underline{di}$.

Table 3. Means, standard deviations, and frequency distributions for oxidation ratio, normative c, q, pl, and H_2O content of Cenozoic andesites.

	Ox	c	q	pl	H_2O
Mean	0.267	0.28	13.57	54.34	1.26
Standard Deviation	0.156	0.78	6.64	5.95	1.08
Origin	0	0	0	18.00	0
Class interval	0.033	0.333	1.50	2.00	0.10
< Class 1		1445*	26**		14***
Class No.					
1	15	59	31	0	40
2	26	60	44	3	84
3	54	50	62	1	105
4	120	29	86	1	94
5	184	26	120	3	86
6	234	25	100	4	118
7	255	21	123	0	86
8	182	13	150	5	109
9	169	7	161	2	95
10	119	6	144	1	85
11	84	5	162	7	73
12	78	7	114	17	63
13	53	7	110	37	58
14	33	1	89	52	62
15	21	1	78	82	54
16	28	2	55	125	41
17	16	0	46	187	50
18	13	3	24	269	39
19	10	2	16	257	49
20	7	0	14	246	30
21	14	1	4	202	33
22	9	1	6	146	28
23	6		5	72	25
24	11		0	38	17
25	8		0	11	22
26	8		0	6	19
27	2		2	1	21
28	7	1	1		13
29	4		0		19
30	3		1		15
> Class 30					128

* Norms contain di.
** Norms contain ol.
*** H_2O analyses not available in time for computation.

The rather common occurrence of c in andesite norms is of course well known, but no estimate of the relative frequency of andesite norms containing c, or of the amounts of c they contain, has previously been offered. The sample frequency distribution of normative corundum is shown in column 2 of Table 3; c occurs in 327, or 18.4 percent, of the norms, but its amount is usually very small. In the norms in which it occurs, the overage c content is only 1.52 percent; in Cenozoic andesites as a whole this value falls to 0.28 percent. There are occasional instances in which the c content of a norm is quite sizeable -- values of 10 to 15 percent are not unknown -- but these are ordinarily confined to extremely hydrous rocks. In fact, the incidence of corundum in the norm in any amount is much greater in the more hydrous rocks; it occurs in the norms of almost 32 percent of the rocks containing H_2O in excess of 2 percent, but in less than 13 percent of the norms of those containing less than 2 percent of H_2O.

In sum, about a fifth of the analyses of Cenozoic andesites violate the rather general rule that in subalkaline rocks there is a molar excess of alkalis and lime over alumina, but the normative c whose presence signals a violation of the rule usually occurs in no more than token amount. The remaining four-fifths conform to the rule, but rather grudgingly, as suggested by the high average value of the normative ratio hy/(di + hy).

(c) The sample distribution of normative quartz. The rarity with which the name andesite is applied to feldspathoidal lavas of intermediate color index and silica content, the availability and common use of other names for rocks of this composition, and the scarcity of ne-normative analyses of rocks called andesite make it appropriate to exclude such analyses from the present sample. As already announced, of a total of 1821 analyses, 46 hove been rejected for this reason.

With regard to olivine, the situation is less clear. Although a little modal olivine is not infrequently mentioned in descriptions of andesite, the number of analyses which are ol (but not ne) normative is very small. Because modal olivine does indeed occur in andesites, these analyses have been retained, but it is nevertheless true that andesites as named by authors of specific descriptions are nearly always q-normative. In fact, of the 1775 non-ne-normative analyses, only 26 contain normative ol. Andesite is characteristically -- so characteristically that it should perhaps be made a part of the definition -- a rock oversaturated with regard to silica. The frequency of silica oversaturation is hardly much occasion for surprise. Judging from text and reference definitions, however, for a resume of which see Chayes (1965), the extent of silica oversaturation is widely underestimated. The sample distribution of q is shown in column 3 of table 3, and in figure 2. The average value of q is 13.57 for all analyses. There is some association of high individual values with excessive hydration, the average q for the 482 analyses containing more than 2 percent H_2O being 15.71 percent. On the whole, however, the effect of hydration is not critical; average q for the 1293 analyses containing less than 2 percent H_2O is 12.78 percent, only 0.79 less than the grand average.

This surprisingly high value obliges us to acknowledge that there is a sharp distinction between the way in which the group nome andesite is used by petrographic systematists and the way in which the rock name andesite is used by petrographers in their daily work. Rittmann (1962, p. 104) has criticized Daly's overage andesite on the ground that it "corresponds in chemical composition to a typical dacite." On the basis of normative quartz content the same criticism could be brought against more than two-thirds of the analyzed specimens described in the literature as andesite. Names supposedly reserved for rocks intermediate between the systematists' definitions of andesite and rhyolite are in fact very sparingly used. In principle, dacite, quartz-dacite, and rhyodacite denote rocks intermediate in composition between andesite and rhyolite; that is what systematists and authors of text and reference works have been saying for more than half a century. In practice, however, rhyodacite, when used at all, is merely a fancy nome for rhyolite, while dacite and quartz dacite are names sometimes -- and on the whole rather rarely -- applied to rocks usually called andesite.

(d) Normative plagioclase content. In Rosenbusch's definition of andesite the an content of plagioclase was critical, and in most modern definitions it retains much of its importance; rocks in which the plagioclase is predominantly more sadic than calcic oligoclase or more calcic than sodic labradorite are not likely to be called andesite. The former may sometimes be called oligoclase andesite, but it is far more likely that they will be given names like trachyandesite, mugearite, etc., while the latter are almost certain to be called basalt. As Rittmann (1962, p. 101, for instance) and many others have pointed out, however, zoning of phenocryst and groundmass plagioclase, incomplete crystallization, and fineness of grain often make efficient application of this criterion difficult or impossible. Except that it takes no account of Al_2O_3 which may enter minerals other than feldspar, the normative ratio an/(an + ab) is probably often a far better estimate of the average or over-all an content of plagioclase in a completely crystallized andesite than can be obtained by microscopic study. (If crystallization is incomplete, no direct estimate is possible.) Through an oversight discovered too late for remedy, the frequency distribution of this ratio was not obtained. Separate distributions for ab, an, and ab + an were obtained, however, and

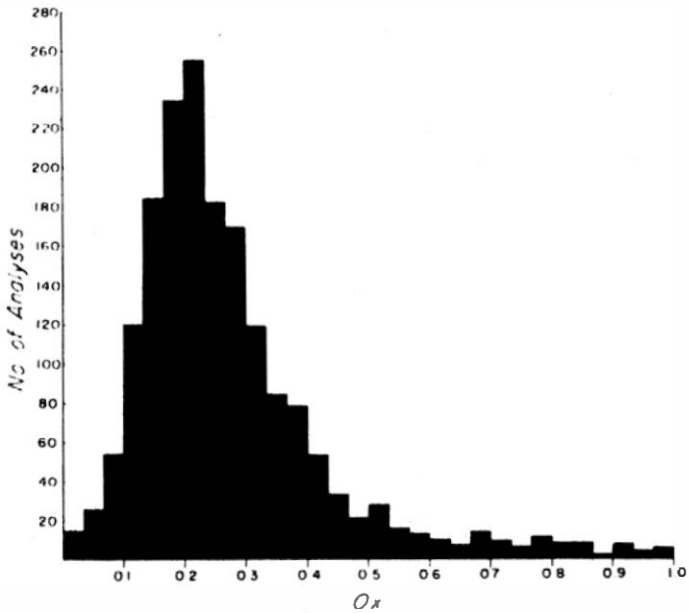

Figure 1.
Sample distribution of the ratio
Ox = molar Fe_2O_3/(molar Fe_2O_3 + molar FeO).

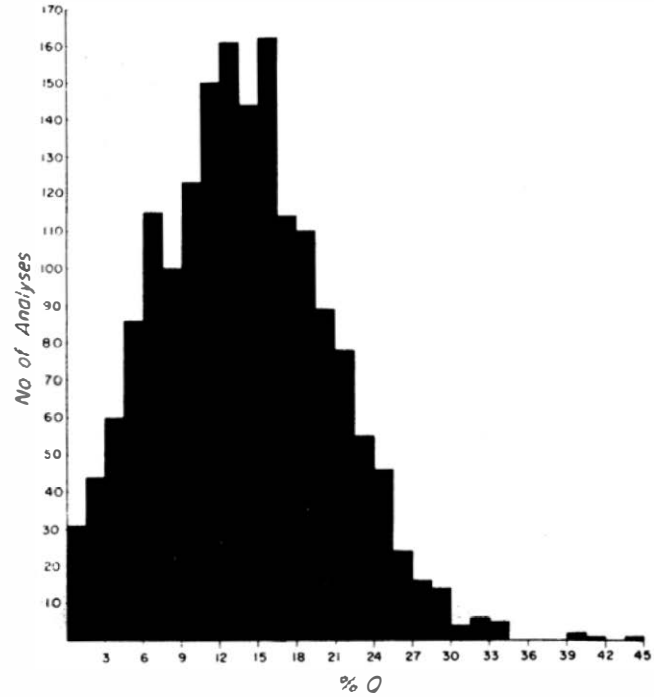

Figure 2.
Sample distribution of normative q.

that for ob + on is shown in column 4 of table 3. The average an content is 27.30 percent, so the ratio of average on to average (ob + on) is 0.502, and this is probably not very different from the average of the ratio. The sample distribution of the ratio, unfortunately, cannot be inferred from those of its numerator and denominator. It is interesting that the variance of (ob + an) is less than the variance of either on or ab, so that on and ab must be negatively correlated; in fact the product moment correlation between them is -0.59, so that 35 percent of the variation of either may be described as an inverse linear response to variation in the other.

(e) Normative color index. As an estimate of its associated modal parameter, the normative color index* enjoys the same advantages and suffers from the same disadvantages as the normative ratio on/(ob + on). Petrographers are inclined to take a more generous attitude toward it, however, for they are nearly always unwilling and are frequently unable to obtain estimates of the modal color index micrometrically. The average value of the normative color index in the data upon which this paper is based is 21.3 percent; unfortunately, as with the ratio on/(ob + on), its frequency distribution has not been obtained at the present writing. The on content of normative plagioclase and the normative color index will be discussed more fully in a later communication.

The H_2O Content of Andesites

From the often explosive character of andesite eruption and the abundance of pyroclastic materials found among its products it is clear that the H_2O content of andesite magma is far from negligible. The sample frequency distribution of total H_2O is shown in table 3. The average value for total H_2O is 1.24, but the distribution is strongly skewed and almost J-shaped. The median is between 1 and 1.1, suitably close to the mean, but the mode is in the vicinity of 0.5. The observed H_2O content of andesite of course provides no sound basis for estimating the H_2O content of andesite magma, since much H_2O may escape as steam during eruption and a large but variable and unknown amount may be added after solidification, either hydrothermally or by surficial weathering.

The sorting programs used in preparing this report contain an option permitting rejection of analyses having more than some given amount of H_2O, the specific amount being one of the input variables. Considerable experimentation has shown that the effect of this option on the sample distributions of oxides, and of many normative parameters as well, is very slight. The principal effect of H_2O-based rejections is simply to reduce sample size, and here it may be devastating; as has been noted above, for example, if analyses containing over 2 percent of H_2O are rejected, the sample size is reduced by more than 27 percent. All of the frequency distributions recorded in tables 2 and 3 are for the full sample.

* In these rocks the sum of normative oxides and silicates other than q, or, ab, an, and ne.

Acknowledgments

The rock analysis file has benefited enormously from the labors of Y. Suzuki, D. Velde, and W. Bryan. To minimize clerical work and avoid the danger of unauthorized release of data, the collection is largely confined to published analyses. Temporary exceptions to this rule hove been made for the purpose of this report; I om grateful to A. McBirney, R. Forbes, Y. Katsui, and D. Wise for prepublication release of data for Alaska, the western United States, Central and South America. Much of this information appears publicly for the first time elsewhere in this volume. G. Ponto kindly provided the Hungarian data and the related bibliography. The distribution of the variable hy/(di + hy) was examined at the suggestion of H. S. Yoder, Jr. I om indebted to him and to W. Bryan for much thoughtful comment and criticism, and wish also to thank L. Finger for generous and ingenious assistance with the programming.

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ANDESITE IN TIME AND SPACE

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Abstract

Andesite, as defined by SiO_2 - alkali relation, occurs in various ages from early Precambrian (older than 2400 m.y.) to Recent. Although it is the most predominant rock type in the orogenic belts, it occurs also in non-orogenic continental areas, island arcs in oceans, and typical oceanic islands. Thus its occurrence is not necessarily related with the presence of sialic crust. Basalt, andesite, dacite, and rhyolite are less alkalic in composition on the oceanic side of continental margins and island arcs than those on the continental side. Andesites of lower alkali contents are associated with low-alkali tholeiite, and those of higher alkali contents with high-alkali tholeiite and high-alumino basalt. This association indicates that the andesites of differing alkali contents are derived from the different basalt magmas through fractionation.

Introduction

Andesite is by far the most voluminous material erupted along the orogenic belts, active continental margins, and island arcs. Some geologists appear to suppose that its average composition is close to the estimated gross average composition of the continental crust. In connection with the genesis of this important rock type, it is worthwhile to review its distribution in different geologic ages and different geologic environments, and also the association of andesites of different chemical compositions with different primary basalt magma types. However, it is necessary to make such a review on the common basis regarding the usage of the term "andesite."

Definition

Most geologists would agree that the term "andesite" is used for rocks with SiO_2 contents intermediate between those of basalt and dacite, say between 53 and 65%, and alkali contents lower than those of mugearite, trachyandesite, and trachyte having the same SiO_2 range as that of andesite. Andesite is generally silica-oversaturated.

Figure 1 illustrates the SiO_2-total alkali relation of tholeiite and high-alumina basalt and associated andesite, dacite, and rhyolite and that of alkali basalt, mugearite, trachyandesite, trachyte, and alkali rhyolite, all of Miocene to Recent age, from central Japan, Korea, and Manchuria. In this figure, line AB separates the field of the alkali rocks above from that of the basalt-rhyolite series below. The latter is further divided by line CD into the fields of the rock series derived from the high-alumino basalt magma and that derived from the tholeiite magma. It has been shown elsewhere (Kuno, 1966a) that most basalt-rhyolite series of the Circum-Pacific belt and Indonesia also plot either between lines AB and CD or below line CD. Fig. 2 shows one such example.

Some rocks of oceanic islands which plot above line AB were once called "andesine andesite" and "oligoclase andesite," but Macdonald (1960) proposed to discard these names and call them "hawaiite" and "mugearite" respectively. They all plot above line AB of Fig. 1.

Some petrologists appear to restrict the use of the term andesite to those rocks with comparatively low $\Sigma FeO/MgO$ ratio. In other words, those rocks produced by fractionation with enrichment of iron relative to MgO are not called andesite.

In Fig. 3 are plotted aphyric rocks of the pigeonitic and hypersthenic rock series of the Izu-Hakone region. The intermediate rocks of the former series have high $\Sigma FeO/MgO$ and some of them have ΣFeO even higher than 10% (Table 1).

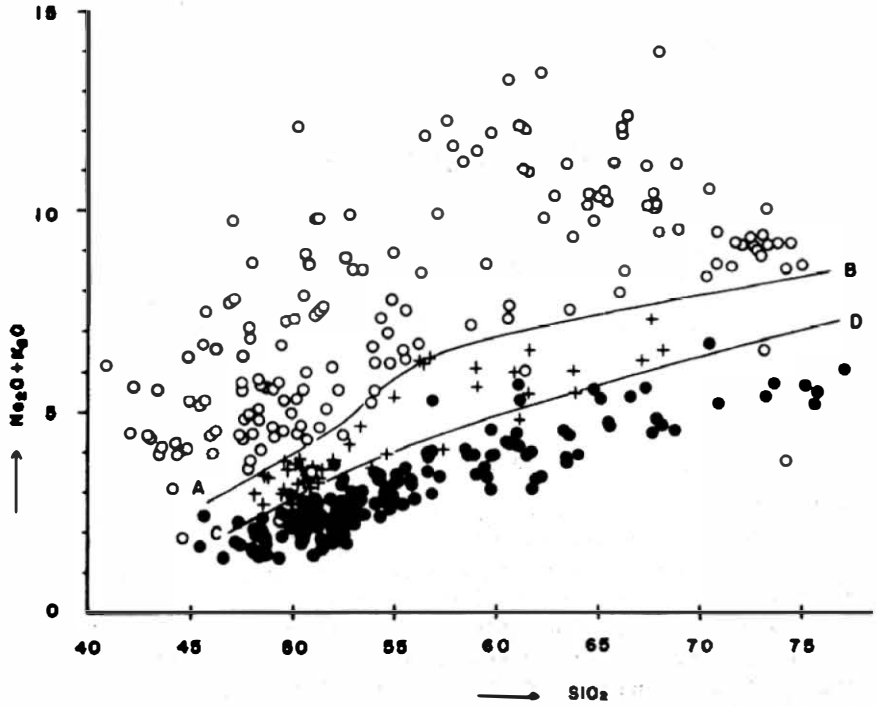

Figure 1. $Na_2O + K_2O$ versus SiO_2 diagram for aphyric and porphyric volcanic rocks from Izu-Hakone (the pigeonitic rock series in solid circles), from Huzi and Sidara (the high-alumina basalt series in crosses), and from Japan Sea side of southwestern Japan, Korea, and Manchuria (the alkali rock series in open circles). Lines AB and CD represent the general boundaries between the fields of the three series.

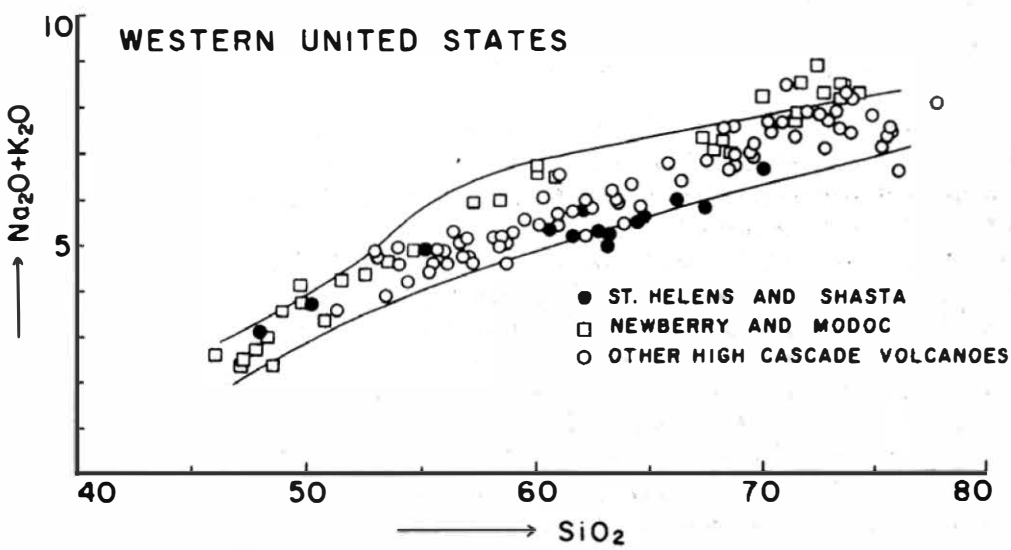

Figure 2. $Na_2O + K_2O$ versus SiO_2 diagram for volcanic rocks of the High Cascades. The curves are the reproduction of lines AB and CD of Fig. 1.

Table 1. Chemical analyses of some andesites with high Σ FeO/MgO ratios.*

	1	2	3	4	5	6	7
SiO_2	60.52	63.84	62.37	54.68	60.59	59.39	59.64
Al_2O_3	12.90	15.82	12.04	12.88	15.07	14.32	14.61
Fe_2O_3	2.82	0.95	1.87	1.76	2.31	2.60	4.28
FeO	8.68	5.02	5.81	10.32	5.73	5.41	3.88
MgO	2.18	1.67	0.97	2.74	1.73	2.13	2.10
CoO	6.91	4.88	3.51	6.29	4.94	5.12	4.68
Na_2O	2.70	3.88	3.47	3.28	4.29	4.44	4.24
K_2O	1.52	2.12	2.34	1.64	1.59	2.40	1.96
H_2O+	0.10	0.45	5.54	3.03	1.58	1.68	1.67
H_2O-	0.22	- -	0.44	0.81	0.26	0.18	0.29
TiO_2	0.74	0.87	1.06	1.91	1.25	1.91	1.74
P_2O_5	0.02	0.22	0.30	0.13	0.43	0.51	0.47
MnO	0.15	0.17	0.24	0.14	0.19	0.17	0.14
SrO	0.09	- -	- -	- -	- -	- -	- -
Others	0.05	- -	0.07	- -	- -	- -	- -
Total	99.60	99.89	100.03	99.61	99.96	100.26	99.70
Norm. Q	18.54	18.14	22.98	8.67	15.42	10.99	15.64

* Explanations:

1. Aphyric andesite, an Old Somma lava of Hokone Volcano, Japan. Analyst, K. Nagashima.
2. Aphyric andesite obsidian, on essential block ejected in 1707. Huzi Volcano, Japan. Analyst, S. Tanaka (Tsuya, 1955).
3. Pigeonite-bearing andesite (inninmorite) from Mull, Scotland. Analyst, Radley (Bailey et ol., 1924).
4. "Basalt" of Deccan traps from Bombay Island (SiO_2 = 57.09 on anhydrous basis). Analyst, H. B. Wiik (Sukheswola and Poldervaart, 1958).
5. Andesite (icelandite) from Thingmuli Volcano, Iceland. Analyst, I.S.E. Carmichael (Carmichael, 1964).

6. and 7. Andesites of the Galápogos Islands. Analyst, K. Aoki (McBirney and Aoki, 1966).

However, Kuno (1950) classified all the intermediate rocks of the two series as andesite, disregarding Σ FeO/MgO and absolute amount of Σ FeO, because they oll plot below line AB of Fig. 1 and have color indices between the proposed arbitrary limits of 35 and 10 (Kuno, 1950).

Rocks with Σ FeO/MgO similar to those of the intermediate rocks of the pigeonitic rock series and with SiO_2-alkali relation lying below line AB of Fig. 1 ore described from some regions other than Japan. Chemical analyses of some of these rocks are quoted in Table 1 and ore plotted in Figs. 4 and 5.

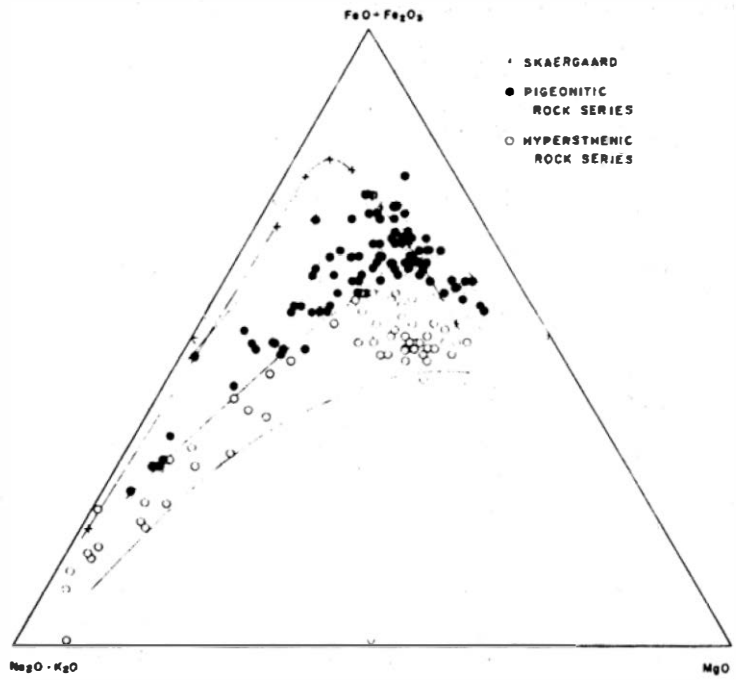

Figure 3. MgO--FeO + Fe_2O_3 x 0.9--Na_2O + K_2O diagram for aphyric rocks of the pigeonitic and hypersthenic rock series from Izu-Hakone. The curves represent the general limits of the fields for the two series.

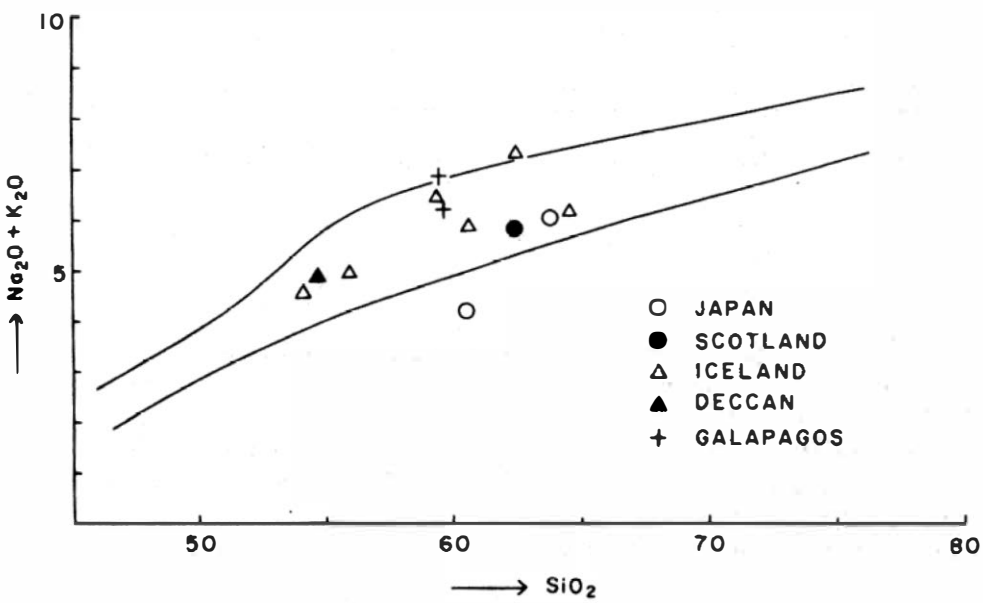

Figure 4. Na_2O + K_2O versus SiO_2 diagram for the andesites of Table 1. All the "basaltic andesites" and "andesites" of Iceland (Carmichael, 1964) are also plotted. The curves are the reproduction of lines AB and CD of Figure 1.

Whether the rocks quoted in Table 1 are called andesite or not depends completely on personal preference. In view of the absence of any reason to introduce a new petrographic name for such rocks, the term andesite is used throughout this paper.

Distribution in Time

The oldest known rocks in the Canadian shield comprise suites of rocks including tholeiite and high-alumina basalt, andesite, dacite, and rhyolite. They are found from several localities in southern North West Territories, eastern Ontario, western Quebec, and northern Minnesota (Baragar, 1966; Goodwin, 1967 and oral communication, 1967). Although they are older than 2400 m.y., they are so little metamorphosed that their original chemical compositions are still retained. The andesites of the suites are generally low in alkalies and in $\Sigma FeO/MgO$.

It is quite likely that volcanic rocks of andesitic composition are commonly present among other Precambrian rocks, but because of the absence of chemical analyses, they are not properly classified. In addition, where these rocks are altered or metamorphosed to greenschist, amphibolite, etc., they are usually described as basic volcanic rocks and are even supposed to have been originally "basalt."

Andesites are also common among Paleozoic and Mesozoic formations, but partly for the same reasons as those above mentioned, they are little recognized as such. For example, some volcanic rocks interbedded with the younger Paleozoic eugeosynclinal deposits of Japan appear to be andesite, but no chemical analysis is available.

A great amount of andesitic volcanic rocks is represented among the Jurassic and Cretaceous formations of southern and eastern Manchuria. A thick sequence of andesite was deposited in the Cretaceous basin extending from southern Korea to southwestern Japan.

The common occurrence of andesite in Cenozoic orogenic belts is well known and its petrographic characters are described in detail.

Distribution in Space

Andesite is the most predominant rock type in the orogenic belts and island arcs. Its occurrence is not necessarily connected with the granitic crust. Thus andesite occurs commonly in oceanic island arcs such as the Izu-Marianas and the South Sandwich. The Izu-Mariana Islands are not floored by the granitic crust. Andesite occurs even in the Galapagos Islands (Table 1) which are typical oceanic islands, though in small quantity.

In non-orogenic continental regions, andesite is found in association with tholeiitic plateau basalt such as in western Scotland, Deccan, and Parana, Brazil. These oceanic and non-orogenic continental andesites are mostly high in $\Sigma FeO/MgO$ (Table 1 and Fig. 5), indicating that they are products of fractionation of basalt magmas under moderately low oxygen partial pressure (Osborn, 1959; 1962). Kuno (1968) classified these andesites as belonging to the moderate-iron concentration type of tholeiite and high-alumino basalt series.

Field Associations with Different Basalt Magma Types

In the Circum-Pacific volcanoes, andesite may or may not be associated with basalt. Even in the latter case, basalt is almost invariably present within the same province if broadly taken. Basalt associated with andesite is either tholeiite or high-alumino basalt. Andesite associated with tholeiite is generally lower in alkalies than that associated with high-alumino basalt, if rocks of the same SiO_2% are compared. This relation holds both for andesites with high and low $\Sigma FeO/MgO$ (Kuno, 1966a), indicating their close genetical connection with the respective basalt magma types.

In Iki Island and some other regions of southwestern Japan (Aoki, 1959; Aoki and Ōji, 1966) and in the Mozambique region, eastern Africa (Holmes, 1916), andesite is closely associated with alkali basalt. This would suggest that andesite is produced from alkali basalt magma, possibly through contamination by granitic material.

Rocks Nos. 1 and 2 of Table 1, both from Japanese volcanoes, were probably derived from low-alkali tholeiite magma and high-alumino basalt magma respectively, as judged from their association with these basalt types in the respective volcanoes. Among the basalts of oceanic islands and among the plateau basalts, high-alumino basalt is rather rare and its place is taken by high-alkali tholeiite which plot between lines AB and CD of Fig. 1. Thus in Hawaii, a complete gradation is seen from low-alkali tholeiite like the Japanese tholeiite, passing through high-alkali tholeiite, to alkali basalt

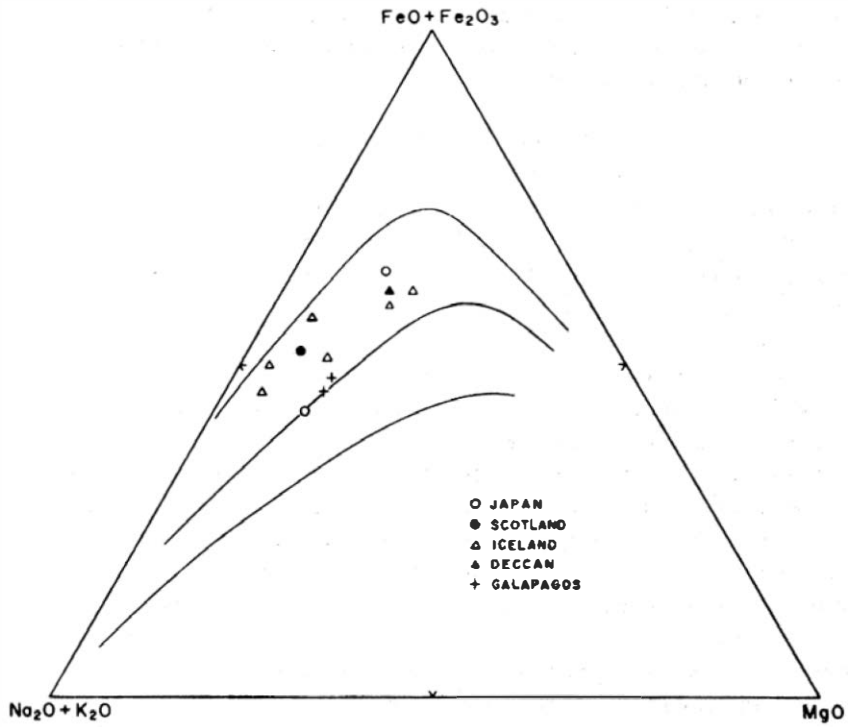

Figure 5. MgO--FeO + Fe_2O_3 x 0.9--Na_2O + K_2O diagram for the rocks plotted in Figure 4. The curves are the reproduction of those in Figure 3.

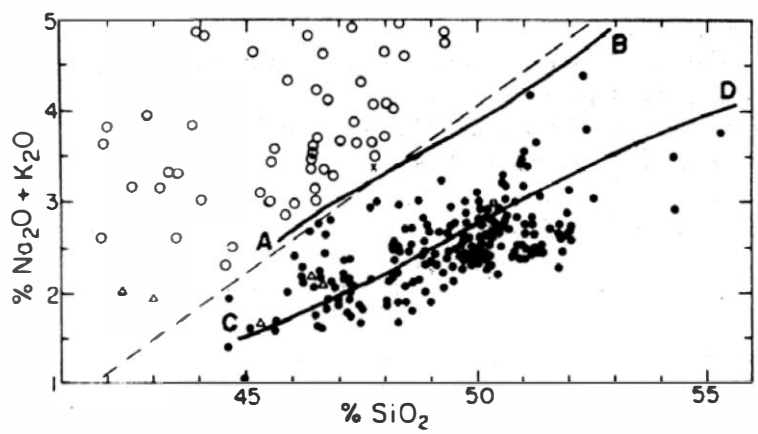

Figure 6. Na_2O + K_2O versus SiO_2 diagram for Hawaiian tholeiite (solid circles) and alkali basalt (open circles) after Macdonald and Katsura (1964). The broken line is the boundary between the fields for the tholeiite and alkali basalt as given by the authors. Lines AB and CD are reproduction of those in Figure 1. Note that line AB coincides with the boundary between the Hawaiian tholeiite and alkali basalt.

(Fig. 6) (Kuno, 1965; 1967). As judged from their positions in Fig. 4, the andesites from Scotland, Iceland, Deccan, and Galápagos may have been derived from the high-alkali tholeiite.

Lateral Variation of Andesite Composition Across Continental Margin and Island Arcs

Kuno (1966a) has shown that zones of tholeiite, high-alumina basalt, and alkali basalt, all of Quaternary age, are arranged from the Pacific side to the continental side of the Japanese Islands. He also showed that Quaternary andesite, dacite, and rhyolite occurring within the tholeiite zone are less alkalic than those within the high-alumino basalt zone, if rocks of the same SiO_2 percent are compared, and that a similar zonal variation of volcanic rock composition exists in most parts of the Circum-Pacific belt and Indonesia.

This association strongly indicates that the andesite, dacite, and rhyolite of these regions were produced by fractionation of both the tholeiite and high-alumina basalt magmas. Contamination may have played a role, but its effect was not so strong as to mask the chemical characteristics of these differentiates inherited from their parent basalts.

The association in question is very difficult to explain by the theories which attribute the origin of andesite magma to the partial melting of eclogite in the mantle (Green and Ringwood, 1967) or to the melting of some older crustal material.

Chemical analyses of pre-Quaternary volcanic rocks of these regions are rather scanty, except for some limited regions, so that it is not certain whether a similar variation exists among Tertiary and pre-Tertiary rocks. However, Chihara (1967) and others (unpublished data quoted in Kuno, 1966b) found that Miocene volcanic rocks of the northeastern Honsyu show a variation similar to that of the Quaternary rocks. It is very likely that the Japanese Tertiary volcanic rocks in general show a similar relation.

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HIGH PRESSURE EXPERIMENTAL STUDIES ON THE ORIGIN OF ANDESITES

Trevor H. Green[1/] and A. E. Ringwood [2/]

Abstract

A high pressure experimental study of the partial melting fields of synthetic high-alumino olivine tholeiite, high-alumino quartz tholeiite, basaltic andesite, andesite, dacite and rhyodacite under dry and hydrous ($P_{H_2O} < P_{LOAD}$) conditions has been carried out to evaluate proposed hypotheses of origin of the calc-alkaline series from the upper mantle.

At 27-36 kb garnet and clinopyroxene are the liquidus or near-liquidus phases in dry tholeiite, basaltic andesite and andesite while quartz is the liquidus phase in dry dacite and rhyodacite. The calculated compositions of liquid fractionates for varying degrees of melting of the quartz eclogite bulk composition broadly follow the calc-alkaline trend. At 9-10 kb under hydrous conditions ($P_{H_2O} < P_{LOAD}$) sub-silicic amphibole and pyroxenes are the near-liquidus phases in tholeiite and basaltic andesite compositions. Calcic plagioclase and garnet occur nearer the solidus. The calculated liquid fractionates follow the calc-alkaline trend.

These experimental results support two complementary models for the derivation of the calc-alkaline igneous rock suite from the mantle by a two-stage process, either (1) by partial melting of quartz eclogite at 80-150 kms depth or (2) by partial melting or fractional crystallization of hydrous basalt or amphibolite at 15-80 kms depth. There is probably a complete continuum of fractionation processes occurring with increasing depth. Thus in the downward sinking mafic oceanic crust of a convection cell (as in the hypothesis of sea-floor spreading) if partial melting takes place at depths of 15-45 kms. fractionation trends will be governed mainly by separation of amphibole, but at 45-80 kms trends will be governed by separation of garnet, clinopyroxene and amphibole, and at 80-150 kms garnet and clinopyroxene separation will determine the liquid fractionation trends. This may result in definitive chemical characteristics (eg K_2O content) of various calc-alkaline suites, depending on their depth of origin.

Introduction

Members of the calc-alkaline igneous rock suite, particularly andesites, are the major igneous rock types found associated with active orogenic areas, especially in continental margin and island arc regions (e.g. Circum-Pacific belt). These areas are believed to be places of active continental growth, and if as has been suggested by Rubey (1951, 1955) and Wilson (1954) the continental crust has developed gradually over geological time as a result of processes occurring in the mantle, then some mechanism for origin of the calc-alkaline suite from the upper mantle would provide the most satisfactory means of obtaining new continental crust. Such a mechanism would be in harmony with observed abundance and occurrence of common igneous rocks, and with some geochemical models for the over-all composition of the continental crust (Taylor and White, 1965). Accordingly, the problem of derivation of sialic material (viz., the calc-alkaline series) from the mantle merits consideration, and this contribution summarizes on experimental approach directed towards investigating proposed models for the mantle origin of the calc-alkaline rocks. A complete description and discussion of the experimental work involved has been given elsewhere (T. H. Green and Ringwood, 1968a).

Other Investigations

One of the earliest proposals for the origin of the calc-alkaline suite was by fractional crystallization of a basaltic parent (Bowen, 1928). A key factor in this proposal to obtain more silica-enriched

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daughter liquids was the incongruent melting of enstatite to form olivine + silica-rich liquid, known to occur at atmospheric pressure. Later, Boyd and England (1963) showed that this reaction relation probably occurs at pressures of up to 5 kb under dry conditions, but at pressures higher than 5 kb congruent melting takes place. Thus oversaturated liquids may only be derived from olivine-normative parent compositions at depths of less than about 15 km by fractional crystallization under dry conditions. However, several lines of evidence indicate that the calc-alkaline series is not derived by fractional crystallization of a basaltic parent under dry conditions at these depths (Poldervoart and Elston 1954, T. H. Green and Ringwood 1968a).

O'Hara (1963a, b) demonstrated that under dry conditions at pressures of 30 kb the garnet-pyroxene tie line forms a thermal barrier between undersaturated olivine-and oversaturated quartz-bearing assemblages. Thus oversaturated magmas may only be derived at great depth in a dry mantle if parent oversaturated compositions (e.g. quartz eclogite) are present in the mantle and undergo partial melting. However, there is abundant evidence that the mantle has an over-all undersaturated composition, probably approximating to 3 parts peridotite and 1 part basalt (termed pyrolite, Ringwood 1966). Hence, from Boyd and England's results and O'Hara's results, it is apparent that oversaturated calc-alkaline suite rocks cannot be derived by a simple, single-stage process of melting of a dry upper mantle.

In the present work two complementary two-stage models for the origin of calc-alkaline rocks (particularly andesites) are investigated.

The first model resulted from an hypothesis for a mechanism for orogenesis formulated by Ringwood and D. H. Green (1966) on the basis of experimental work on the basalt-eclogite transition. Their work showed that given favourable reaction kinetics basalt would transform to eclogite at the pressure-temperature conditions existing in the earth's crust. It is envisaged that in the first stage of a cycle of active orogenesis and continental growth, large piles of basalt ore extruded. Over a long period of time this basalt pile may transform to quartz eclogite*. The quartz eclogite ($\rho \sim 3.45$ gm/cm^3) is denser than the ultramafic upper mantle ($\rho \sim 3.3$ gm/cm^3), and if the mass is large enough, it begins to sink into the mantle. In the early stages, sinking is relatively slow, and results in formation of a geosyncline. At a later stage, sinking becomes catastrophic, leading to severe crustal deformation and folding of the geosyncline. Eventually the sinking eclogite reaches a level in the mantle (probably at depths of 100-150 kms) where the combined effect of increase in temperature resulting from viscous dissipation and increase in temperature with depth is sufficient to cause partial melting of the eclogite. Magmas thus produced rise upwards and it is suggested that these magmas may represent the calc-alkaline suite, and contribute to new continental crust in orogenic areas.

There is a strong link between such a two-stage model for the derivation of the calc-alkaline series by partial melting of quartz eclogite and the concept of sea-floor spreading (Hess 1962). In this concept the location of the downward movement of many of the proposed convection cells corresponds to the location of calc-alkaline volcanism in island-arc regions. This connection may be explained in terms of the basalt-eclogite transition (Ringwood and D.H. Green 1966). Newly formed basaltic or omphibolitic oceanic crust spreads from the ridges towards the continental margins where it is forced under the continents forming the oceanic trench systems. As the oceanic crust is forced deeper it is subjected to higher pressure and higher temperature conditions, and the basalt to eclogite transformation takes place. The dense eclogite continues sinking into the mantle, and eventually undergoes partial melting. As indicated above, the magmas so produced may represent the calc-alkaline series and intrude upwards into the island arc regions.

The second model involves partial melting of a basic lower crust under hydrous conditions or alternatively fractional crystallization of basalt under hydrous conditions at 30-40 kms depth. This hypothesis has appeared frequently in the literature (Daly 1933, Coots 1962, Hamilton 1964, Lidiak 1965, and Branch 1967) but until the present work, had not been subjected to a quantitative experimental investigation. The necessary conditions may be obtained when a rising basalt magma derived from partial melting of the mantle at greater depths (e.g. D. H. Green and Ringwood 1967b) is contaminated with

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* There is an extensive range of olivine-normative basaltic compositions which, together with quartz-normative basalts, will transform to quartz-bearing eclogites under appropriate conditions (e.g. high-alumino olivine tholeiite with 9.3% normative olivine has 8.5% normative quartz when calculated in terms of on eclogite norm -Ringwood and D. H. Green, 1966). Most basalts occurring in large scale basaltic volcanic provinces, e.g. Hawaii (Macdonald and Kotsura 1964) and Iceland (Carmichael, 1964) are olivine or quartz-normative tholeiites and fall into the category producing quartz-bearing eclogites, if they transform to an eclogite assemblage.

water at depths of 30-40 kms. Subsequent fractional crystallization under conditions of $P_{H_2O} < P_{LOAD}$ will involve a large separation of amphibole and to a lesser extent ortho-and clino-pyroxene and possibly calcic plagioclase and garnet. The residual liquids derived from this crystallization may correspond to members of the calc-alkaline suite.

Alternatively the derivation of calc-alkaline magmas may be the result of a two-stage hydrous process (complementary to the two-stage anhydrous process outlined earlier). In this case, access of water to the large pile of basalt developed in the first stage, results in conversion of the basalt to amphibolite (rather than to eclogite as in the anhydrous case). Subsequent heating of this amphibolite may result in partial melting. The pressures at which the melting takes place may be as high as 10 kb, corresponding to the base of the crust, and the water vapour pressure is likely to be less than the load pressure.

The hypothesis of origin of calc-alkaline rocks involving hydrous conditions may also be related to the concept of sea-floor spreading. Thus the sinking limb of the convection cell may introduce water from the hydrosphere into the mantle, either contaminating rising basalt magma, altering the nature of the crystallizing phases, or causing the sinking basic oceanic crust to change to amphibolite, as required in the second case of this hypothesis, described above. This link with the sea-floor spreading hypothesis also may explain the occurrence of calc-alkaline rocks in a particular tectonic environment viz. associated with the down-moving limb of the convection cell driving the spreading of the sea floor.

Experimental Procedure

The details of the procedure are reported by T. H. Green and Ringwood 1968a; briefly, a series of synthetic glasses with compositions corresponding to typical members of the calc-alkaline series were prepared. The compositions are given in Table 1. These glasses were crystallized in platinum capsules under anhydrous conditions over a range of pressures and temperatures, using a piston-cylinder solid medium pressure apparatus (Boyd and England 1960 and T. H. Green, Ringwood and Major 1966). Experiments were conducted under hydrous conditions at only 9-10 kb, in both platinum and graphite capsules. At the conclusion of a run the sample was examined optically and by x-ray diffraction, to identify the phases present and estimate their relative proportions. Where the crystal size was large enough, polished mounts were prepared and phases were quantitatively analyzed using an electron microprobe (ARL, EMX model).

The electron microprobe analytical technique adopted consists of analyzing the unknown phases and comparing their compositions with a series of standards of approximately similar composition (e.g. olivine, garnet and amphibole natural mineral standards and synthetic glasses of approximate orthopyroxene, clinopyroxene and feldspar compositions). Using this direct calibration method, no corrections have been made for matrix effects, and the method of counting for fixed specimen currents has been followed. The accuracy of analysis is sufficient for the purpose of indicating fractionation trends of major elements in typical calc-alkaline compositions under certain P-T conditions, which is the main aim of this experimental work.

Anhydrous experiments

A. Results: Qualitatively, the experiments show that in the high-alumino olivine tholeiite, high-alumina quartz tholeiite, basaltic andesite and andesite compositions, the crystallization is dominated by pyroxene and plagioclase from 0-18 kb, with the proportion of pyroxene increasing relative to plagioclase with increasing pressure. In contrast, at 27-36 kb the major crystallizing phases in each of the above compositions are garnet and clinopyroxene. The proportion of garnet relative to clinopyroxene near the liquidus increases with increasing pressure and with increasing silica content. Thus garnet is the liquidus phase in andesite at 27-36 kb, joined by pyroxene at lower temperatures, and the proportion of garnet relative to pyroxene is higher near the liquidus in the basaltic andesite at 27-36 kb than in the basaltic compositions. In the dacite composition plagioclase is the liquidus phase at 9 kb, changing to quartz at 18 kb, and at higher pressures. Quartz is joined by garnet and clinopyroxene at lower temperatures in the high pressure region. Quartz is also the liquidus phase in the rhyodacite composition at 27 kb.

Another important qualitative feature of these results is that the liquidus of the andesite falls in a marked low temperature trough between more acid and more basic compositions at high pressure as shown in fig. 1 where the extrapolated liquidus temperature and sequence of crystallization of near-liquidus phases are given for the compositions ranging from high-alumino quartz tholeiite to rhyodacite.

EXPLANATION OF FIGURES ON OPPOSITE PAGE

Fig. 1. Extrapolated liquidus temperatures and sequence of crystallization at 30 kb (adamellite = rhyodacite). Solid line represents liquidus, dashed line inferred solidus.

Fig. 2. Experimentally determined fractionation trends at 18 kb shown on on FMA plot. Note: In this and subsequent FMA diagrams: F = FeO + 0.9 Fe_2O_3; M = MgO; Alk = Na_2O + K_2O; OT = high-alumino olivine tholeiite; QT = high alumino quartz tholeiite; BA = basaltic andesite; A = andesite; D = dacite.

Fig. 3. FMA plot showing experimentally determined fractionation trends at 27 kb. The encircled points represent the plots of the residua - the numbers correspond to the numbered points on the fractionation trends.

Fig. 4. FMA plot showing experimentally determined fractionation trends at 36 kb. The encircled points represent the plots of the residua - the numbers correspond to the numbered points on the fractionation trends.

Fig. 5. FMA plot for the Aleutian Islands colc-alkaline province (from data collected in Green 1967). The experimentally determined fractionation trends at 27-36 kb are superimposed on this plot os solid lines for comparison between the natural and experimental fractionation trends.

Fig. 1

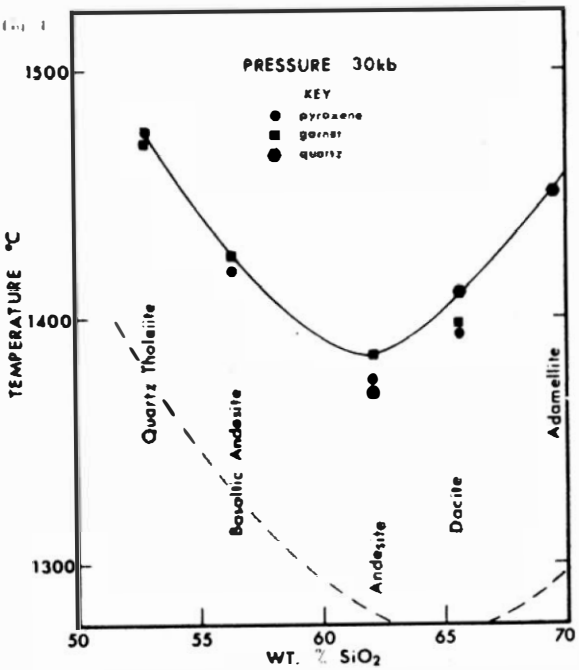

Fig. 3

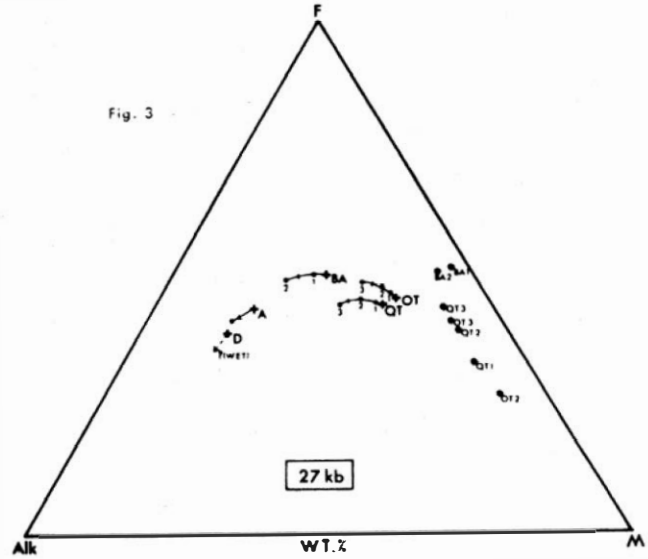

Fig. 2

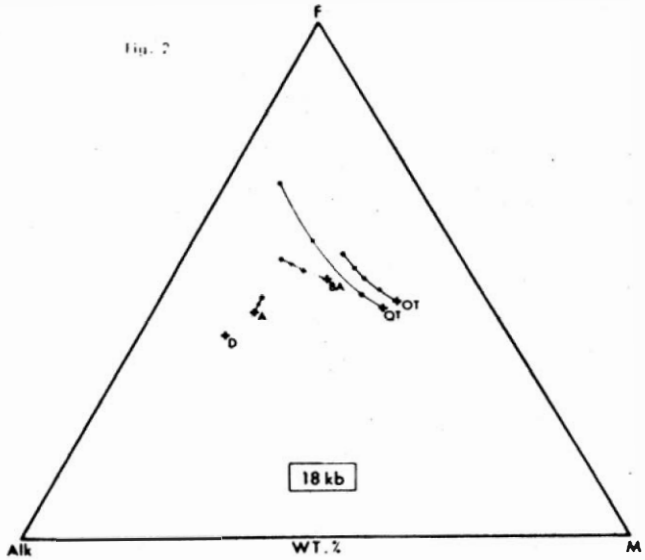

Fig. 4

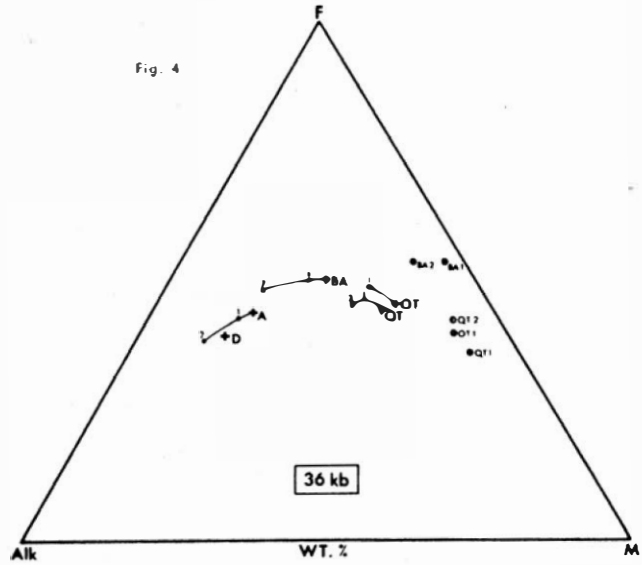

Fig. 5

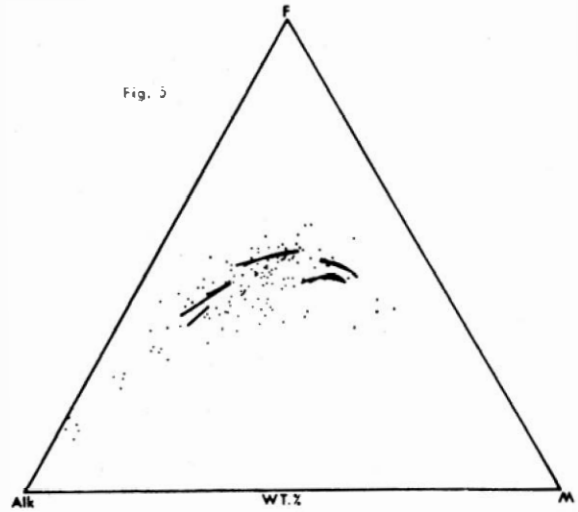

Table 1. Compositions and norms of rock mixes used in the experimental work.

	1. High-alumina olivine tholeiite	2. High-alumino quartz tholeiite	3. Basaltic andesite	4. Andesite	5. Dacite	6. Rhyodacite 1[c] (adamellite)
SiO_2	50.3[a]	52.9	56.4	62.2[a]	65.0[a]	69.6
TiO_2	1.7[a]	1.5	1.4	1.1[a]	0.7[a]	0.6
Al_2O_3	17.0[a]	16.9	16.6	17.3[a]	16.1[a]	14.7
Fe_2O_3	1.5[b]	0.3[b]	3.0[b]	0.3[b]	1.4[b]	1.7[b]
FeO	7.6[b]	7.9[b]	5.7[b]	5.9[b]	3.5[b]	1.8[b]
MnO	0.16	0.2	0.1	0.1	0.1	0.1
MgO	7.8[a]	7.0	4.3	2.4[a]	1.8[a]	1.0
CaO	11.4[a]	10.0	8.5	5.2[a]	5.0[a]	2.5
Na_2O	2.8[a]	2.7	3.0	3.3[a]	3.6[a]	3.4
K_2O	0.18[a]	0.6	1.0	2.3[a]	2.1[a]	4.6
	100.4	100.0	100.0	100.1	99.3	100.0
MOL. PROP. $\frac{100\ MgO}{MgO + FeOTotal}$	60.7	60.4	47.7	41.0	40.3	36.0
CIPW NORMS						
Qz	- -	1.3	10.7	15.5	21.7	25.3
Or	1.1	3.5	5.9	13.6	13.0	27.2
Ab	23.7	22.8	25.4	27.9	30.5	28.8
An	33.3	32.2	28.9	25.7	21.5	11.2
Diop	18.9	14.2	10.8	0.2	2.3	0.9
Hyp	11.9	22.6	11.3	14.8	7.7	3.0
Ol	6.2	- -	- -	- -	- -	- -
Mt	2.2	0.4	4.3	0.4	2.0	2.5
Ilm	3.2	2.8	2.7	2.1	1.3	1.1

[a] Denotes content determined by electron probe analysis of a glass fragment.
[b] Denotes chemically determined content (E. Kiss, A.N.U., analyst).
[c] Prepared by D. H. Green and Lambert (1965).

This diagram also clearly shows the change in liquidus phase from garnet to quartz as the composition changes from andesite to dacite.

Quantitatively, important compositional features of the garnet and clinopyroxene crystallizing at 27-36 kb include a high alumino content (and low silica content) of the pyroxene, increase in almandine content of the garnet as the bulk composition changes from basalt to rhyodacite, and higher Fe/Mg ratio of garnet compared with coexisting clinopyroxene.

B. Interpretation of results: The higher liquidi of the dacite and rhyodacite, and the presence of quartz on the liquidus of these two compositions at pressures of 27-36 kb under anhydrous conditions, indicate that at depth andesite is a lower melting fraction than the more acid composition. Thus at depths of 100-150 kms fractional crystallization of basalt and basaltic andesite by separation of garnet and clinopyroxene will cause the composition of the liquid fractionate to move towards that of andesite.

The importance of garnet and aluminous clinopyroxenes as the cocrystallizing phases in the basaltic composition is that because of their subsilicic character, they provide a highly efficient means of

enriching the fractionating liquid in silica and alkalies. A sharp rise in the Fe/Mg ratio of the liquid, due to crystallization of low Fe/Mg clinopyroxene is precluded by the simultaneous crystallization of olmandine-rich garnet.

Calculation of fractionation trends

Using the probe determined compositions of the crystallizing phases and estimating their relative proportions by optical and x-ray means, the fractionation trends at various pressures hove been calculated. These ore illustrated in the FMA diagrams of figs. 2-4. At 18 kb where crystallization is dominated by pyroxene, and to a lesser extent plagioclase, there is a morked trend towards iron-enrichment (cf. Skaergaard, Wager 1960; Thingmuli, Iceland, Carmichael 1964). In striking contrast to this trend, at 27 and 36 kb there is no pronounced iron enrichment, and instead the calculated liquid compositions broadly follow the colc-alkaline trend. This is shown in fig. 5 where the experimentally determined trends at 27-36 kb ore superimposed on on FMA plot for the Aleutian Islands colc-alkaline province.

The results have so for been discussed in terms of fractional crystallization of a basaltic composition at high pressure. However, the some observations apply to the reverse case of fractional melting of a similar composition at high pressures where the sub-solidus mineral assemblage consists of garnet, clinopyroxene and quartz. It is envisaged that varying degrees of fractional melting can give rise to liquids of a typical colc-alkaline nature eg. basaltic andesite and andesite. The residuum is composed of varying proportions of garnet and clinopyroxene, depending on the degree of melting. Thus at depths of 100-150 kms, if the temperature is sufficiently high for partial melting of the eclogite to take place under dry conditions, the early forming liquid will trend towards on ondesitic composition rather than more silicic compositions. About 40-50% melting will produce a typical ondesitic composition. The degree of melting will to some extent govern the Fe/Mg ratio of the liquids obtained, since the Fe/Mg ratio of the garnet and clinopyroxene (as well as the relative proportions of garnet and clinopyroxene) varies with temperature. Thus a family of compositions with some variation in Fe/Mg ratio, but nevertheless still with an over-all calc-alkali trend showing only slight iron enrichment relative to magnesium, may be obtained by the fractional melting of eclogite at high pressure.

Hydrous experiments

A. Results: This has so for been essentially a reconnaissance investigation to observe the effect of significant water pressure (less than total pressure) on the nature and sequence of crystallization in typical colc-alkaline compositions. Because of the type of experimental apparatus avoiloble and the procedure adopted (T. H. Green and Ringwood 1968a), there has been no close control of P_{H_2O}, but at 9-10 kb the water vapour pressure has resulted in lowering the liquidi of the compositions studies by about 200° C. High-alumino quartz tholeiite, basaltic andesite and andesite compositions have been investigoted at 9-10 kb and 900-1100°C.

In the basalt, clinopyroxene is the liquidus phase at 1100°C joined by orthopyroxene and amphibole at lower temperatures (e.g. 1040°C). Amphibole is the dominant phase at 960° C and below. Plagioclase appears at 920° C. Accessory pseudobrookite (?) is also present. A similor sequence of crystallization occurs in the basaltic andesite composition. In contrast to these two compositions where plagioclase does not appear until temperatures well below the liquidus for hydrous conditions, in the andesite composition at 10 kb, clinopyroxene and plagioclase are near-liquidus phases at 940° C. These phases ore joined by garnet, amphibole, orthopyroxene and accessory pseudobrookite (?) at 900° C.

Analyses of clinopyroxene, orthopyroxene, amphibole and plagioclase crystallizing from the high-alumina quartz tholeiite have been obtained. The pyroxenes show high alumina contents (7.5 - 10.6%) and low silica contents (47.2 - 48.0%). The amphiboles are also high in alumina (14.8 - 15.8%) and low in silica (39.8 - 40.5%) and approximate to tschermakitic hornblendes. The Fe/Mg ratio in amphibole is always higher than the same ratio in the coexisting pyroxenes. The plagioclase crystallizing well below the liquidus is calcic (An_{66}) when compared with plagioclases crystallizing from similar compositions under anhydrous conditions (T. H. Green 1967).

B. Interpretation of results: In spite of the limitations of the experimental procedure these results strongly support the hypothesis for the origin of the colc-alkaline series by the hydrous partial melting at fractional crystallization of a parent basalt composition as outlined earlier (p. 23). Thus the large field of crystallization of the sub-silicic amphibole together with subordinate clinopyroxene, minor orthopyroxene and possibly calcic plagioclase, provides an efficient mechanism for silica and

Table 2. Calculated compositions of liquid fractionates and crystalline residua derived from the high-alumino quartz tholeiite at 9-10 kb under wet conditions[a].

Pressure		9 kb	10 kb	10 kb
Temperature		1,040° C	960° C	920°C
Nature and estimated % of crystals extracted	Initial liquid	18% cpx 5% omph 2% opx 1% ilm	18% cpx 25% omph 2% opx 1% ilm	18% cpx 32% omph 3% plag 2% opx 1% ilm
Liquid fractionate				
SiO_2	52.9	55.9	59.7	64.5
TiO_2	1.5	0.8	0.4	0.1
Al_2O_3	16.9	19.4	20.2	19.9
Fe_2O_3	0.3	0.4	0.5	0.7
FeO	7.9	7.2	5.8	3.7
MnO	0.2	0.3	0.3	0.4
MgO	7.0	4.4	2.1	2.0
CoO	10.0	7.8	6.7	3.9
Na_2O	2.7	3.3	3.4	3.6
K_2O	0.6	0.8	0.9	1.0
	100.0	100.3	100.0	99.8
Mol. prop. $\frac{100\ MgO}{MgO + FeO\ Total}$	60.4	50.9	37.5	45.3
CIPW norm				
Qz		5.5	14.4	25.3
Or		4.8	5.4	5.9
Ab		27.9	28.8	30.5
An		35.7	33.2	19.3
Cor		- -	1.4	5.8
Diop		2.4	- -	- -
Hyp		21.9	15.3	12.1
Mt		0.6	0.7	1.0
Ilm		1.5	0.8	0.2
Crystal residuum				
SiO_2		44.8	43.0	42.7
TiO_2		2.5	2.7	2.7
Al_2O_3		9.7	12.3	14.2
FeO		9.1	10.1	11.2
MgO		14.6	12.9	11.0
CoO		16.6	13.8	14.8
Na_2O		1.0	1.8	1.9
K_2O		0.04	0.2	0.2
		98.34	96.8	98.7
Mol. prop. $\frac{100\ Mgo}{MgO + FeO}$		74.2	69.5	63.7

alkali enrichment, and to a smaller extent, alumino enrichment (before crystallization of calcic plagioclase begins). Marked iron enrichment is prevented by the large amount of crystallization of amphibole with a relatively high Fe/Mg ratio, counteracting the effects of crystallization of pyroxenes with low Fe/Mg ratios. With increasing crystallization of plagioclase in extreme cases of fractionation the K/No ratio of the fractionating liquids will increase.

As indicated, the results obtained for the experimental crystallization of the high-alumina quartz tholeiite, basaltic andesite and andesite under hydrous conditions ($P_{H_2O} < P_{LOAD}$) are directly applicable to fractional crystallization of a hydrous basaltic magma at 30-40 kms depth. These results may also be applied in the reverse case of fractional melting of a basaltic composition at high pressure, where the sub-solidus assemblage consists mainly of amphibole, pyroxenes and plagioclase, and possibly minor quartz and garnet. It is proposed that varying degrees of partial melting give rise to liquids comprising a typical calc-alkaline suite. For $P_{H_2O} < P_{LOAD}$ temperatures necessary to produce calc-alkaline liquids at 30-40 kms depth would range from 900°C in the case of dacite and rhyodacite, to about 1000°C for basaltic andesite. After on andesite is extracted the residuum will constitute about 45% by weight of the initial basalt.

Calculation of fractionation trends

The compositions of residual liquids from the basalt have been determined using the measured compositions of the crystallizing phases (correcting for iron loss as outlined in T. H. Green and Ringwood 1968a) and their estimated proportions. The calculated liquid fractionates are given in Table 2. They show marked silica and alkali enrichment, and also some alumina enrichment in the early stages. The $\frac{100Mg}{Mg + Fe}$ ratio obtained for varying degrees of crystallization follows that of the typical calc-alkaline trend, showing only minor iron enrichment relative to magnesium. The alumina content of the liquids is high when compared with the content normally found in members of the calc-alkaline series. This is attributed to the fact that the experiments have been conducted on a high-alumina basalt composition. If a basalt with an alumina content of about 14% hod been used, then the alumino enrichment in the early stages, caused by the separation of pyroxenes and amphibole, would probably have resulted in compositions corresponding to basaltic andesite and andesite with alumina contents of 16-17%. Continued fractionation would involve plagioclase so that the alumina content of the liquid would then decrease.

Conclusions

The experimental investigations outlined support two complementary models for the origin of the calc-alkaline series viz (1) by partial melting of quartz eclogite at depths of 80-150 kms or (2) by partial melting of amphibolite or hydrous fractional crystallization of basalt ($P_{H_2O} < P_{LOAD}$) at depths of 30-40 kms. Both provide a highly efficient mechanism for alkali and silica enrichment in liquid fractionates obtained from a parental basic composition. Both models may be closely linked to the concept of sea-floor spreading. They also explain the association of calc-alkaline rocks with a particular tectonic environment, and the derivation of the calc-alkaline suite in areas where no sialic material occurs, thus providing a means of continental evolution from the mantle, by a two-stage process.

The two complementary models described in this paper may be considered as the two extremes of a possible spectrum of processes occurring with increasing depth on the downward moving limb of a convection cell. Thus if a descending oceanic crust of amphibolite partially melts at pressures of about 5-12 kb, fractionation trends will be controlled mainly by amphibole separation, and to a lesser extent, pyroxene separation (as in model 2). Between about 12 and 20 kb pressure amphibole, pyroxene and

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Note to Table 2 (opposite):

[a] The orthopyroxene analysis obtained at 1,040°C, 9 kb has been used in calculations for other experimental runs since it could not be analyzed in these runs. Since only 2% of orthopyroxene is extracted, any variations in its composition will not seriously affect the compositions of the liquid fractionates or crystalline residua. Also 1% of ilmenite is extracted as port of the crystalline residua. The reason is that on accessory iron-titanium rich opaque mineral phase occurred in the experimental runs in graphite capsules where no iron loss took place. This phose could not be analyzed quantitatively and as a first approximation for these calculations was token as ilmenite.

garnet may all be involved in governing the fractionation trends. At greater pressure, above 20 kb, amphibole is unlikely to be a stable phase (D. H. Green and Ringwood 1967a), even in the presence of water, and so the fractionation trends will be governed by garnet and clinopyroxene (as in model 1). Thus the partial melting of quartz eclogite model should still be applicable in the presence of water, so long as the pressure-temperature conditions are outside the stability field of amphibole.

The continuum of processes between the two models with increasing depth may explain certain element variations observed in the calc-alkaline series. Dickinson (1968) demonstrated that for circum-Pacific calc-alkaline volcanic chains there is a "correlation between the over-all level of potash content in a given calc-alkaline suite, and the vertical depth from the sites of eruption to the inclined seismic zone dipping beneath the volcanic chain or arc." This correlation consists of an increasing potash content with increasing vertical depth between the volcanoes and the Benioff zone.

Applying the two models for the origin of the calc-alkaline series, we suggest that the calc-alkaline rocks originating at shallow levels (eg. 15-45 kms) would have been derived by processes involving the extraction of amphibole containing a small but significant content of K_2O (0.2 - 0.4%, T. H. Green and Ringwood 1968a). However with increasing depth amphibole would play an increasingly minor role in the fractionation processes (extracting smaller amounts of K_2O from the parent composition) until at depths of 80-150 kms garnet and pyroxene, with negligible K_2O, would have dominated processes involving derivation of calc-alkaline rocks. Thus liquid fractionates derived at greater depths should have a higher K_2O content relative to the liquids derived at shallower levels, where a small but significant amount of K_2O remained in the residual extract. There will be a complete transition between these extremes since at intermediate depths (eg. 45-80 kms) all three phases, amphibole, garnet and clinopyroxene will constitute the residuum.

Finally, brief mention will be made of salient geological features which support these concepts for the origin of the calc-alkaline suite. The presence of almandine-rich garnet phenocrysts (often in association with quartz phenocrysts) in andesites, dacites and rhyodacites may be explained by the results of the high pressure experimental work, since these phases have been obtained on and near the liquidus of andesite, dacite and rhyodacite compositions experimentally (T. H. Green and Ringwood, 1968 a,b). Thus relict garnet phenocrysts in calc-alkaline rocks may indicate that the host rocks crystallized from magmas derived at great depths eg. according to model 1.

Similarly, the presence of tschermakitic hornblende-rich gabbroic inclusions with associated aluminous pyroxenes and calcic plagioclase in calc-alkaline rocks (Yamazaki et al 1966) may represent evidence of crystallization of a hydrous magma at depths of 15-45 kms, according to model 2.

Detailed trace element and isotope data for various calc-alkaline provinces may provide the key to determining the extent to which the genesis of a particular group of calc-alkaline rocks was governed by the separation of an amphibole-pyroxene residuum or a garnet-clinopyroxene residuum (ie. to determine which of the two models may apply in explaining the origin of a calc-alkaline sequence, where there is no direct mineralogical evidence of deep-level crystal fractionation processes). So far trace element and isotope data have been used to demonstrate that old sialic crustal material cannot have played a major role in the genesis of the calc-alkaline suite (Hurley et al., 1965, Taylor and White, 1965, Doe, 1967). In particular, initial strontium isotope ratios found in calc-alkaline rocks commonly range from 0.704-0.708 (Hurley et al., 1965, Ewart and Stipp, 1968). Such values are in agreement with the two-stage models outlined, in which calc-alkaline magmas are derived from basic material with a low $\frac{Sr^{87}}{Sr^{86}}$ ratio and a low rubidium content. There can only be minor involvement, if any, with sialic material enriched in radiogenic strontium.

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EXPERIMENTAL ASPECTS OF CALC-ALKALINE DIFFERENTIATION

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Abstract

Recent experimental work at atmospheric pressure bearing on the origin of calc-alkaline andesite is reviewed. An understanding of the highly complicated phase relations of basaltic and andesitic magma systems is being approached by study of model systems. By means of the $FeO-Fe_2O_3-SiO_2$ model are illustrated the two dominant trends in sub-alkaline igneous rocks, the SiO_2-enrichment or calc-alkaline trend and the FeO-enrichment or tholeiitic trend. With the addition to this system of MgO, then of $MgO+CaO+Al_2O_3$, and then with the further addition of Na_2O, these two distinct trends become more like those to be expected in natural magmas. Fractional crystallization of olivine basalt produces andesitic liquids in these model systems provided a small amount of O_2 is added to the condensed phases. This may occur in a natural magma body if a few percent of H_2O diffuses from the synclinal rocks into the magma and H_2 diffuses out into the country rocks.

Introduction

High temperature experimental research on silicate systems during the early years of the Geophysical Laboratory opened a fascinating and sound approach to the origin of the calc-alkaline rocks. The first study published from this laboratory, that by Day and Allen (1905) on the plagioclase solid solution series set the direction. Succeeding investigations and writings of N. L. Bowen were especially significant. To igneous petrologists this is of course an old story, but nevertheless the physico-chemical principles discussed in connection with the phase diagrams being developed, and their application to the origin of the calc-alkaline series of igneous rocks bear re-reading. The discontinuous reaction series as exemplified by olivine-pyroxene relations in the binary system $MgO-SiO_2$ coupled with the continuous reaction series of the plagioclase feldspars were concepts of great significance in igneous petrology. Bowen's (1915) discussion of hoplo*-systems on the basis of his phase diagram for the system An-Ab-Di is a gem. With this model system he was able to illustrate clearly the complex phase relations during coprecipitation of plagioclase and a pyroxene and to indicate the possibilities and trends of differentiation in calc-alkaline magmas.

Model systems such as An-Ab-Di are tremendously useful for showing what mechanisms and processes are possible and the consequences and limitations they impose on theories of the origin of magma series. But the model systems of course do not serve to prove that differentiation occurred a certain way or indeed that it occurred at all. As the model system is increased in complexity to approach more closely the actual natural system, more confidence develops in its applicability. With this in mind, techniques were developed for handling the component FeO, and this resulted in the magnificent report by Bowen and Schairer (1935) on the system $MgO-FeO-SiO_2$. In its application to igneous differentiation, this model system was useful especially in showing that with extreme fractional crystallization in this system a high iron oxide residual liquid developes, and in showing however that for certain initial liquid compositions the liquid will change from undersaturated to oversaturated during crystallization if fractionation is only slight to moderate in extent. The authors emphasized the tentativeness of conclusions to be drawn from this system used as a model for natural magmas and the need for evaluating the simultaneous effect of other constituents, for example anorthite, on crystallization paths and the effect of high pressure in changing the phase relations.

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* The prefix, hoplo, meaning simple, will be used as did Bowen (1915) in his discussion "haplobosaltic, haplodioritic and related magmas."

Since the thirties very interesting progress has been made by experimentalists in the study both of more complex model systems and of the effect of high pressure on phose relations. This lotter will be discussed by others on this program. I would like to review briefly the development of more complex models of natural magmas and their significance for colc-alkaline differentiation. These ore atmospheric pressure models, applicable in general up to the pressure at which garnet becomes a stable phose in equilibrium with liquid in basaltic rocks, or as judged from recent work (Cohen, Ito and Kennedy, 1967), up to pressures of about 17 kilobors, corresponding to maximum depths of 50 to 60 kilometers.

$MgO-FeO-Fe_2O_3 - SiO_2$ as o model system

The system $MgO-FeO-Fe_2O_3-SiO_2$ is on especially significant model for the sub-alkaline magmas because it builds on the important bose just mentioned, the system $MgO-FeO-SiO_2$, by adding another of the important oxides, and because the effect of oxygen partial pressure (pO_2) on phose relations is illustroted. Although there still ore no lime, alumino, or alkalis in the model and therefore no feldspar or augite as crystalline phases, certoin relations and implications bearing on colc-alkaline differentiation emerge from examination of this system that were not evident in the more simple models.

Phase relations in the system $MgO-FeO-Fe_2O_3-SiO_2$ ore illustrated in Fig. 1, after Muon and Osborn (1956). The composition of pyroxene and olivine in this system is represented by the cross-hatched lines on the bose, and of the mognesioferrite-mognetite solid solutions by a similar line on the front face. For each of these, as well as the several other crystalline phases shown, there is a primary phose volume in the tetrahedron, i. e., o composition volume in which this phose is the first to crystallize from liquids in this volume on equilibrium cooling. Crystallization of the phose causes the liquid composition to change as the crystals ore subtracted from it. The liquid composition in equilibriumwith the separating crystals consequently moves over to a boundary surface where a second phose joins the first one in crystallization. The liquid will then proceed along the surface separating the two primary phose volumes until a boundary curve is reached which is the juncture of three primary phases, at which a third crystalline phose appears; and the liquid will then move down this boundary curve.

The primary phose volume of olivine is a brood zone extending from left to right completely across the tetrahedron in the lower, central part. Forsterite separates from liquids in the left face, fayalite in the right face, and forsterite-fayolite solid solutions from all liquids in the olivine volume in the tetrahedron. Next behind the olivine primary phose volume is a narrow prism for pyroxene. This narrows from left to right and terminates before reaching the right face. The field of tridymite (labeled silica to include also cristobolite) is next behind pyroxene and is separated from olivine by the pyroxene field except near the right side. The magnetite volume, from which the $MgFe_2O_4-Fe_3O_4$ solid solutions crystallize is in the upper port of the tetrahedron and rests on top of the olivine and pyroxene volumes.

The heavy lines ore boundary curves representing liquid compositions in equilibrium with three crystalline phases and a gas phase.

A peridotite composition in this model system lies in the high MgO port of the olivine volume. Below the solidus the hoploperidotite consists of olivine, pyroxene and magnetite. On heating this crystalline aggregate the first liquid will hove a composition on the line cz, in equilibrium with olivine, pyroxene and magnetite. The amount of liquid now increases rapidly with rise in temperature because the temperature slope of line cz is low. Liquid composition moves to the left along cz until magnetite disappears, then continues along the pyroxene-olivine surface until pyroxene disappears. At this point a relatively lorge volume of low viscosity liquid has formed, and this is "primary" hoplobosoltic magma. The liquid needs only to be separated from the residual olivine crystals. Further rise in temperature causes the liquid to increase in amount and to change composition slowly, for the liquidus slope is now steep in this olivine primary phose volume. The further choinge in the liquid composition is simply addition of the olivine composition moving the liquid toward the composition of a primary olivine basalt.

The primary hoplobasoltic liquid so formed lies in the olivine volume. On equilibrium crystallization of this liquid, olivine crystals first separate but then will react with the liquid to completely disappear as pyroxene crystallizes, or to portly disappear if the initial liquid composition is that of on olivine basalt. When all crystalline the body is a hoplogobbro, composed of pyroxene and magnetite or it will contain also some olivine if the initial liquid was on olivine basalt.

Fractional crystallization rather than equilibrium crystallization of the basaltic liquid is of especial interest. With extreme fractional crystallization the liquid will move to the boundary curve dz (tridymite-mognetite-pyroxene), and will move down to the right finally approaching s in composition. Extreme iron oxide enrichment without silica enrichment occurs in the resulting residual liquids. In this

fractional crystallization olivine first crystallizes, then ceases to crystallize as the liquid moves along dz, but then later again is a crystallizing phase until the liquid disappears. Either pyroxene or magnetite can be the second phase, but normally pyroxene. Pyroxene crystallization stops as the liquid moves through the point z. Once magnetite starts to crystallize it continues to do so until the liquid is exhausted. Magnetite crystallization prevents the liquid from going to high Fe^{3+}:Fe^{2+} ratios which otherwise would be the case as olivine and pyroxene with predominantly ferrous iron separate. As the liquid moves along dzs, the Fe^{3+}:Fe^{2+} ratio in the liquid decreases from approximately 2:1 to 1.5:1. Magnetite is therefore an important phase in this fractional crystallization serving as a maximum regulator on the Fe^{3+}:Fe^{2+} ratio in the liquid. Because of the configuration of the univariant curves, however, the beginning of crystallization of magnetite does not cause the liquid to change direction toward higher SiO_2 contents.

In the foregoing the system is treated as being closed. The oxygen partial pressure drops continually and by several orders of magnitude during the extreme fractional crystallization of a haplobasaltic liquid. If instead, the system is open with respect to O_2 in such a manner that the oxygen partial pressure does not drop so seriously, the configuration of the boundary curves is very different. Magnetite crystallization now is along a curve of liquid change toward higher SiO_2 contents. I would like to discuss this case briefly, even though it has been treated elsewhere (Muan, 1955; Muan and Osborn, 1956; Osborn, 1959) because an appreciation of its significance is essential to understanding what follows. A straightforward way to treat this case is to assume that the pO_2 remains constant during the crystallization or that a fixed CO_2:H_2 or H_2O:H_2 ratio in the gas phase is used. In the latter two cases the pO_2 does drop over the temperature range of crystallization, but not nearly as much as it does in the closed system. We will use the case of pO_2 remaining constant. To do this I would like to turn briefly to the system FeO-Fe_2O_3-SiO_2.

In Fig. 2 is shown the phase diagram for the system FeO-Fe_2O_3-SiO_2, after Muan (1955).

We will take mixture a, a composition in the magnetite field to illustrate the two types of crystallization: (1) Crystallization at constant total composition (closed system), and (2) crystallization at constant pO_2 (system open with respect to O_2 so that pO_2 remains constant). Inasmuch as neither solid solution nor incongruent melting are involved in the crystallization of liquid a, paths of equilibrium and fractional crystallization are the same, simplifying the discussion.

(1) Crystallization of mixture a at constant total composition. This is the type of crystallization path ordinarily considered for condensed silicate systems, and holds for mixture a if the mixture is enclosed in a container so that the O_2-content as well as that of Fe and Si remain constant. As mixture a is cooled to its liquidus temperature, 1480°, the pO_2 drops to 10^{-3} atm. and crystals of magnetite appear. With continued cooling and precipitation of magnetite, the composition of the liquid changes along a straight line ob to b where fayalite begins to crystallize. As the liquid changes composition from a to b, the temperature and pO_2 drop continuously to 1145° and $10^{-9.3}$ atm. respectively. With further cooling, the liquid changes abruptly in direction of movement, the coprecipitation of fayalite and magnetite causing the liquid to move from b to the entectic e. At e the temperature remains constant as magnetite, fayalite and tridymite crystallize out together until the liquid disappears. As the liquid moved from b to e the temperature dropped from 1145° to 1140°, but the pO_2 reversed its direction of change and increased from $10^{-9.3}$ to 10^{-9} atm.

(2) Crystallization of mixture a at constant pO_2. In this type of crystallization the condensed phases are in equilibrium with a gas phase having a constant pO_2. As magnetite precipitates, the liquid must follow a pO_2 isobar along the liquidus surface. By definition the liquid composition cannot deviate from that of the line representing the pO_2 at the liquidus temperature of a, 10^{-3} atm. In other words, the 10^{-3} atm. isobar becomes the path of crystallization. On crystallization therefore the liquid follows the path ad as magnetite crystallizes. The composition d is the lowest temperature point on the 10^{-3} atm. isobar. Hence the liquid can go no farther but must crystallize completely at d to a mixture of magnetite and tridymite. In moving from a to d the O_2-content of the condensed phases has increased. This is apparent from the fact that liquid d has almost the same Fe_2O_3/FeO ratio as liquid a, but the crystals that have separated ($FeO \cdot Fe_2O_3$) have a much higher Fe_2O_3/FeO ratio. As the liquid reaches point d, the total composition of the mixture is point c, about 60% magnetite and 40% liquid d. Approximately 0.8% O_2 has been added to the mixture. Further O_2 is added as liquid d crystallizes to a mixture of tridymite and magnetite and the total mixture composition changes along the isosilico line of to f.

The difference in the two types of crystallization, constant total composition and constant pO_2 is of course striking. The final liquid in one case is e, in the other is d. The crystalline aggregate in one case is composed of fayalite, magnetite and tridymite of total composition a, and in the other of

Captions for Figures on Opposite Page.

Figure 1. Tetrahedron to illustrate liquidus phose relations in the system $MgO-FeO-Fe_2O_3-SiO_2$, after Muon and Osborn (1956). The heavy lines represent univoriant curves within the tetrahedron along which three crystalline phases, one liquid and vapor are in equilibrium. Arrows indicate the direction of decreasing temperature. The triangular plane $MgO-Fe_3O_4-SiO_2$ passing through the tetrahedron is shown by light lines and is presented separately in Figures 3 and 4. Abbreviations used ore: HEM = hematite, MAGN. FER = mognesioferrite, SIL = silica, MAG = magnetite, PER = periclase, OL = olivine, PY = pyroxene, WÜST = wüstite, M.WÜST = magnesiowüstite.

Figure 2. Liquidus phose equilibrium diagram for the system $FeO-Fe_2O_3-SiO_2$, after Muan (1955). Heavy lines ore boundary curves, light lines are liquidus isotherms, dash-dot lines are liquidus pO_2 isobars.

Figure 3. Diagram to illustrate liquidus phose relations in the system $MgO-FeO-Fe_2O_3-SiO_2$ at $pO_2 = 10^{-0.7}$ atm. (air), after Muan and Osborn (1956). The position of this pO_2-isoboric plane within the tetrahedron is shown in figure 1. The heavy lines represent pO_2-isobaric univariont boundary curves, and the light solid and dashed lines ore isotherms on the liquidus surface. The light dashed-triple dot lines ore curves of constant Fe_2O_3/FeO ratio in the liquid and indicate the position of the air isobaric surface within the tetrahedron of figure 1. Compositions of olivine and pyroxene solid solutions in the system have been recalculated with all iron oxide os Fe_3O_4 so that their composition joins, shown as cross-hatched lines, lie in this plane.

Figure 4. Sketch of $pO_2 = 10^{-0.7}$ atm. surface for further illustration of courses of crystallization at constant pO_2, after Osborn (1959).

Figure 5. Tetrahedron to illustrate liquidus phase relations in the system Mg_2SiO_4-iron oxide-$CaSiO_3-SiO_2$ at $pO_2=10^{-0.7}$ atm., after Osborn (1962).

Figure 6. Tetrahedron to illustrate liquidus phose relations in the system MgO-iron oxide-$CoSiO_3-SiO_2$ at the pO_2 of the equilibrium decomposition of pure CO_2, after Presnall (1966).

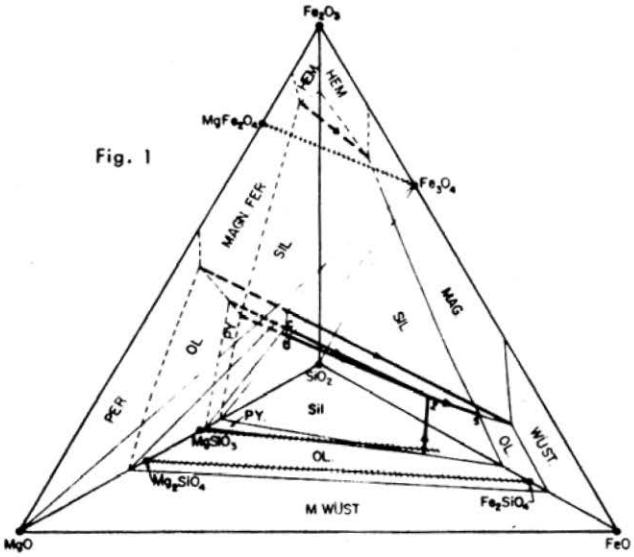
Fig. 1
Fe_2O_3
HEM
$MgFe_2O_4$
Fe_3O_4
MAGN FER
SIL
MAG
OL
PER
PY
SiO_2
Sil
$MgSiO_3$
OL
Mg_2SiO_4
Fe_2SiO_4
WUST
M WUST
MgO
FeO

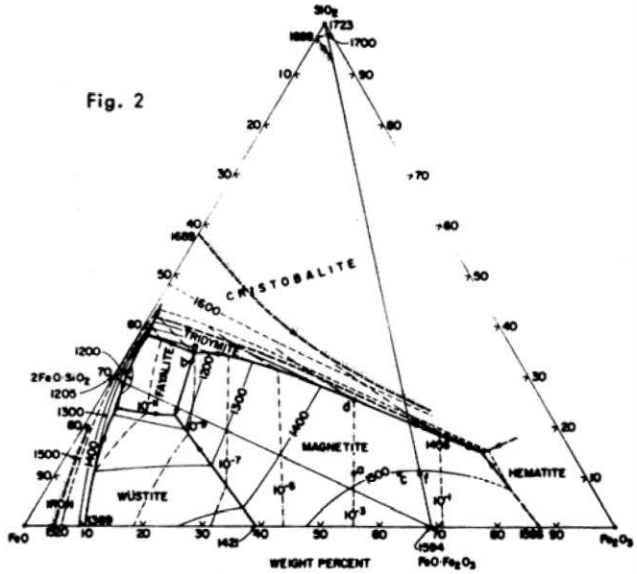
Fig. 2
SiO_2
CRISTOBALITE
TRIDYMITE
TRIDYMITE
$2FeO \cdot SiO_2$
MAGNETITE
HEMATITE
WÜSTITE
IRON
WEIGHT PERCENT
FeO
$FeO \cdot Fe_2O_3$
Fe_2O_3

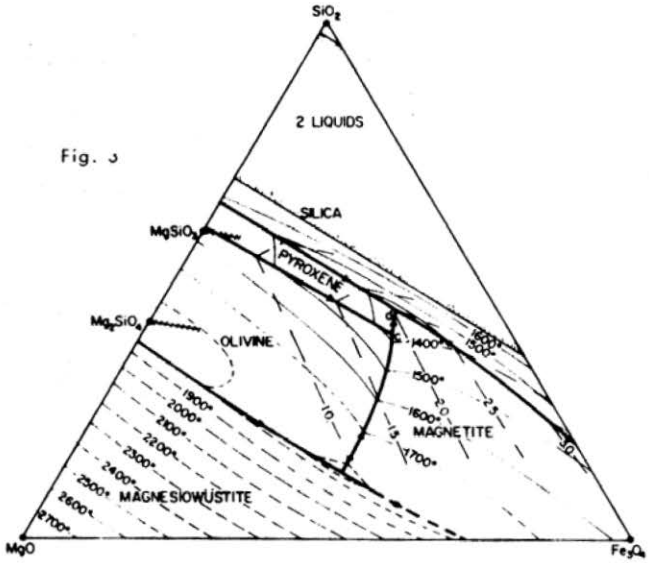
Fig. 3
SiO_2
2 LIQUIDS
SILICA
$MgSiO_3$
PYROXENE
Mg_2SiO_4
OLIVINE
MAGNETITE
MAGNESIOWÜSTITE
MgO
Fe_3O_4

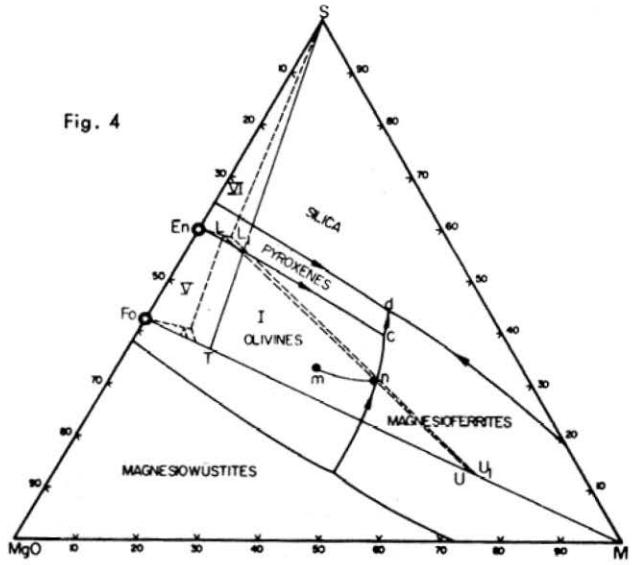
Fig. 4
S
SILICA
En
PYROXENES
Fo
OLIVINES
MAGNESIOFERRITES
MAGNESIOWÜSTITES
MgO
M

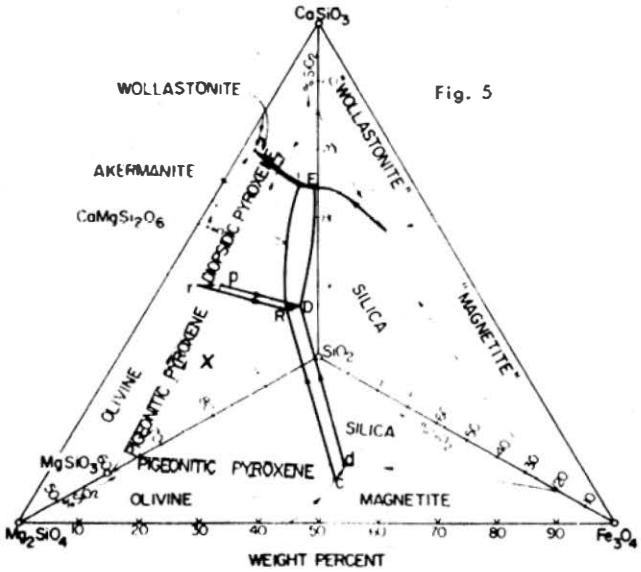
Fig. 5
$CaSiO_3$
WOLLASTONITE
AKERMANITE
$CaMgSi_2O_6$
DIOPSIDE PYROXENE
PIGEONITE PYROXENE
OLIVINE
SILICA
MAGNETITE
SiO_2
$MgSiO_3$
PIGEONITIC PYROXENE
OLIVINE
MAGNETITE
Mg_2SiO_4
Fe_3O_4
WEIGHT PERCENT

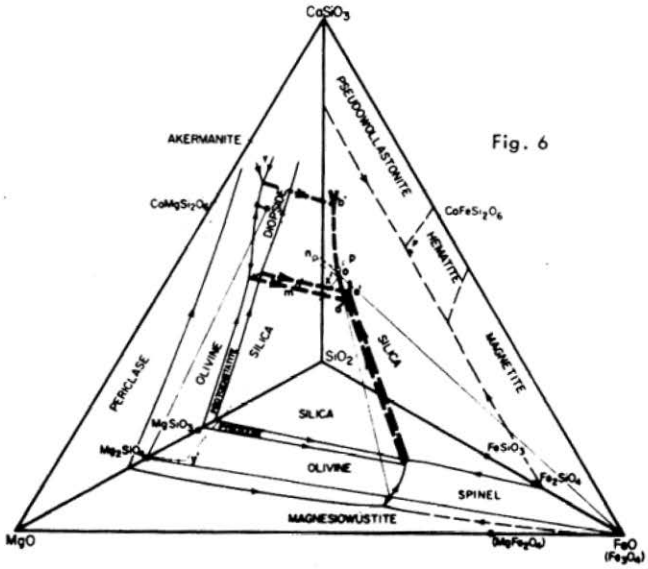
Fig. 6
$CaSiO_3$
AKERMANITE
PSEUDOWOLLASTONITE
$CaMgSi_2O_6$
$CaFeSi_2O_6$
HEMATITE
PERICLASE
OLIVINE
SILICA
SiO_2
MAGNETITE
$MgSiO_3$
$FeSiO_3$
Mg_2SiO_4
Fe_2SiO_4
OLIVINE
SPINEL
MAGNESIOWÜSTITE
MgO
FeO

magnetite and tridymite of total composition f. Note that the very different paths of crystallization are not related to magnetite crystallization, for magnetite crystallizes continually in both cases. The configuration of the oxygen isobars and direction of slope of liquidus surface, requiring oxygen addition for the constant pO_2 case, are the significant factors. The manner of change of pO_2 during crystallization is obviously a very important consideration.

Returning to the system $MgO-FeO-Fe_2O_3-SiO_2$ (Fig. 1) we see that the same principles apply in contrasting the two types of crystallization, but the picture is much more complex because another dimension is present and both solid solution and incongruent melting are involved.

In the tetrahedron of Fig. 1 exist surfaces (not shown) of constant pO_2. During crystallization at constant pO_2 in this tetrahedron the liquid must stay on a pO_2-isobaric surface just as the liquid must stay on a pO_2-isobaric line in the $FeO-Fe_2O_3-SiO_2$ triangle (Fig. 2). The air isobaric surface ($pO_2 = 10^{-0.7}$) lies near the $MgO-Fe_3O_4-SiO_2$ join in Fig. 2. Phase equilibrium data for this isobaric surface have been plotted on the $MgO-Fe_3O_4-SiO_2$ plane by calculating all iron oxide as Fe_3O_4, and shown by light lines within the tetrahedron (Fig. 1) and as a separate diagram in Fig. 3 (after Muan and Osborn, 1956). An idea of the position and shape of the isobaric surface for $pO_2 = 10^{-0.7}$ in the tetrahedron can be judged from the lines of equal Fe_2O_3:FeO ratio in the liquid shown on Fig. 3.

In Fig. 4 (after Osborn, 1959) is shown the same phase relations but with a few points and lines added which are significant for a detailed explanation of crystallization paths. Such an explanation has been previously made and is not needed for this discussion. I want only to point out the very great difference in path of crystallization where pO_2 is kept constant as in Fig. 4 from the case described above where total composition remains constant. If an olivine basalt composition such as m is fractionally crystallized, the liquid moves to the magnetite (or magnesioferrite) boundary curve and then turns abruptly to move to c and then to d. At d, the minimum liquidus point on this isobaric surface, the liquid remains constant in composition, just as at point d in Fig. 2, while magnetite, pyroxene and tridymite crystallize until the liquid is exhausted. Liquid m is an olivine hoplobasalt, for an equilibrium crystallization it will consist of olivine, magnetite and pyroxene. Liquid n is a hoplobasalt for an equilibrium crystallization it will consist only of pyroxene and magnetite. Liquid c is a hoplandesite and liquid d a hoplandesite or hoplodacite. Both c and d on crystallization consist of pyroxene, magnetite and tridymite. Just as in the case of mixture a of Fig. 2, fractional crystallization of mixture m or n at constant pO_2 requires addition of O_2 to the condensed phases.

The configuration of the univariant curves in Fig. 4 is such that a pronounced effect of magnetite crystallization is to cause an abrupt change in direction of the course of the crystallizing liquid from increase in FeO with little or no increase in SiO_2 to increase in SiO_2 with little or no increase in FeO. Thus there can be two important effects of magnetite crystallization. In the first as mentioned earlier, crystallization of magnetite is a regulator on Fe_2O_3:FeO ratio in the liquid. The magnetite primary phase volume surface in the tetrahedron acts as a ceiling on this ratio. In the second case and while still exerting this Fe_2O_3:FeO ratio ceiling effect, crystallization of magnetite regulates the rate of increase of FeO versus SiO_2 of the liquid, for the magnetite primary phase volume cuts off the olivine and pyroxene volumes so that the crystallizing liquid cannot move to high iron-oxide contents. This will occur if the pO_2 does not decrease as fast as it would if the system is closed, and the lower the decrease in pO_2 during crystallization, the greater is the second effect of magnetite crystallization; that is, the more the fractionating liquid increases in SiO_2-content rather than in FeO content.

Returning to the tetrahedron (Fig. 1), with fractional crystallization under conditions of constant total composition, the liquid moves down dz as magnetite, pyroxene and tridymite crystallize. (The liquid will reach z if fractionation is sufficiently extreme, but will cross from dz to cz before the liquid reaches z, and then proceed down cz to z. In leaving dz and moving to cz, tridymite crystallization is replaced by that of an iron-rich olivine.) But if O_2 is added to the system, the liquid stops at a point such as d, its location depending on the pO_2, and this point is like a eutectic just as is point d in Fig. 2. A large amount of liquid of this fixed composition is present which crystallizes at the constant composition of point d. Now in both cases magnetite crystallizes, but I want to emphasize by use of this diagram the difference in effect. For both types of fractionation magnetite crystallization is the regulator on Fe_2O_3 content of liquid. Because of magnetite precipitation the liquid cannot move higher into the tetrahedron than the bottom surface of the magnetite volume. But when O_2 is added to the system so that the pO_2 drop is less than in the closed system, then magnetite crystallization causes also this second effect, that of blocking the liquid from moving down the pyroxene-magnetite surface toward z. In the case just described of fractionation at constant $pO_2 = 10^{-0.7}$ atm., magnetite crystallization forces the liquid to cross along the magnetite-pyroxene surface from c to d and terminate its movement.

In a previous paper (Osborn, 1962) where sub-alkaline igneous rock reaction series were

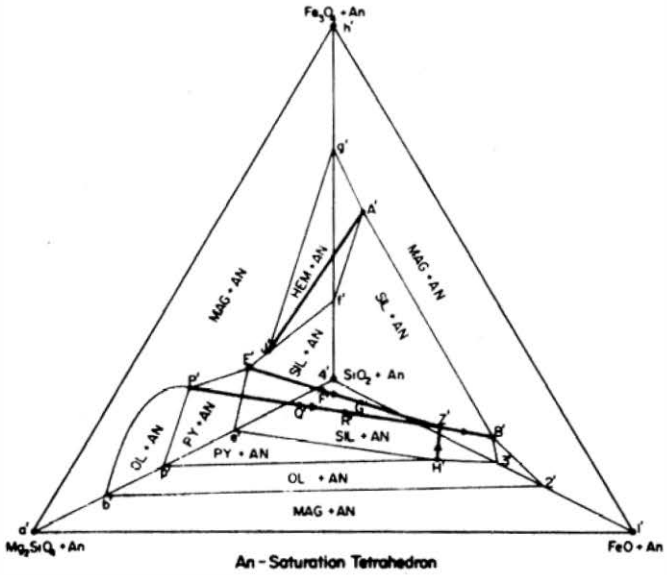

Figure 7. Tetrahedral liquidus phase equilibrium diagram representing the anorthite-saturation volume for the system Mg_2SiO_4-FeO-Fe_2O_3-$CaAl_2Si_2O_8$-SiO_2, after Roeder and Osborn (1966). Data for points F', G' and B' are shown in Table 1.

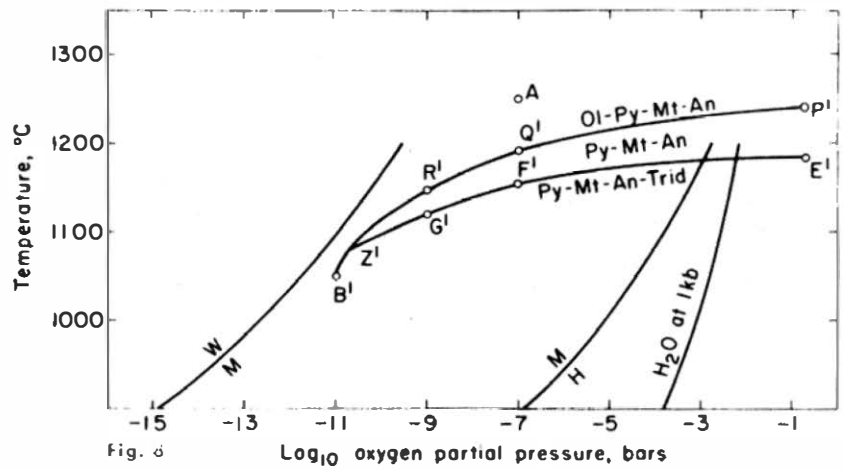

Figure 8. Sketch to show pO_2-T relations along univariant curves of Figure 7. The curves W/M and M/H are the equilibrium curves for wüstite-magnetite and magnetite-hematite, after Eugster and Wones (1962), and the water curve is from data tabulated by Kennedy (1948).

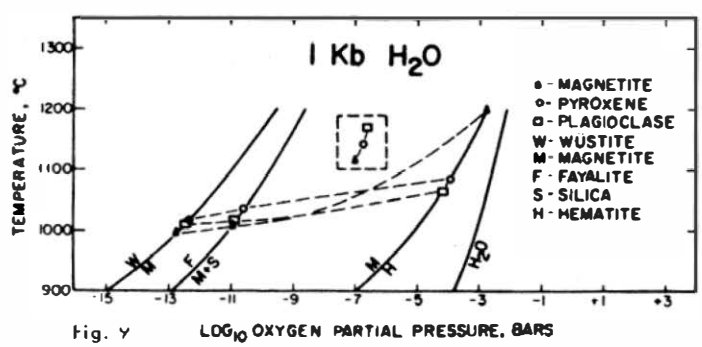

Figure 9. Diagram to illustrate the combined effect of oxygen partial pressure and water partial pressure on the crystallization sequence for a basalt, after Osborn (1963). A Columbia River Basalt cooling in a sealed tube under its own oxygen partial pressure and at a total pressure of approximately 1 atm. has the order of crystallization as indicated by the symbols within the dashed rectangle. This some basalt at the oxygen pressures of the three buffers and at 1000 otm. water pressure has the crystallization sequences as indicated by symbols on the buffer curves.

discussed, I showed magnetite as a phase in the calc-alkaline and not in the tholeiitic or FeO-enriched series. I did not mean to imply that magnetite would not be present in the latter but only that "magnetite is not a major phase" (Osborn, 1962, p. 22). It is unlikely that in a differentiating tholeiitic magma the pO_2 will remain continually too low for magnetite to crystallize at least as a late phase. In the calc-alkaline series however I am presuming that crystallization of magnetite is of prime importance as in constant pO_2 crystallization in the model system in order that the trend toward enrichment of the liquid in SiO_2 develop. Judged on the basis of phase relations in this model system, $MgO-FeO-Fe_2O_3-SiO_2$, the calc-alkaline trend develops during fractional crystallization when magnetite crystallization occurs simultaneously with addition of O_2 to the condensed phases. It is then that the course of the liquid is toward higher SiO_2 content and a lower $FeO:Fe_2O_3$ ratio and lower total iron-oxide content.

Reaction to the foregoing might be that: (a) the system $MgO-FeO-Fe_2O_3-SiO_2$ is too simple a model, and (b) the pO_2 is unrealistically high. With respect to the first, we have now studied phase relations with the addition of CoO, then CoO + Al_2O_3, and currently CoO + Al_2O_3 + Na_2O. The same type of relations seem to hold. With respect to pO_2 relations, the pO_2 needs to be high in this simpler system for it to be a good model inasmuch as liquidus temperature and iron oxide contents are higher than in the more complex natural system and hence oxygen pressures are higher.

The model system $MgO-FeO-Fe_2O_3-SiO_2$ + CoO

Let us look very briefly at the situation with a CoO addition. Fig. 5 (after Osborn, 1962) is a sketch to illustrate phase relations in a part of the five-component system $CoO-MgO-FeO-Fe_2O_3-SiO_2$, at the constant pO_2 of $10^{-0.7}$ atm. Phase relations in this system of course approach more closely to those in a natural magma for we observe for example that primary phase volumes are present for two pyroxenes, both the diopsidic or augitic, and the pigeonitic or hypersthenic. Note especially that the large magnetite volume blocks the boundary curves from moving far toward high iron-oxide contents. The base of this tetrahedron is the $pO_2 = 10^{-0.7}$ atm. plane of Figs. 2 and 3. As the constituent, $CoSiO_3$ is added, the same general relations obtain, with D being the eutectic in this pO_2-isobaric system to which the olivine haplobasaltic and haplobasaltic liquids move on fractional crystallization. Liquid D is in equilibrium with two pyroxenes, magnetite and tridymite. Presnall (1967) studied phase relations in this system over a range of pO_2's. His diagram at the pO_2 produced by the equilibrium decomposition of pure CO_2 is shown as Fig. 6. The oxygen partial pressures of this diagram are realistic as a model of natural magmas. Relations are similar to those of Fig. 5.

The model system $MgO-FeO-Fe_2O_3-SiO_2$ + CoO + Al_2O_3

Addition of CoO + Al_2O_3 to the system $MgO-FeO-Fe_2O_3-SiO_2$ has been done and the phase relations of this complex six-component system studied in a part of the region of geologic interest--the part where the ratio of CoO to Al_2O_3 is one. In an attempt to show phase relations in this system, an An-saturation tetrahedron was produced (Fig. 7, after Roeder and Osborn, 1966). The phase relations shown in this tetrahedron are those where anorthite is always one of the phases present. Note the configuration of the boundary curves. They are strikingly like those in the system $MgO-FeO-Fe_2O_3-SiO_2$. With constant total composition crystallization (closed system), a haplobasaltic liquid on extreme fractional crystallization will move to z' and then on down z'B' to approach the high-FeO residual liquid B' where the pO_2 is about 10^{-11} atm. But if the pO_2 of the system holds at 10^{-7} atm. the final liquid has the composition of F', or if the pO_2 is 10^{-9} atm., the residual liquid will have the composition of point G'. Liquids F' and G' are in equilibrium with anorthite, pyroxene, magnetite and tridymite. It thus seems clear that the model relations illustrated by the tetrahedron for the system $MgO-FeO-Fe_2O_3-SiO_2$ hold for the much more complicated system where CoO and Al_2O_3 are added, and the same implications for petrogenesis apply. The composition of F', G' and B' are shown in Table 1.

A haploandesitic liquid, F', results from fractional crystallization of a haplobasalt in the system of Fig. 7, if pO_2 is 10^{-7} atm. at the stage where pyroxene, anorthite, magnetite and tridymite coexist with liquid. A haplo-ferrobasaltic liquid, B', results from extreme fractional crystallization where total composition of the mixture remains constant. In the former case, liquid F' is produced in large volume, i.e., as much as about 50% of the volume of the original haplobasaltic liquid is liquid of composition F', derived from the original liquid by precipitation of olivine, pyroxene, anorthite and magnetite. In contrast, only a very small amount of liquid can approach B' in composition. The farther toward B' the liquid moves the higher is its FeO content and the less there is of it. Point F' on the other hand is of the nature of a eutectic where the composition of the initial liquid, haplobasalt in this case, is sufficiently close to the point F' and the compositions of the crystalline phases separating from the liquid as it

Table 1. Data for Points F', G' and B' of Figure 7.

Point	pO_2	Composition (wt %) SiO_2	Fe as Fe_3O_4	MgO	CaO	Al_2O_3	Temp. °C	Crystalline Phase at Liquidus
F'	10^{-7}	55	14	6	9	16	1155	An + Py + Trid + Mgt
G'	10^{-9}	51	21	6	8	14	1120	An + Py + Trid + Mgt
B'	10^{-11}	45	38	0	6	11	1050	An + Fay + Trid + Mgt

approaches F' ore sufficiently for away from F' that a large volume of the eutectic liquid results on crystallization of the initial hoplobosoltic liquid.

In understanding pO_2-temperoture-composition relationships for fractional crystallization in the $MgO-FeO-Fe_2O_3-An-SiO_2$ system, it may be helpful to refer to a plot of significant data on o pO_2-T diagram, Fig. 8. The lines W/M and M/H represent respectively the wüstite-magnetite and magnetite-hematite equilibria. The action far the calc-alkaline magmas lies between these two. The heavy lines P'Q'R'Z', E'F'G'Z' and Z'B' ore the boundary curves in Fig. 7 for the univoriant equilibria ol-py-mgt-on-liq-gos, py-mgt-on-trid-liq-gas, and ol-mgt-an-trid-liq-gas respectively in the $MgO-FeO-Fe_2O_3-An-SiO_2$ system.

If an olivine basalt at point A is fractionally crystallized, then for this model system $MgO-FeO-Fe_2O_3-An-SiO_2$ the liquid will be andesitic if it develops o composition lying approximately within the triangular field Q'-F'-G', and this will happen if sufficient O_2 is added to the system. If A is strongly fractionated as a closed, dry system, the liquid will approach Z' in composition or in extreme cases even B' and will be strongly enriched in FeO--o ferrogabbro.

Experiments with natural basalts and andesites

A pertinent question is whether or not the relations discussed for this model system relate significantly to the natural system in a geosyncline. To produce andesite by fractional crystallization of a basaltic magma, o small amount of O_2 must be added to the magma (Osborn, 1959). This apparently requires water. But calculations indicate that simply adding water to the magma and then treating the system as closed during crystallization is not sufficient to provide the required O_2 addition and at the same time to maintain on adequate pO_2 level for production of an andesitic liquid if fractional crystallization is strong. A breathing action on the part of the magma body is probably required to produce on andesite: H_2O inhaled by the magma and H_2 exhaled. This maintains the required metabolism for the body in developing the ondesitic liquid during fractional crystallization.

With H_2O present, phose relations ore somewhat different than in the dry model systems. We hove attempted to obtain some information on this aspect of the problem by using natural basalts and andesites, measuring pO_2, and determining the effects of both pH_2O and pO_2 on crystallization. This has been reported in three papers (Osborn, 1963, Hamilton, Burnham and Osborn, 1964, Fudoli, 1965). In Fig. 9 ore summarized some of the results. Within the square inset ore plotted data for o basalt crystallizing under equilibrium conditions as a dry, closed system. Equilibrium crystallization sequence of this some rock at 1000 bars water pressure (~ 3% H_2O) is shown by the other points. These other points were determined at the pO_2 of the three buffers, hematite-magnetite, foyolite-magnetite-silico, and wüstite-magnetite. With this water content, the liquidus temperature was lowered from 1170° to the neighborhood of 1025°. Plagioclase was the primary phose in the dry system, pyroxene in the system containing water, or magnetite at the highest pO_2's. Although the crystallization temperatures ore lower and the order of crystallization somewhat different, fractional crystallization will probably be similar in nature to that of the model, dry system. Pyroxene, plagioclase and magnetite will precipitate to produce on ondesitic magma if sufficient O_2 is added.

Conclusion

Phose equilibrium studies of model systems of basalts and andesites as well as of these rocks themselves provide a developing picture of certain possibilities for production of ondesitic magma by frocti-onal crystallization of olivine basaltic magma. It is o very complicated picture. From the laboratory stondpoint further work con ond is being done which may be opplicable to the question of the origin of the calc-alkaline andesites. In our laborotories soda is being added along with lime and alumina to $MgO-FeO-Fe_2O_3-SiO_2$ to move the model closer to natural magmas. Hill and Roeder (1967) are concluding some interesting experimental work on the conditions for crystollizotion of spinel from basoltic liquids. Investigotions of model systems or actual rocks at high pressures being carried out at several institutions are developing very interesting relations among phases--essential studies for evaluating the depth factor. These experimental programs coupled with increasingly significant analytical studies on trace elements, isotope ratios and phose composition of andesites and related rocks insure that we will need another conference in the near future to collect again the current ideas on andesites.

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TRACE ELEMENT CHEMISTRY OF ANDESITES AND ASSOCIATED CALC-ALKALINE ROCKS

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Abstract

Average data for 45 elements are given for high-Al basalt, low-silica andesites, low-K andesites, ANDESITES, high-K andesites, dacites, rhyolites and granodiorites. The characteristic features of the trace element chemistry of the andesites are:

(1) The large cations (Cs, Ba, Rb, K, Pb) are variable but generally low in abundance, similar to average basaltic concentrations, K/Rb ratios are high and Rb/Sr ratios are low.

(2) The rare earths have low total abundances. The rare earth relative abundance patterns vary from those subparallel to the chondritic pattern to those close to the sedimentary pattern.

(3) The large highly charged cations (Th, U, Zr, Hf, Sn, Nb) have concentrations similar to average basaltic levels. The Th/U ratios ($\sim$ 3) are lower than average upper crustal ratios.

(4) Nickel and cobalt are low in abundance and Ni/Co ratios are low ($\sim$1). The chromium contents are low and variable, but vanadium and scandium are present at high levels. The distribution of these elements in andesites resembles that in high-Al basalts.

These data are discussed in relation to the three main hypotheses of the origin of the calc-alkaline association.

1. Fractional crystallisation of basaltic magma. Low concentrations of those elements (e.g., K, Rb, Cs, Ba, rare earths, Th, U, Zr, Hf, Li) typically concentrated by this process, are observed in andesites. The high abundances of V and Sc in andesites are not consistent with large scale crystallisation and removal of magnetite. Derivation by fractional crystallisation from high-Al basalt is limited by the similar nickel contents of andesites and high-Al basalts.

2. Mixing of basalt with crustal material. The addition of typical upper crustal material to basic magma, in the proportions necessary to account for the major element composition, introduces amounts of many trace elements (e.g., Ni, Cs, Rb, rare earths, Th, U) in excess of those observed by factors of at least two.

3. The trace element data are consistent with a model of two stage derivation of calc-alkaline rocks from the mantle. In the postulated model, the first stage involves partial melting of primitive mantle. Ni, Co and Cr remain in the refractory phases (olivine, chromite, orthopyroxene). The larger cations are concentrated by melting of minor mantle phases. Variable Rb/Sr ratios result. This material forms part of the anomalous upper mantle zone with low P wave velocities in orogenic areas. The second stage involves partial melting of this material at depths less than 70 km and eruption of the calc-alkaline volcanic rocks. Depending on the time interval between stages one and two, variations in $Sr^{87}Sr^{86}$ ratios may occur. The eruptive rocks will show variable concentrations of the large cations, the rare earths and the large highly charged cations reflecting the details of the two stage process.

Introduction

The unique association of andesites, dacites and rhyolites in areas of orogenic activity has long been recognised. These rocks hove been referred to collectively as the calc-alkaline suite, but in this paper the term CALC-ALKALINE ASSOCIATION is preferred since the latter term does not have the petrogenetic implications of a linked differentiation sequence.

The chemistry and petrology of the rocks of the colc-alkaline association ore distinct from those of other rocks of "intermediate" composition. Fractionation of tholeiitic and alkali basalts gives rise to rocks which have previously been referred to as andesites. These include hawaiites (previously andesine andesites), mugearites (previously oligoclase andesites), benmoreites and tristanites (previously No and K trachyandesites), and icelandites (formerly tholeiitic or pigeonitic andesites). The chemistry and geological setting of these relatively small scale derivatives of basaltic magma ore different from the voluminous calc-alkaline andesites of the orogenic regions (Taylor 1968) and they are not considered in this paper.

The importance of the colc-alkaline association lies in its close connection with orogenic activity in areas of varying crustal thickness. If these rocks were derived from the mantle, as argued in this paper, then variations in chemical and isotopic composition may reflect similar variations in the mantle and a complex history of derivation from more primitive mantle material. If the association is of mantle origin, it constitutes a major source of new sialic material and makes a substantial contribution to continental growth, as outlined by Taylor and White (1965) and Taylor (1967).

The rocks of the colc-alkaline association hove been comparatively neglected, on account of the difficulties inherent in applying standard petrographic techniques to rocks which contain o lorge proportion of fine-grained or glossy groundmoss. Attention has recently been focused on these rocks by the application of modern geochemical techniques.

Geological Setting

Recent eruptions of the colc-alkaline rocks are absent from the ocean basins and from the stable shield areas. From many published descriptions, they appear to be the most voluminous eruptive rock of the orogenic regions. "The characteristic rocks of most of the volcanic island orcs about the northern and western Pacific Ocean ore high-alumina basalt, andesite and dacite. Andesite is the most abundant but any of the three main types may dominate within one temporal or spatial port of a province" (Hamilton, 1964). Coots (1962) in a summary of extensive work in the Aleutians orc notes that "the Quaternary volcanoes are mode up of rocks that range in composition from olivine basalt to rhyolite, but ore predominantly andesite, with pyroxene andesite most abundant." Many similar observations apply to the circum-Pacific region. Long continued andesitic vulcanism since the Mid-Palaeozoic has been recorded from the Pacific margin of North America by Dickinson (1962). Occasionally, as in New Zealand, the acid eruptive rocks ore most abundant.

The association of andesitic volcanism with island orcs in areas of thin crust is noteworthy. Data from Coots (1962), Shor (1964), and Menard (1964) on the crustal structure of island orcs indicates crustal thicknesses up to 15-20 km beneath the islands, with thinner crust under the trenches. Commonly the mantle under the islands has low P wove velocities (7.5-8.0 km/sec). Similar low velocity zones occur in the upper mantle beneath the Pacific margin of North America (Thompson and Tolwani, 1964), likewise an orogenic zone with abundant colc-alkaline volcanic rocks.

Mineralogy

The essential minerals of andesites are pyroxene and plagioclase. The groundmoss typically constitutes 50-60% of the rock and commonly contains gloss. The groundmoss pyroxene consists typically of tiny tabular crystals of hypersthene and this appears to be a characteristic feature. Plagioclase usually occurs as lorge phenocrysts 1-2 mm. in length. Commonly a core of moth-eaten appearance, with glassy blebs, is surrounded by finely zoned plagioclase with perhaps 20 zones. Oscillatory zoning is common. The overage is labradorite (An_{60}) and typically about 30% of the rock is plagioclase. Hypersthene (typically En^{65}) commonly occurs as large phenocrysts in addition to being present in the groundmoss and is typically less than 10% of the rock. Augite and hornblende ore less common. Magnetite and ore

minerals generally are not prominent. Olivine is not common except in the more basic varieties, where large phenocrysts, typically Fo_{60}, occur. The normative composition of andesites has about 14% quartz (Chayes, 1965); tridymite and cristabalite, the low density polymorphs of silica typical of volcanic rocks, are common.

Average Rock Types

The distinctive features of the major element chemistry of the calc-alkaline or orogenic association are high Al content, the Fe/Mg ratios, low K and high Co concentrations. The variation in concentration of Al, Fe, Mg, Co and No is rather small. In contrast, two elements, Si and K, show significant, and to some extent, independent variations. Although there are some overlops in composition, it is useful to distinguish four varieties of andesites. The most common type, here termed ANDESITE, has on overage SiO_2 content of about 60% and contains about 1.5% K_2O. This composition is equivalent to the overage andesite of Taylor and White (1965). This overage is close to the average andesite of Daly (1933), but is distinctly higher in silica content than the average calc-alkali andesite of Nockolds (1954) which contained 54% SiO_2. This low silica value resulted from restricting the term andesite to rocks with less than 10% normative quartz. Chayes (1965) has shown that the typical calc-alkaline andesite of the circum-Pacific region averages 14% normative quartz.

The LOW-SILICA ANDESITES, average about 55% SiO_2 and about 1% K_2O. The above two types are distinguished by variation in silica content.

The potassium contents may vary by a factor of four or five in andesites of the same silica content (Dickinson, 1968) and similar trace element differences are encountered. Although the variations in composition are probably continuous, it is convenient to distinguish LOW-K and HIGH-K ANDESITES, with K_2O contents less than 0.7% and greater than 2.5% respectively.

In addition to the andesite compositions, data have been included for other rocks typically associated with andesites in orogenic areas. The complete list of rock types is:

1. High-Al basalt: $<$ 53% SiO_2
2. Low-Silica andesite: 53-56% SiO_2; 0.7-2.5% K_2O
3. Low-K andesite: $<$ 0.7% K_2O 53-62% SiO_2
4. ANDESITE: 56-62% SiO_2; 0.7-2.5% K_2O
5. High-K andesite: $>$ 2.5% K_2O; 53-62% SiO_2
6. Dacite: 62-68% SiO_2
7. Rhyolite: $>$ 68% SiO_2
8. Granodiorite

The data are presented in the tabulation proposed by Taylor (1965B). The sources used in compiling the averages are given in the appendix to Tables 1 to 6. For certain groups of elements, such as the ferromagnesian trace elements, a large body of data exists, but for most elements, the number of determinations is very limited.

For some of the less common rock types (high-Al basalt, low-K and high-K andesites and dacites) the number of complete analyses is so few that no attempt has been made to produce an average composition. It has been considered preferable to quote analyses of typical rocks.

Despite the very limited amount of analytical data some interesting patterns may be discerned. The conclusions reached are of necessity tentative because the data are few. Nevertheless, several significant points emerge in the discussion. They are presented here as a stimulus to thinking and hopefully to encourage the study of the trace element composition of the calc-alkaline association.

In the discussion which follows, most attention is given to the andesite data because they are the principal volcanic rock types in many orogenic areas.

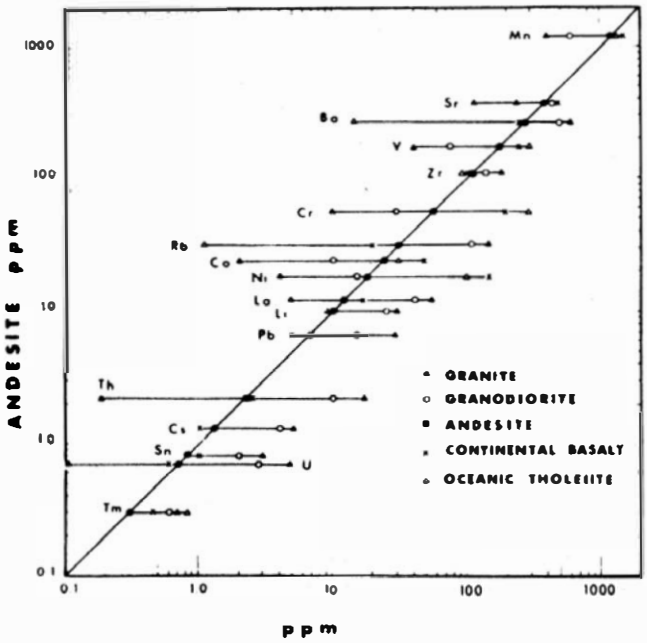
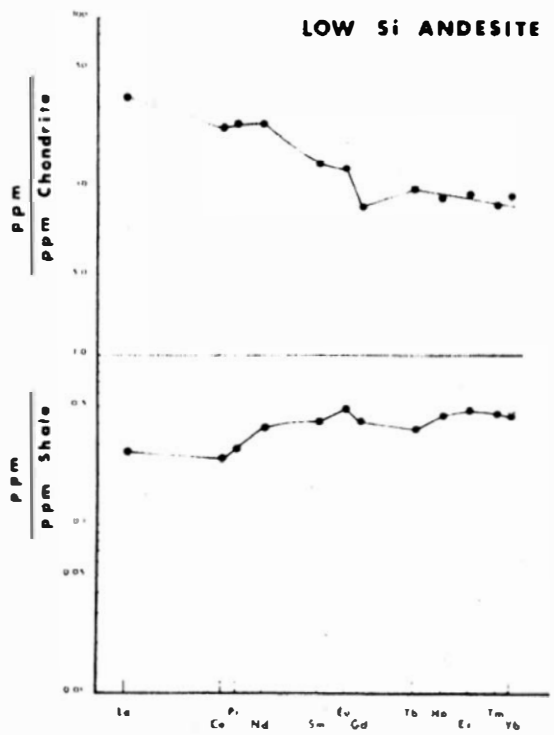


Figure 1. Comparison of the overage trace element composition of ondesites with those of common rock types. Data from Tables 1–6 and from Toylor (1968). The ondesite data ore plotted on the vertical axis, and the compositions of the other rocks ore given on the horizontal axes. As on aid to clarity, the points for each element ore joined and the andesite compositions ore plotted on the 45° diagonal line. This is the line of equality of composition with andesites. Increasing distance from this line indicates increasing disparity in composition. Note that the abundances of Mn, Sr, Bo, Zr, Rb, La, Li, Pb, Th, Cs, Sn, and U in continental basalts ore close to the andesite values.



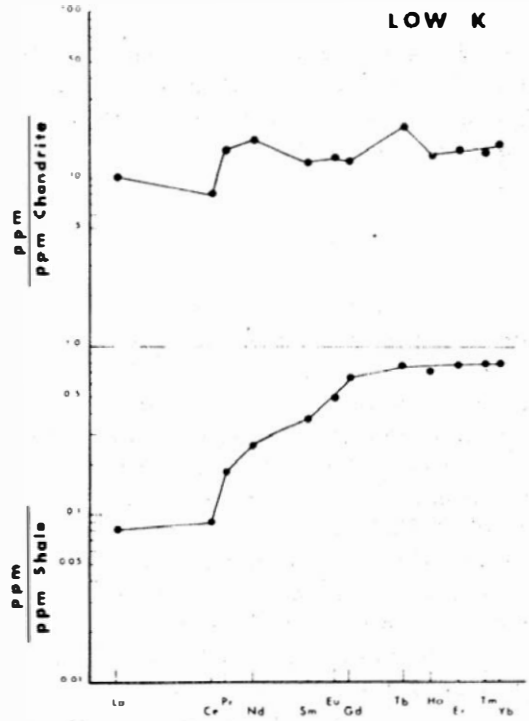


Figure 2. Rare earth patterns for Low-K ondesite. Figures 2-8 are constructed osfollows. The abundances of the individual rare earth elements are divided, element by element, by the abundances in chondritic meteorites (Haskin et al. 1966, Table 8) and separately, by the abundances in North American shales (Hoskin, et ol. 1966, Table 28). Both these patterns ore represented on the diagram by the horizontal line at 1.0. Distance from this line represents the relotive concentration differences, and changes in slope represent changes in the rare earth abundance patterns. Data ore from Table 3. The Low-K andesite rare earth abundance pattern is sub-parallel to the chondritic pattern, and element abundances ore enriched by a foctor of about 15. Relative to the shale pattern, the large rare earths (Lo-Eu) show marked depletion.

Figure 3. Rare earth diagram for low-silica andesites. Note that the pattern from Gd-Yb is subparallel to the chondritic pattern and that the larger rare earths Lo-Eu ore enriched relative to chondrites and depleted relative to the shales.

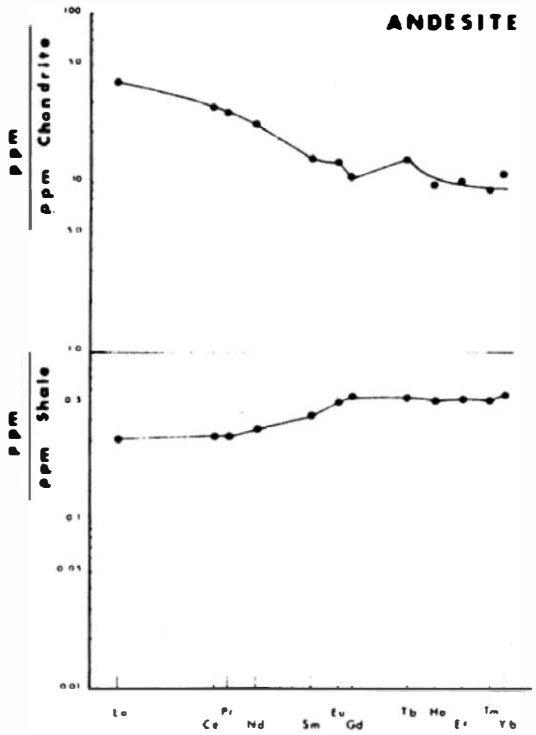


Figure 4. Rare earth diagram for andesites. The patterns are similar to those for the low-silica andesites. Note depletion of the large rare earths relative to the shales, considered to be typical of upper crustal material. The Eu abundances are normal.

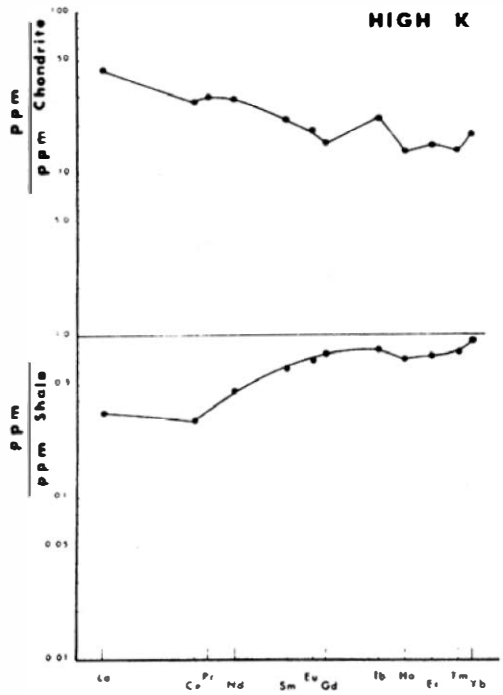


Figure 5. Rare Earth diagram for High-K andesite. Note that the total abundance of the rare earths is greater than in the andesites proper, but that La and Ce are depleted in the high-K type.

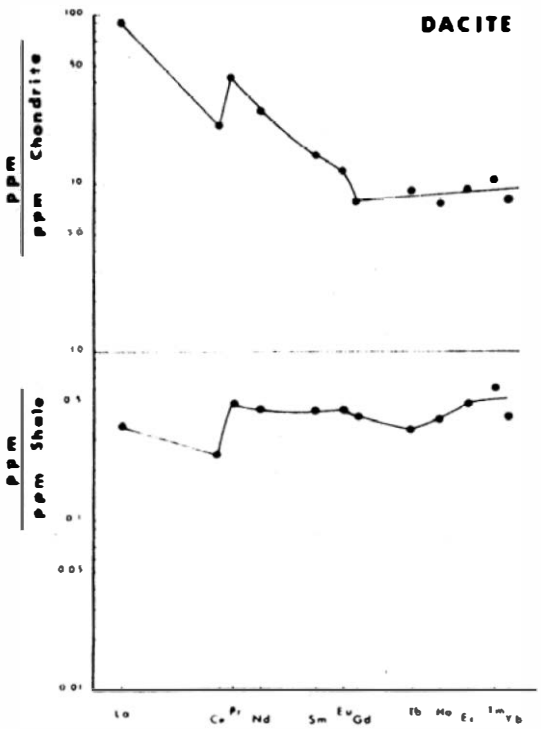


Figure 6. Rare earth pattern for dacite. Note that Ce is depleted, but the other large rare earths, La-Eu are enriched relative to the andesite pattern.

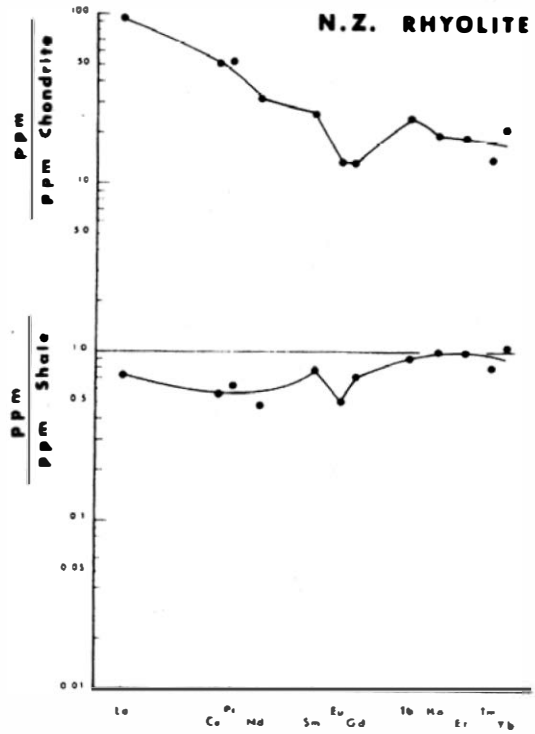


Figure 7. Rare earth pattern for Taupo rhyolite. Note slight Eu depletion. The patterns are similar to the andesites, but the absolute concentrations are greater.

Abundance and Distribution of Trace Elements

In this section, the discussion follows the order of the elements listed in the tables. The difficulties in depicting large quantities of data in a clear manner have led to the adoption of the system of plotting shown in Figure 1. The normal andesite average is plotted on the vertical axis, and averages for other rock types of interest are plotted on the horizontal axis. Points lying along the 45° diagonal indicate equality of composition. Data are taken from this paper and from Taylor (1968) for granites, oceanic tholeiite, and continental basalts.

Although the major element abundances (except for K) are "intermediate" between those observed in basalts and granites, the trace element concentrations do not fall midway between those observed in common basic and acidic rocks, and the andesites are not "intermediate" rocks from the standpoint of trace element abundances.

Large cations

These comprise, in order of decreasing radius, Cs, Rb, Tl, Ba, Eu, Pb, and Sr. (Table 2).

Strontium is abundant in andesites, partly reflecting the high Ca content and the high modal amounts of plagioclase, typically labradorite (An_{60}). The Sr content of plagioclase reaches a maximum about this composition (Ewart and Taylor, in prep.).

The other elements of this group are notably low in andesites (Figure 1). Only in the high-K andesite do the concentrations reach levels expected of rocks whose major element chemistry has been often regarded as typically intermediate between basalt and granite. The K/Rb ratios are variable but tend to be high (> 400). They are notably high in the low-K andesites and there is a general fall in the ratio with increasing K content for the data given here for the andesites. The average dacite K/Rb ratio is 390. The so-called "dacite" for Saipan which contains 80% SiO_2, has a K content of 1.04% and a K/Rb ratio of 470. High K/Rb ratios, such as these, argue against the operation of fractional crystallisation, at least under low pressures. The Taupo rhyolites have typical upper crustal ratios of 250, but do not display the enrichment of Rb common in late stage granitic rocks of similar major element chemistry (Taylor et al., 1968).

K/Rb ratios as low as 250 have been found in New Zealand andesites. The ratio appears to be variable in calc-alkaline rocks and a large scale study would be a useful supplement to the investigation of the potassium variations begun by Dickinson and Hatherton (1967).

Barium is generally low in abundance in andesites. In addition to the average data given in Table 7, Markhinin et al. (1964) have provided barium averages for the volcanic rocks of Kamchatka and the Kurile Islands. These data are given in Table 7. The values listed for the various rock types are similar to those given here. Ba/Rb ratios are high because of the low abundance of Rb, and Ba/Sr ratios are high. Rb/Sr ratios are very low.

Lead is very low in abundance, but is higher in the high-K andesites, in common with the other large cations.

The ratios among the large cations are commonly useful petrogenetic indicators (Taylor 1965A). For example, low K/Rb and high Ba/Sr ratios can be attributed to fractional crystallisation in magmas. The K/Rb and Ba/Rb ratios are high and the Ba/Sr ratios are low in andesites with values typical of unfractionated material. Even the dacites do not show the changes in these ratios expected from the operation of fractional crystallisation (Duncan, personal communication).

The rare earths

The absolute abundances of the rare earths in andesites are low. The total rare earth contents (ΣREE+Y) are usually less than 100 ppm. High K andesites have higher rare earth abundances and the low K andesites have extremely low total rare earth abundances (Table 3).

The rare earth data are shown in Figures 2 to 8. In these diagrams, the abundances of the individual rare earth elements have been divided element by element, by the abundances in chondritic meteorites and in North American shales. This method of presenting the data allows a direct comparison both of the relative patterns and relative abundances. The rationale for comparison with the chondritic and shale data is that these apparently represent the two uniform rare earth abundance patterns. The chondritic pattern is reasonably inferred to be that of unfractionated non-volatile solar system material, and probably typical of the earth as a whole and the shale pattern is inferred to be typical of the upper

crust exposed to weathering. The small rare earths (Gd-Yb) parallel both the chondritic and sedimentary rock patterns, and have typically about half the absolute concentrations of these found in shales. The large rare earths (La-Eu) are enriched relative to the chondritic patterns and depleted relative to the sedimentary patterns. The absolute abundances are about 1/2 to 1/3 of the sedimentary abundances (Fig. 4). The low-K andesite shows a pattern sub-parallel to the chondritic pattern (Fig. 2) with extreme depletion of the large rare earths (La-Eu) relative to the sedimentary pattern.

The high-K andesite (Fig. 5) has higher concentrations than normal andesite, but shows a rather similar relative abundance pattern.

The dacite pattern is enriched in the large rare earths and resembles the rhyolite pattern (Figs. 6 & 7).

The interpretation of the rare earth patterns in terms of geological processes is not yet clear. Studies of highly fractionated leuco-granites (Taylor et al 1968) reveal that enrichment of the large rare earths does not always occur in late stage differentiates, but that these elements may be depleted relative to sedimentary RE patterns, until the RE pattern approaches that of chondrites. In other granites, extreme enrichment of the large rare earths may result (eg. G-1). Many of these variations probably reflect modal variation of the accessory minerals such as apatite, monazite etc. Rare earth patterns for individual andesites show much variation, ranging from patterns sub-parallel to the chondritic pattern to those similar to the sedimentary patterns. No relative enrichment of large rare earths over that observed in the sedimentary pattern has been found to date.

Eu depletion and Eu/Gd ratios

The Eu/Gd ratio is a useful measure of variations in Eu content relative to the other rare earths. The behaviour of Eu is usually attributed to the presence of Eu^{2+} entering feldspar, thus becoming separated from the other rare earths present as trivalent ions. Depletion of Eu may reach spectacular levels, with the Eu/Gd ratio falling by a factor of 10 or more (Taylor et al 1968), in highly fractionated rocks.

There is no sign of Eu depletion in andesites, (Fig. 4). There is some evidence of slight Eu enrichment in andesites but there is not enough data to clearly distinguish any trend toward Eu enrichment. There is a slight change in Eu/Gd ratios between low-K and high-K andesites but it is probably not significant.

Large highly charged cations

These include Th, U, Zr, Hf, Sn, Nb and Mo. As a class, these elements are low in abundance in andesites compared with upper crustal materials. The concentrations are in general reminiscent of basaltic abundances (Fig. 1). Th/U ratios (average~3) are significantly lower than those observed in upper crustal material which are typically in the range 3.5-4.

The high-K andesites exhibit higher concentrations of these elements but the Th/U ratio does not appear to be higher. The ratio is also low in the dacite. Zr and Hf are also enriched in the high-K andesite, but the Zr/Hf ratio is unaltered.

Average abundances for Zr are given by Markhinin and Sapozhnikovo (1962b) for the volcanic rocks of the Kuriles and Kamchatka, (Table 7). The values for basaltic andesites (= low silica andesites) are similar to those given here, but the values for andesites, dacites and rhyolites are higher. These increased concentrations probably reflect the occurrence of high-K andesites in the Kurile Islands (Dickinson 1968).

The large highly charged cations (Th, U, Hf, Nb and Mo) are typically concentrated in volatile rich magmas (e.g. nepheline syenites). Their enrichment in the high-K andesites may be due to an increase in the volatile content of the magmas. The frequently explosive nature of andesitic vulcanism points to the importance of volatiles in the processes of orogenic vulcanism but little evidence remains in the bulk chemistry of the andesites. The New Zealand ignimbrites, products of highly explosive volcanic processes, do not exhibit any diagnostic features in the trace element chemistry of the operation of such processes. Variations in the degree of partial melting and the amount of minor phases involved appear adequate to account for the observed fluctuations in concentration of these elements.

Ferromagnesian elements

These elements which enter 6 fold co-ordination positions in silicates include Mn, Cu, Co, Ni, Li, Sc, V, Cr and Ga. They are arranged here in order of valency and ionic radii, but a future classification based on crystal-field stabilisation energies might prove more useful. Many more data are

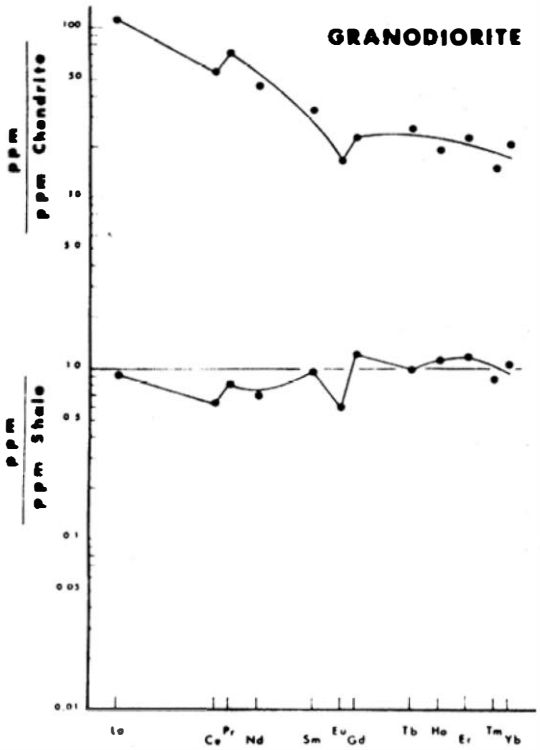


Figure 8. Rare earth pattern for granodiorite. Note that this is sub-parallel to the shale pattern and that the granodiorite and the shale have about the same concentrations.

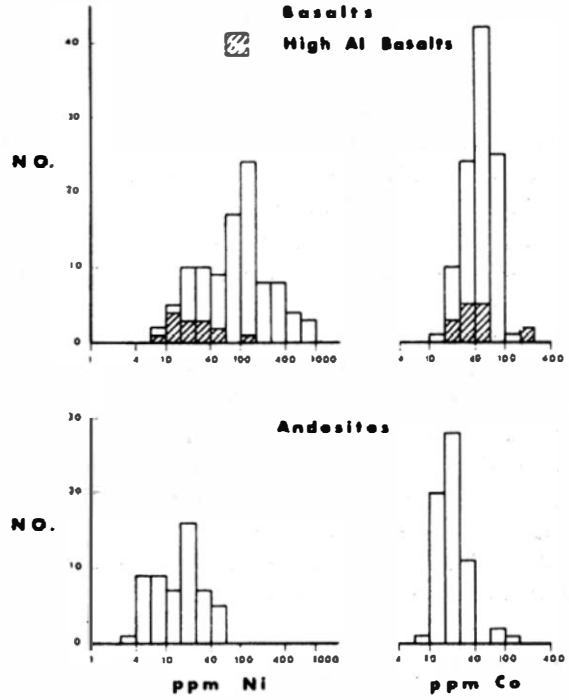


Figure 9. Frequency diagram of the distributionof nickel and cobalt in andesites and basalts. The intervals are 1.0, 1.6, 2.5, 4.0, 6.3, 10, 16, 25, 40, 63, 100, 160, 250, 400, 630, and 1000 ppm. Andesite data are from the following sources. New Zealand, Japan. (Taylor and White 1966) Fiji, Bougainville (Taylor and Blake in prep.). Aleutian Islands (Coats, 1952, 1959, Coats et al. 1961, Drewes et al. 1961, Lewis et al. 1960, Nelson 1959, Powers et al. (1960). Western United States (Nockolds and Allen (1953). Basalt data from Turekian and Carr (1960), Nockolds and Allen (1954, 1956), Nesterenko et al. (1964) and Turekian (1963). High-Al basalt data from Table 10. Note that the andesite nickel values are much lower than those in basalts but ore similar to high-Al basalts. Cobalt is depleted to a lesser extent in andesites compared to basalts.

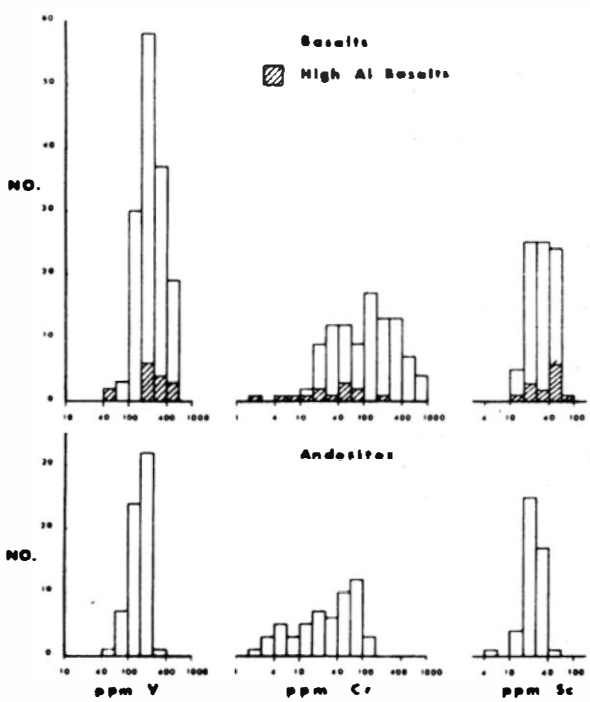


Figure 10. Frequency diagram of the distribution of vanadium, chromium and scandium in ondesites and basalts. Sources of data as for Figure 9. The distribution of chromium is similar in high-Al basalt and andesites. Note the high V and Sc contents in andesites, comparable with the concentrations in basaltic rocks.

available for these than for most of the other elements discussed in this paper. They ore readily determined by spectrographic methods of analysis and data exist for many samples from the Aleutian Islands. (See various numbers of U.S. Geological Survey Bull. 1028) and the Kurile Islands and Kamchatka (Table 7).

Average data for Cu, Co, Ni, V and Cr in the volcanic rocks from Kamchatka and the Kurile Islands, from Markhinin and Sopozhnikovo (1962a) ore given in Table 7. The concentrations are comparable to those for the andesite averages reported here.

Manganese is commonly about 1000-1500 ppm in andesites and shows the small range in concentration typical of this element. It is not a particularly useful or diagnostic element. Copper and lithium are typically low in abundance and resemble typical basaltic concentrations. Nickel, and to a lesser extent, cobalt is very low in abundance in andesites. Except for higher concentrations in some low-silica andesites which ore possibly accumulative rocks this low abundance of nickel appears to be quite characteristic. The Ni/Co ratio is typically less than one. Fig. 9 shows the distribution of nickel and cobalt in andesites, compared to high-Al basalts and all basalts. The histograms are plotted on a logarithmic bose to cover the wide range in composition, and to adequately display the lower abundance levels. It con be seen that the distribution is lognormal.

Chromium shows considerable scatter. It is commonly low but occasionally high in abundance (Fig. 10). Cr is lower in andesites than in basalts, but similar to the high-Al basalt abundances. Fryklund and Fleischer (1963) have given a survey of scandium abundances in volcanic rocks. Their data for calc-alkaline rocks are given in Table 8. The values are comparable with those reported here. It is clear from their study that there is little difference between the Sc content of basalts and andesites (Fig. 10). Vanadium is high in abundance and is very close to its basaltic abundances (Fig. 10). There is little difference between the abundances of V and Sc in basalts and high-Al basalts. Data for high-Al basalts are given in Table 10 and show marked differences in the concentrations of Cr, Ni and Ni/Co ratios compared to other basalt types.

The similarity in the relative abundances of Ni and Cr and Ni/V ratios in high-Al basalts and andesites is noteworthy. The High-Al basalts and the andesites show very similar relative abundances of the ferromagnesian trace elements. (Figs. 9 and 10).

The very low chromium and nickel contents (~3 ppm) and the low Ni/Co ratio (0.23) in the high-K andesites are noteworthy. The Cr/V ratio (0.019) is very low. These values indicate that the high-K andesites are not derived from normal andesites by simple addition of potassium and related elements, but that other processes are responsible.

Chalcophile elements

The abundances of these elements are generally low, although data ore not complete for this group. The abundances are not very distinct from the basaltic abundances.

Discussion

The trace element data provide some new constraints on theories dealing with the origin of calc-alkaline igneous rocks. Although there are many variations, these theories may be classified into three main types:

(a) Derivation by fractional crystallisation from a parental basaltic magma.

(b) Origins involving mixing, "hybridisation," contamination of basaltic magma with "sial," granitic, upper crustal or crustal material.

(c) Processes involving partial or complete melting of deep crust or upper mantle producing primary magmas. The restriction of these rocks to orogenic areas and their absence from areas of true oceanic crust necessitates multistage models for theories of mantle derivation.

(a) Fractional crystallisation

The trace element data provide limitations for hypotheses based on these processes.

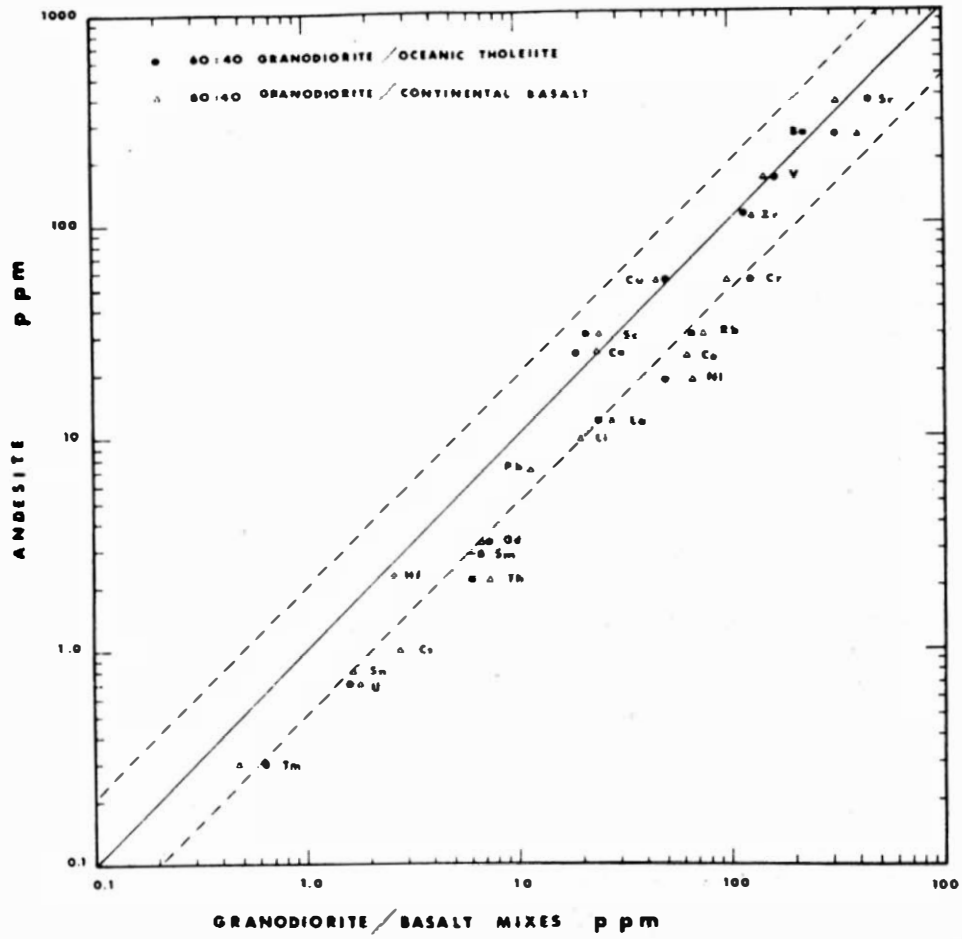


Figure 11. Comparison of average andesite composition with 60:40 mixes of granodiorite with continental basalt and oceanic tholeiite. These mixtures are chosen to give the appropriate major element composition of andesites. Data from Tables 1-8 and Taylor (in press). Points lying along the solid 45° diagonal line represent similar abundances in the andesites and the mixes. Increasing distance from this line indicates increasing disparity in composition. Points falling within the dashed lines represent compositions within a factor of two of that of andesite. Note that many diverse elements fall outside these limits (e.g. Cr, Rb, Ce, Ni, La, Li, Gd, Sn, Th, Cs, Sn, and U). This indicates that mixtures of basalt and granodiorite, taken as representative of upper crustal material, do not produce the trace element composition of andesites.

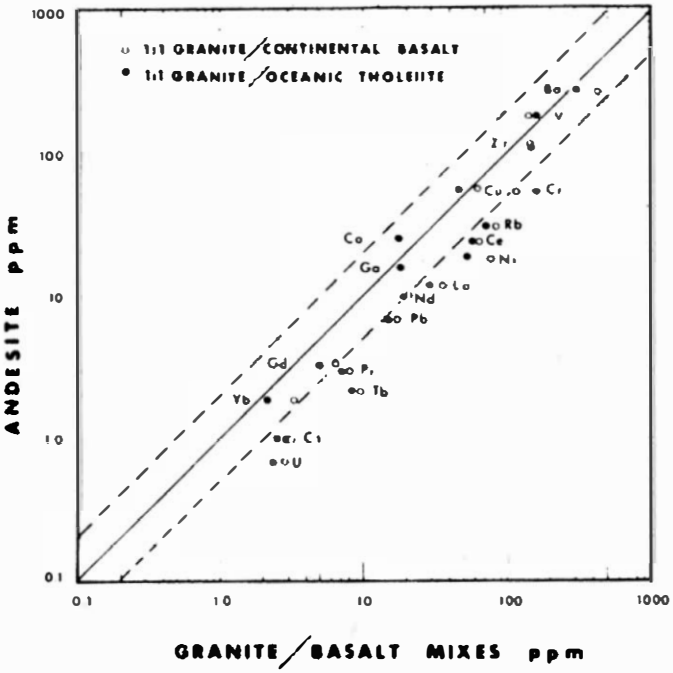


Figure 12. Comparison of overage andesite composition with 50:50 mixes of granite and basalt, chosen to give the andesite major element composition. Plotting is the some as in Figure 11. The granite-basalt mixes show numerous differences outside a factor of two with the andesite abundances. Note the similarity to Figure 11.

(1) Those elements which are normally concentrated by processes of fractional crystallisation, or differentiation, are low in absolute abundance, being in general not very different from the concentrations found in basaltic rocks. These include the large cations (Cs, Rb, Tl, Ba) the rare earths, and the large highly-charged cations (Th, U, Zr, Hf). The abundances for these elements resemble those of continental basaltic rocks. (Fig. 1).

The element ratios are perhaps more diagnostic. K/Rb, K/Cs, Ba/Rb and Eu/Gd ratios are all high. Rb/Sr and Ba/Sr ratios are low. Operation of processes of fractional crystallisation produces the opposite effect (low K/Rb, K/Cs, Ba/Rb and Eu/Gd and high Rb/Sr and Ba/Sr ratios) (Taylor 1965A). The data do not preclude the operation of limited fractional crystallisation, for example from a primary andesitic magma, but the trace element data do not demand such an explanation. The dacites which might be expected to show the best evidence of such processes, do not appear to be highly fractionated rocks and the ratios discussed above show little change from andesitic values. The data for the high-K andesite could be interpreted as indicating derivation by limited fractional crystallisation from an andesitic magma, but might just as well indicate variations due to limited wall rock reaction or to variation in parent material, or depth of melting as suggested by Dickinson (1968).

(2) Derivation by fractional crystallisation from high-Al basalt is limited by the similar Ni contents and Ni/Co ratios of andesites and high-Al basalts. Nickel enters the earliest available octahedral sites and is strongly depleted in the residual magma. It is accordingly difficult to devise fractionation schemes, involving crystallisation and removal of minerals with such sites (eg. olivine, and ortho or clinopyroxene) without reducing the nickel concentration.

(3) Osborn (1962) has proposed that if basalt is crystallising under conditions of constant moderate oxygen pressure, early crystallisation of magnetite will result. Crystallisation and separation of this magnetite would account for the lack of iron enrichment in the calc-alkaline association, assuming that the calc-alkaline rocks are derived from more basic rocks by differentiation. However, removal of magnetite will deplete the magma in the ferromagnesian elements which enter magnetite. Duncan and Taylor (in press) have analysed magnetites from andesites and dacites from New Zealand. These contain high concentration (0.5 - 0.8%) of vanadium. The loss of magnetites having these compositions will strongly deplete the magma in vanadium. For example if magnetite representing 1% by weight of the magma were removed this would result in a decrease of 50-80 ppm V in the remaining total-rock. The small differences in the Vanadium content of basalts (including high-Al basalts) and andesites are shown in Figure 10. Calculations indicate that the vanadium content restricts the removal of magnetite to about 2%, which is insufficient to explain the decrease in iron content between basalt and andesite.

(b) Mixing hypotheses

These have been popular theories because the major element composition of andesites, excluding potassium, may be approximated by 50:50 mixes of basalt and granite, or 40:60 mixes of basalt and granodiorite. Limited amounts of mixing are not ruled out, but the trace element data do not support hypotheses involving bulk addition of material of typical upper crustal composition with basaltic magma. It is possible to involve special rock types, but the uniform nature of andesitic volcanism requires a uniform process involving common and abundant materials.

The consequences of some simple mixing models are explored in the following sections.

(1) Mixing with upper crustal material.

Fig. 11 shows 60:40 mixes of average granodiorite with average continental basalt (approximately 3 tholeiitic / 2 alkali basalt) and low-K oceanic tholeiite compared with andesite averages. The data are from Taylor (1968). The 60:40 mix gives the appropriate major element composition. Where the compositions are equivalent, the points will lie along a 45° diagonal line. Increasing distance from this line represents increasing disparity in composition. The dashed lines enclose concentrations within a factor of two of the andesitic composition. Abundances outside these limits are considered distinctly different. In the mixes, Rb, Cs, La, Ce, Pr, Nd, Sm, Gd, Tm, Cr, Th, U, Ni, Sn and Li are more abundant than the andesite average by a factor of two or more. This problem is not solved by mixing granite rather than granodiorite, although the proportion of this rock type decreases to 50% to account for the major element content. This decreased amount in the mix is offset by the higher abundances of the trace elements in granites. Fig. 12 shows the composition resulting from the granite-basalt mixes, and it is clear that this diagram is generally similar to Figure 11, with numerous elements being too high in abundance in the mixes compared with the andesites. Mixing of limited amounts (> 10%) are not of course ruled out. The high-K andesites might be derived by such a process but it should be noted, for example, that the low Th/U ratio (2.5) does not offer much evidence for mixing of upper crustal material

where the ratio is greater than 3.5. The Ni and Cr contents of these rocks are so low as to preclude the presence of basalt in the mix. The trace element data in the dacites, where the high SiO_2 content could reflect a hybrid origin, do not provide much support for such hypotheses.

The low nickel content of andesites restricts the amount of tholeiitic or alkali basalt in such mixes to about 20-30%, providing further difficulties for the hypothesis, since the Vanadium contents in andesite and basalt are similar. Since both V and Ni would be principally derived from the basaltic member, it is difficult to construct realistic mixing models.

The arguments for mixing hypotheses apply to areas where upper crustal acidic material is available for mixing. In many regions (Aleutians, Morianas, Solomon Islands) such material is locking, as noted by a number of recent workers; Gorshkov (1962) Hamilton (1964) Taylor and White (1965, 1966) Taylor (1967, 1968), Green and Ringwood (1966) and Dickinson and Hatherton (1967).

(2) Mixing with deep crustal material.

Depending on our ideas about the composition of deeper (20-40 km) parts of the crust it is possible to propose suitable mixes of basalt with this material to account for the composition of andesites. Such calculations are probably futile. The crust in orogenic areas appears to be thin rather than thick (Thompson and Talwani 1964, Pakiser and Zietz 1965). The deeper crustal zones, which are possibly depleted in many of the elements which are low in andesites, are probably not present in areas where the calc-alkaline rocks occur.

One basic fact, unrelated to trace element chemistry, but worth noting here, is the occurrence of these similar rock types in areas of differing crustal thickness, as emphasised by Gorshkov (1962). The genesis of andesites in orogenic area appears unrelated to variations in crustal thickness.

(3) Mixing with deep-sea clays.

Many suggestions are current that the oceanic crust is being transported down the dipping seismic zone underneath island arcs. Accordingly, mixes of basalt with deep-sea clays must be considered as possible sources of calc-alkaline magmas. The composition of the deep-sea clays is unique for a number of elements (Table 9). Nickel is particularly high (225 ppm) and the Ni/V ratio is nearly 2 compared with about 0.1 for andesites. The Ni/Co ratio is about 3 compared with 0.75 for andesites. Thus deep sea clays provide excess amounts of nickel, in particular, which has to be removed during the processes of magma formation. This situation is compounded by the high nickel content of "oceanic" basaltic magmas if these are the other component. Further difficulties are provided by the high contents of Cs, Ba, Pb, Mn, Cu, Li and a high Th/U ratio (5.4) in the clays. The concentrations of these elements are far in excess of those observed in andesites and probably restrict the amount of deep sea clay to a few per cent, if this process operates to form andesitic magmas.

Coats (1962) has proposed a model which explains the production of andesitic magma in the Aleutians arc as due to the transportation of trench sediments down the dipping seismic plane and to mixing of this material with basaltic magma. This model does not suffer from the compositional restrictions imposed by the deep sea clays. However, the process is self limiting, since much of the sediment is derived from the volanoes. The terrigenous component will be labelled with high Sr^{87}/Sr^{86} ratios. Such suggestions do not invalidate models based on sea-floor spreading, transport of basic material down the dipping seismic zone, and subsequent melting of this material to produce andesites. The trace element data indicate that the deep-sea clays do not fill any significant role in such a process.

(c) Primary magma

The difficulties associated with other origins for andesites and associated rocks allow serious consideration to be given to the possibility that these rocks originate as a "primary" magma. Several lines of evidence point to a mantle origin. These are:

(1) the occurrence of andesites in areas of thin crust, such as the island arcs.

(2) generally low initial $^{87}Sr/^{86}Sr$ ratios (Hedge, 1966; Ewart and Stipp, 1968).

(3) the large volumes of magma of similar chemistry erupted in areas of differing crustal chemistry, and thickness.

(4) the trace element chemistry.

If these rocks are the products of mantle melting, then it is a necessary requirement that the processes of magma generation, or the mantle compositions in orogenic areas are distinct from those in intra-oceanic and shield areas (Taylor and White 1965).

The critical features of the trace element chemistry which have to be explained by theories of mantle origin include the following:

(a) The large cations are present in low concentrations, and show a wide range in composition. The K/Rb and Rb/Sr ratios are variable. The Sr content is high.

(b) The total rare earth contents are low and the patterns are variable between chondritic and sedimentary.

(c) The large highly charged cations are present in low but variable concentrations. Th/U ratios are low. The three groups of elements discussed above show approximate positive correlations with the potassium content.

(d) Nickel and cobalt are low in abundance, and the Ni/Co ratio is low. Chromium is low but variable. Vanadium and scandium are present in high concentrations. The variations among the ferromagnesian trace elements are of critical importance for theories of origin. The similarity in the relative abundances of Ni, Co, V, Sc and Cr between high-Al basalt and andesite is noteworthy, and would suggest that these rock types formed by similar processes, rather than that andesites are derived from high-Al basalts.

Evidence for two stage process

In contrast to alkali and tholeiitic basalts, calc-alkaline rocks are not observed to erupt in ocean basins or shield areas. They are thus not 'primary' magmas derived in a single stage from the mantle. The trace element data are consistent with derivation by a two or multistage process from primitive mantle. Such features as the variable concentrations of the large cations, the rare earths and the large highly charged cations, all of which will be derived from minor mantle phases, are suggestive of multistage processes. The strongest evidence from the trace element chemistry comes from the low content of nickel and the relative abundances of the other ferromagnesian trace elements. Ni, Co, Cr and V preferentially enter octahedral co-ordination sites due to crystal field effects (Burns and Fyfe 1964). There is an abundance of such sites in minerals (notably hypersthene and clinopyroxene) crystallising from andesite magma. If nickel were present, it would be accomodated mainly in the orthopyroxenes. Crystallisation and removal of olivine would preferentially remove nickel and cobalt, but olivine is not a common phase in andesites and there is little evidence of accumulation of olivine on the scale required to deplete the magma in nickel. Olivine andesites, although not unknown, are rare. There is no evidence from the Mg contents or the Mg/Fe ratios of removal of olivine on a large scale. It is accordingly concluded that nickel was low ($\sim$ 20 ppm) and that the Ni/Co ratio was low ($\sim$1) in the magma from which the andesites crystallised. These values are very different from those predicted in primitive mantle material or in melts derived from them. Most of the nickel and cobalt in the upper mantle will be contained in olivines, orthopyroxenes and clinopyroxenes. Based on the nickel content and Ni/Co ratios of peridotites, values of the order of 1000-2000 ppm Ni and 100-200 ppm Co with Ni/Co ratios about 10 may be anticipated. Alkali and tholeiitic basalts, derived from this material average about 120 ppm Ni and 50 ppm Co (Ni/Co$\sim$ 2.5). If we take these values as representative of partition occurring between melt and residue, then it is difficult to produce melts from primitive mantle with nickel contents of 20 ppm, and occasionally as low 1-2 ppm. The chromium content provides a similar but less persuasive example. Although andesites contain high concentrations of the trivalent cation vanadium, the chromium content is low and variable. For the same reasons as in the case of nickel, it is concluded that the initial andesite magma had a similar low and variable chromium content. The distinction between the behaviour of Cr and V, both trivalent cations, is consistent with the presence of Cr in a separate minor phase (eg. chromite) in the mantle, where it is probably in the range 1000-5000 ppm. It is postulated that the andesite magma contained the same ferromagnesian trace element pattern as is now exhibited by the rocks. Such abundances are difficult to derive in a single stage from current models of mantle composition. This evidence from trace element chemistry is consistent with the two-stage processes proposed by Green and Ringwood (1966, 1968).

Anomalous upper mantle zones

Our knowledge of the structure of the upper mantle in orogenic regions is becoming clearer as a result of recent investigations, (Thompson and Tolwoni 1964, Pokiser and Zietz 1965, Oliver and Isocks 1967, Holes et ol. 1968). In the search for differences in upper mantle structure between orogenic and non-orogenic regions, two regions appear promising.

Oliver and Isocks (1967) hove drawn attention to the presence in the Tongo-Kermadec orc of on anomalous zone of high S and probable high P wove velocities. This zone lies just under the dipping seismic zone, and is about 100 km thick.

A second region of anomalous upper mantle has been postulated by Thompson and Tolwani (1964) and Pokiser and Zietz (1965) for the Western United States. This zone which occurs immediately beneath the crust, at depths of about 30-70 km is characterised by low Pn velocities. This zone is distinct from the Gutenberg low velocity zone, apparently present at depths of 100-200 km over wide areas, both in orogenic regions (Holes et ol 1968) and in oceanic areas (H. Doyle, J. Cleary personal communication).

The composition of the zone of low P wove velocities in orogenic areas is problematical. However, if andesites and calc-alkaline rocks ore derived from this zone by partial melting, then it is probably more fractionated than primitive upper mantle and may be represented by compositions such as 2 peridotite / 1 basalt rather than the 3 peridotite/ 1 basalt composition of pyrolite (Ringwood 1962).

Model for Mantle Derivation of Andesites and Associated Rocks

The following model is proposed as consistent with the constraints imposed by the trace element chemistry. This model derives colc-alkaline magmas by a two stage process from primitive upper mantle material. Two stages at least ore consistent with the trace element data; it does not seem necessary at present to invoke additional ones.

1. First Stage

Separation of a low melting point fraction occurs from the primitive mantle peridotite, which is assumed to be close to the "pyrolite" composition, proposed by Ringwood (1962). The refractory residue includes the phases, olivine, chromite and possibly orthopyroxene. Most of the nickel, cobalt and chromium remains in these residual phases, or is removed by early crystallisation of olivine, depending on the amount of melting. Melting of minor phases (e.g. phlogopite) and other accessory minerals concentrates the large cations, and the large highly charged cations. Since the distribution of these minor mineral phases is probably sporadic, the concentration of these elements will show variations. Relative separation of Rb and Sr, K and Rb, Th and U and the rare earths may occur so that the K/Rb, Rb/Sr and Th/U ratios and the rare earth patterns will be altered from these in the primitive upper mantle. This process operates on a large scale, and the material forms an anomalous upper mantle zone of low P wave velocities in orogenic areas. This first stage may precede the second stage by a considerable period of time, possibly of the order of 100 million years allowing for small changes to occur in the Sr^{87}/Sr^{86} ratios (Ewart and Stipp 1968).

2. Second Stage

Partial melting of the first stage material in the upper mantle in orogenic areas produces magma of andesitic composition. This occurs at depths of less than 70 km in the zone of low P wove velocities, as suggested by Taylor and White (1965). Probably some further changes occur in K/Rb, Rb/Sr and Th/U ratios and the rare earth patterns, but most of the variations are inherited from the first stage. Variable Sr^{87}/Sr^{86} ratios will occur depending on the Rb/Sr ratios and the difference in time between the first and second stages.

The two stage requirement con be met by various orogenic models. It could be reodily fitted to the sea-floor spreading model involving transport of upper mantle down the dipping seismic zone beneath island orcs.

It is consistent with the suggestions of two stage processes by Green and Ringwood (1966, 1968). It is suggested thot the high-Al basalts as well as the andesites and dacites form by this two stage process.

Relationship of calc-alkaline volcanism to continental composition

The problems of continental origin and growth have been reviewed by Taylor (1967). A strong case for continental accretion and growth is made by the geological and geochronological evidence. The chemical composition of the upper portion of the continental crust approximates to granodiorite or greywacke but the composition of the lower portion is unknown. Nevertheless, on any compositional model the over-all composition is strongly differentiated relative to mantle compositions. The geological evidence appears to demand a continuing process of accretion of chemically fractionated material from the mantle to the continents and it was suggested by Taylor and White (1965) and Taylor (1967, 1968) that calc-alkaline volcanism (mainly andesitic) makes a major contribution to continental growth. The grounds for this suggestion are (1) A large volume of calc-alkaline rocks are erupted; (2) Calc-alkaline volcanism is the characteristic volcanic activity in orogenic regions, adjacent to continental margins; (3) There is a strong probability that the calc-alkaline rocks are derived from the mantle; (4) The average composition of andesites makes a suitable over-all continental composition. It is proposed that intracrustal fractionation produces an upper crust of granodioritic composition and a lower residual crust (Taylor 1967, 1968).

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* Sources of data for Tables 1 through 6.

1. High-Al basalt: Data from K-Trig basalt Taupo, New Zealand.

2. Basic andesite: SiO_2 53-56%. Average based on analyses from Bougainville, Solomon Islands (Taylor and Blake in prep); New Zealand, Taylor and Blake (in prep); Japan, New Zealand (Taylor and White 1966); Aleutian Islands (Amchitka, U.S.G.S. Bull. 1028-P (Powers et al. 1960); Semisopochnoi U.S.G.S. Bull. 1028-O (Coats 1959); Unmak U.S.G.S. Bull. 1028-L (Byers, 1959).

3. Low-potassium andesite: Average of Saipan andesites (Taylor and Blake in prep, Taylor 1968) $K_2O < 0.7\%$.

4. Andesite: SiO_2 56-62%. Average data for major elements compiled from analyses of circum-Pacific calc-olkaline andesites. Western United States (Fiske et al. 1953, Coombs 1939); New Guinea (Taylor 1951); New Zealand, Clark 1960, Steiner 1958, Taylor and White 1966; Bougoinville, Taylor and Blake (in prep); Japan (Taylor and White 1966); data for trace elements from New Zealand, Japan, Bougainville, Fiji (Taylor and White [1966] Taylor and Blake [in prep]); Aleutian, U.S.G.S. Bull. 1028.

5. High-potassium andesite: No. 599, Mt. Balbi. Bougainville, Solomon Islands (Taylor and Bloke in prep).

6. Dacite: No. 160 Luluai River Bougainville, Solomon Islands (Taylor and Blake, in prep).

7. Rhyolite: Average of New Zealand rhyolite (Ewart, Taylor and Capp 1968).

8. Granodiorite: Average based on data from Turekian and Wedepohl 1961 (high calcium granites) Kolbe and Taylor 1966, Australian granodiorites. Rare earth abundances from Towell et al. (1965) and Taylor and Capp (in prep).

n.d. : not detected.
\- : no data or insufficient data for averaging.

	High-Al Basalt	Low-Si Andesite	Low-K Andesite	Andesite	High-K Andesite	Dacite	New Zealand Rhyolite	Granodiorite*
Table 1. MAJOR ELEMENTS.								
% SiO_2	51.7	54.9	57.3	59.5	60.8	65.1	75.3	66.9
Al_2O_3	16.9	17.5	17.4	17.2	16.8	16.5	13.5	15.7
FeO	10.4	8.18	7.30	6.10	5.13	3.86	1.68	3.78
MgO	6.5	4.71	3.52	3.42	2.15	1.48	0.25	1.57
CoO	11.0	8.49	8.65	7.03	5.60	4.75	1.49	3.56
Na_2O	3.1	3.43	2.63	3.68	4.10	4.60	4.12	3.84
K_2O	0.4	1.10	0.70	1.60	3.25	2.05	3.39	3.07
TiO_2	-	0.82	0.58	0.70	0.77	0.51	0.27	0.57
Table 2. LARGE CATIONS.								
Cs	-	0.6	-	0.5-1	1-2	<0.5	3.3	4
Rb	9.6	14	10	31	88	44	108	110
Tl	-	-	-	0.2	0.35	0.05	1.1	0.9
Bo	115	200	110	270	400	520	870	500
% K	0.33	0.91	0.59	1.33	2.61	1.70	2.81	2.55
Eu	1.5	0.99	1.0	1.0	1.4	0.90	1.0	1.2
Pb	1.7	3.3	4.0	6.7	7.2	5.2	18	15
Sr	328	430	215	385	620	460	125	440
% Co	7.58	6.07	6.20	5.02	4.00	3.39	1.06	2.54
% No	2.23	2.54	1.95	2.73	3.04	3.41	2.52	2.85
K/Rb	344	650	590	430	297	386	250	230
Ba/Sr	0.35	0.47	0.51	0.70	0.65	1.13	7.0	1.14
Rb/Sr	0.029	0.07	0.047	0.08	0.14	0.096	0.86	0.25
Bo/Rb	12	14	11	8.7	4.5	11.8	8.1	4.5
Table 3. RARE EARTHS.								
La	9.6	10.3	3.1	11.9	13	14	28	36
Ce	19	19	6.8	24	23	19	43	47
Pr	4.1	2.9	1.8	3.2	3.6	5.1	6.4	8.5
Nd	20	14	9.8	13	17	16	18	26
Sm	4.0	2.9	2.6	2.9	4.5	3.1	5.5	6.8
Eu	1.3	0.99	1.0	1.0	1.4	0.90	1.0	1.2
Gd	4.0	2.5	4.0	3.3	4.9	2.5	4.3	7.4
Tb	0.80	0.48	1.0	0.68	1.1	0.45	1.2	1.3
Dy	-	-	-	-	-	-	-	3.2
Ho	1.2	0.63	1.0	0.71	1.0	0.56	1.4	1.6
Er	4.2	1.94	3.1	2.1	3.1	1.97	3.9	4.8
Tm	0.56	0.26	0.46	0.30	0.46	0.36	0.46	0.50
Yb	2.7	1.50	2.7	1.9	3.2	1.4	3.6	3.6
Lu	-	-	-	-	-	-	-	-
ΣREE	71.5	57.4	41	65	76	65	117	148
Y	20	22	25	21	20	20	25	30
ΣREE+Y	91.5	79.4	66	86	96	85	142	178
Eu/Gd	0.33	0.40	0.35	0.30	0.29	0.36	0.24	

* For sources of doto for Tables I through 6, see page 59.

	High-Al Basalt	Low-Si Andesite	Low-K Andesite	Andesite	High-K Andesite	Dacite	New Zealand Rhyolite	Granodiorite*
Table 4. LARGE HIGHLY CHARGED CATIONS.								
Th	1.1	1.34	1.3	2.2	5.5	1.7	11.3	10
U	0.2	0.43	0.4	0.69	2.2	0.62	2.5	2.7
Zr	100	92	90	110	170	100	160	140
Hf	2.6	1.7	2.0	2.3	4.5	3.8	4.5	3
Sn	0.54	0.60	0.70	0.8	2.3	0.39	1.3	2
Nb	4.0	3.7	0.30	4.3	11	6.0	5.6	-
% Ti	-	0.49	0.37	0.42	0.46	0.31	0.16	0.34
Mo	1.7	1.2	-	1.1	7.4	0.49	-	1
K/U	16,500	21,200	14,750	19,300	11,860	27,400	11,200	9,440
Th/U	5.9	3.1	3.3	3.2	2.5	2.7	4.5	3.7
Zr/Hf	38	54	45	48	38	26	36	47
Table 5. FERROMAGNESIAN ELEMENTS.								
Mn	-	1320	1000	1200	1300	580	400	600
%Fe^{2+}	4.51	-	3.18	2.84	2.45	0.76	-	2.01
Cu	35	60	55	54	40	22	6	25
Co	40	28	20	24	13	9	n.d.	10
Ni	25	28	15	18	3	5	n.d.	15
% Mg	3.78	2.84	2.12	2.06	1.30	0.39	0.16	0.95
Li	10	7	-	10	-	-	35	25
%Fe(total)	7.80	6.36	5.67	4.74	3.99	3.00	1.31	2.94
Sc	40	31	31	30	20	11	4.7	14
V	255	200	195	175	160	68	8.5	75
%Fe^{3+}	3.29	-	2.49	1.90	1.54	2.24	-	0.93
Cr	40	85	44	56	3	13	1.7	30
Ga	13	13	-	16	-	-	16	18
%Al	8.68	9.26	9.21	9.10	8.89	8.73	7.14	8.31
Ni/Co	0.86	1.0	0.75	0.75	0.23	0.55	-	1.5
Fe^{2+}/Ni	1400	2270	1590	1580	8170	1520	-	1340
Al/Ga	6680	7380	-	5690	-	-	4460	4620
Cr/V	0.55	0.43	0.23	0.32	0.019	0.19	0.20	0.40
Table 6. CHALCOPHILE ELEMENTS.								
Tl	-	-	-	0.2	0.35	0.05	1.1	0.9
Ag	-	-	-	0.13	0.45	-	-	0.05
Pb	1.7	3.3	4.0	6.7	7.2	5.2	18	15
Cd	-	-	-	-	-	-	-	0.13
Bi	-	-	-	n.d.	-	-	-	-
In	-	-	0.25	-	0.32	-	-	-
Sb	-	0.25	-	0.22	0.79	-	-	0.2
Cu	35	60	55	54	40	6	6	25
As	-	-	-	-	-	-	-	1.9
Ga	13	13	-	16	-	-	16	18

* For sources of data for Tables 1 through 6, see page 59.

Table 7. Average data for volcanic rocks for Kamchatka and Kurile Islands*

	Ba	Zr	Cu	Co	Ni	V	Cr
Basalt	130	100	63	56	61	520	89
Basaltic andesite	200	110	41	39	41	320	63
Andesite	390	250	34	29	33	280	26
Dacite	610	390	25	17	12	176	12
Rhyolite	730	630	3.3	15	11		10

* Markhinin and Sapozhnikova (1962 a, b, 1964).

Table 8.

	Sc ppm A*	B**
Basalt	38	39
Andesite	34	30
Dacite	21	11
Rhyodacite	14	-
Quartz latite	11	-
Rhyolite	5	4.7

* Average Sc content of calc-alkaline volcanic rocks (Fryklund and Fleischer 1963)
** Data from Table 5.

Table 9. Composition of deep-sea clays, compared with averages in andesites.*

	Deep sea clay	Andesite
Cs	6	1
Rb	110	30
Ba	2300	270
Pb	80	7
Th	7	2.2
U	1.3	0.7
Nb	14	4
Mo	27	1
Mn	6700	1200
Cu	250	54
Co	74	24
Ni	225	18
Li	57	10
Sc	19	30
V	120	175
Cr	90	56

* Data from Turekian and Wedepohl (1961).

Table 10. Data for Ni, Co, Cr, V and Sc in High-Al basalts from Marianas and Aleutian Islands. Values for SiO_2, Al_2O_3, Na_2O and K_2O are given.

	MARIANA IDS.		ALEUTIAN ISLANDS												
	Guam		Semisopochnoi					Bogoslof Umnak		Kiska		Segula	Unalaska		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Ni	10	100	30	20	10	7	--	10	40	10	30	30	20	20	40
Co	200	200	30	30	30	20	30	20	20	30	30	40	40	40	40
Cr	9	10	60	20	2	--	--	40	80	6	30	80	20	40	200
V	60	50	300	200	200	200	200	200	200	500	400	300	400	300	300
Sc	40	30	30	20	20	10	20	--	--	50	40	40	40	60	70
SiO_2	53.2	51.1	49.7	50.4	51.6	52.1	52.4	50.1	50.5	48.5	51.7	51.2	47.7	49.5	50.3
Al_2O_3	17.5	18.1	18.8	19.9	19.1	21.3	19.3	23.0	19.7	20.2	19.9	18.9	17.2	17.8	16.5
Na_2O	2.71	2.45	2.98	2.98	3.35	3.32	3.64	2.40	2.71	2.49	3.13	2.57	3.40	2.40	2.50
K_2O	0.94	1.02	0.99	0.87	1.14	1.09	1.24	0.44	0.58	0.45	0.86	0.66	0.72	0.76	0.72

1,2 U.S. Geological Survey Professional Paper 403-C: Table 3, Anal. 9 and 5.
3-7 U.S. Geological Survey Bulletin 1028-O: Table 1, Anal. 1-5.
8,9 U.S. Geological Survey Bulletin 1028-L: Table 2. Anal. 5,6.
10,11 U.S. Geological Survey Bulletin 1028-R: Table 1, Anal. 2,3.
12 U.S. Geological Survey Bulletin 1028-K: Table 1, Anal. 2.
13-15 U.S. Geological Survey Bulletin 1028-S: Table 1, Anal. 2-4.

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DIFFERENTIATION OF CALC-ALKALINE MAGMAS

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Abstract

Because recent geochemical and geophysical data have cast some doubt on the origin of calc-alkaline magmas by contamination of basaltic magma with sialic material, an hypothesis is examined involving differentiation of a parent magma in an essentially closed system at low pressures within the crust. There are many uncertainties in the selection of a single, definite parental magma for calc-alkaline associations, but in most instances a high-alumina basaltic andesite with about 4% $Na_2O + K_2O$ seems to satisfy available criteria. In contrast to crystal fractionation in dry basaltic magmas, which produces (except in late stages) approximately equal partition of Si, Na and K between crystalline phases and liquid, crystal fractionation in calc-alkaline magmas produces strong partition of Si, Na and K into the liquid. Crystallization of calcic plagioclase in the mafic members of calc-alkaline associations may well be responsible for this partition, and this in turn is brought about by the elevated water pressure likely to exist in calc-alkaline magmas. Volatile transfer -- upward concentration of H_2O, NA and K (also Si) in the magma chamber -- although lacking definite supporting evidence, should nonetheless be considered as a possible auxiliary mechanism in the development of calc-alkaline associations.

Introduction

Interest in the calc-alkaline rock association has fluctuated over the past several decades. After the exploratory studies of the 1930's and early 1940's, attention shifted to granites and then basalts. As a result of this work, it became apparent that, rather than constituting the "normal" differentiates of basaltic magma (as envisaged by Bowen, 1928), calc-alkaline associations constitute only one of two contrasted series that can develop from basaltic parent magmas. This distinction was formalized by, for example, Kennedy (1955) who recognized a "Bowen trend" of late enrichment in silica and alkalies (calc-alkaline associations) and a "Fenner trend" of iron enrichment (developed to an extreme degree in the Skaergaard intrusion). Within the last few years there has been renewed research on calc-alkaline rocks, mainly from an analytical and experimental approach.

This paper is an inquiry into some of the salient facets of the calc-alkaline suite of rocks -- their chemistry, mineralogy, and their possible evolution through processes of magmatic differentiation.

Character of the Calc-alkaline Association

One of the most popular methods of illustrating trends in calc-alkaline rocks is the AFM diagram, Fig. 1. The plot illustrates some representative calc-alkaline associations with typically moderate absolute enrichment in Fe (maximum of about 50% of Fe + Mg + K + Na) and the nearly linear increase in Fe/Mg ratio as (Na + K) increase. Volcanic versus plutonic associations cannot be discriminated on this, or any other, type of variation diagram, suggesting that the chemical trend is established before (or in spite of) emplacement in either of these two environments. Whether hornblende or pyroxene is the dominant mafic phase seems to make little difference in the AFM plot. Many rocks, interpreted as cumulates by Nockolds and Allen (1953), plot close to the FM side of the triangle, but they are so scattered that it is difficult to relate them to curves for the individual associations. A plot of Ca, Na, and K in Fig. 2 illustrates that in most associations the ratio K/Na rises at an increasing rate as Ca diminishes.

The mineralogy of the associations is well represented in Bowen's familiar reaction series of plagioclase with olivine, pyroxene, hornblende, and biotite. In hydrous magmas olivine seems to be restricted to the less siliceous compositions; hornblende and biotite are the dominant ferromagnesian silicates in silicic magmas. The Ca-poor clinopyroxene (pigeonite) so typical of many dry basaltic

CAPTIONS FOR FIGURES APPEARING ON OPPOSITE PAGE.

1. AFM variation diagram in wt. % for some representative calc-alkaline associations from plutonic (p) and volcanic (v) environments where the dominant ferromagnesian phase, whether pyroxene (px) or hornblende (hb) is indicated. The list of associations relates to the top-to-bottom order of the curves between the two arrows. All from Nockolds and Allen (1953) except Aleutian (Hamilton, 1964), Guadalupe (Best, 1963 and unpublished data), and Newberry (Williams, 1935). Dotted curve is averaged trend of tholeiitic differentiates from Hawaii (from Richter and Moore, 1966, Fig. 16).

2. Na-K-Ca variation diagram in wt. % far some calc-alkaline associations listed in their top-to-bottom arder of appearance between the two arrows. Trandjhemite trend is from Davis (1963). See caption under Fig. 1 for meaning of code letters.

3. Liquids and corresponding average rocks (solid circles) from the zones in the Skaergaard intrusion (after Wager, 1960, Fig. 11).

4. Plot showing strong partition of (Na + K) into the liquid or residual material of calc-alkaline associations. CC, hornblende-biotite dacite and groundmass glass (Hague and Iddings, 1883, Table 3) and hornblende-plagioclase inclusion in hornblende-biotite dacite (Williams, 1932, p. 366 and 365, nas. 33 and 28) from Chaos Crags, Mount Lassen region. MS, hypersthene-augite-plagioclase pumice and groundmass glass (Hague and Iddings, 1883, Table 2) from Mount Shasta. L, two pairs of plagioclase-hypersthene inclusion and host andesite (Clarke, 1915, p. 172, S & R, p. 173, X & W) from the Mount Lassen region. SN, hornblende-plagioclase inclusian and host granodiorite (Pabst, 1928, 2 & 2a in Table 1) from the Central Sierra Nevada. LA, cumulate allivalite and its intercumulus glass (Lacroix, 1949) and cumulate hornblende eucrite and its intercumulate glass (Lewis, 1964 and written comm.) from St. Vincent. Dashed enclosures are ejected andesite pumice (left) and cumulate blocks (right) from St. Vincent (Lacroix, 1949, nos. 4, 5, 9, 10 & 11).

5. An AFM plot illustrating that the same Fe/Mg ratios occur in the Skaergaard and average calc-alkaline association.

6. Unusually calcic plagioclase in calc-alkaline associations compared to plagioclase in Bushveld, Rhum, Skaergaard and Stillwater layered intrusions. Data for calc-alkaline rocks is from Lewis (1964), except for one point for the Pine Hill, California, pluton (R. Springer, written comm., 1968).

Fig. 1

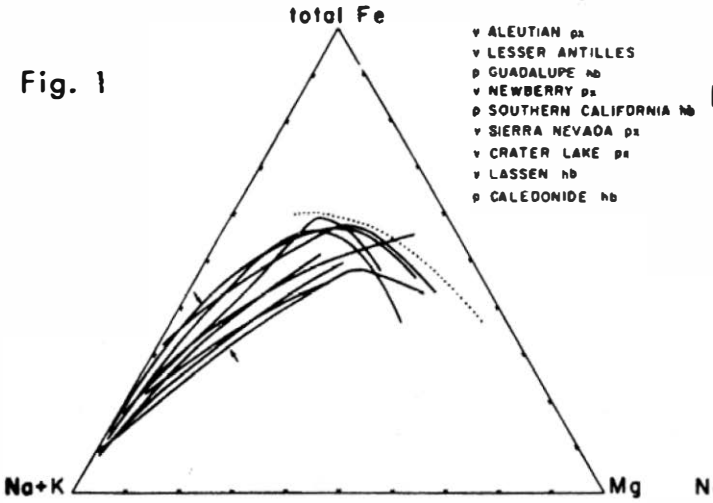


Fig. 2

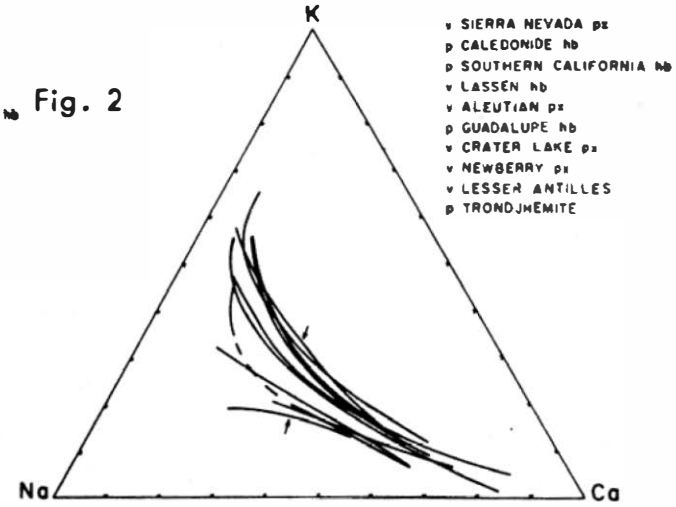


Fig. 3

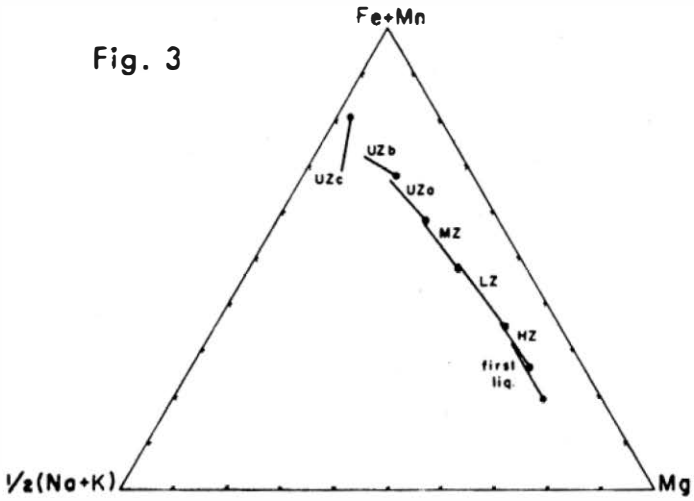


Fig. 4

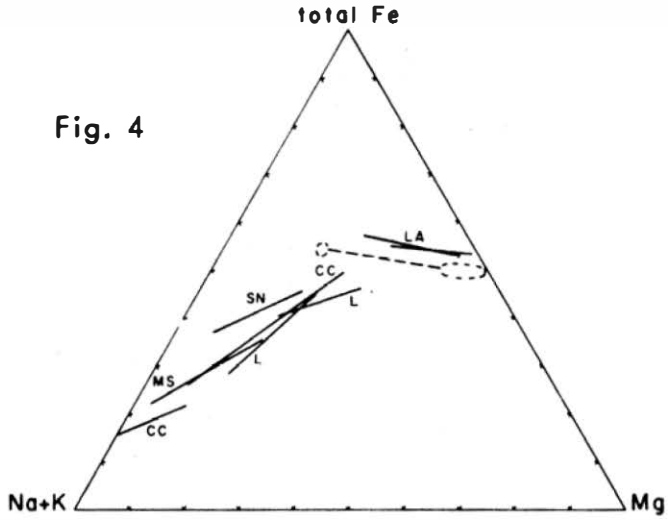


Fig. 5

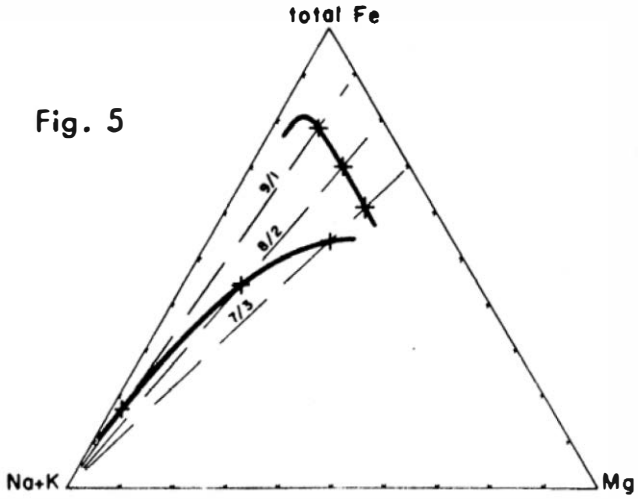
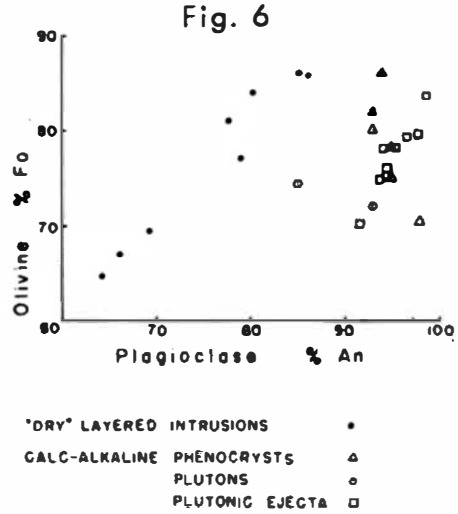


Fig. 6



differentiates is lacking in plutonic calc-alkaline rocks where instead clinopyroxene and orthopyroxene have, respectively, extremely high and low contents of Ca (Best, 1967). Hypersthene is commonly a dominating phase in volcanic rocks and this association has prompted Kuno (1959) to refer to many calc-alkaline associations in Japan as the "hypersthenic rock series."

Although reports on calc-alkaline associations almost universally omit estimates of relative volumes of rock types, there can be no question that neither basalt nor rhyolite (or plutonic equivalents) are as voluminous as intermediate rock types. Larsen (1948) lists for the southern California batholith: gabbro 14%, quartz diorite 51%, granodiorite 33%, and granite 2%. Estimates for the Mount Lassen region, using the geologic map of Williams (1932), give basalt 24%, andesite 66%, dacite 10%, and rhyolite less than 1%.

The order of emplacement of plutonic bodies is generally from the most mafic to the most silicic. In volcanic centers this simple sequence is not always found: in the southern Cascades alternating mafic and siliceous lavas have been extruded within a localized region* and at Mount Lassen composite lavas of andesite-dacite have been erupted (Macdonald and Katsura, 1965).

Evolution of the Association

Several years ago Tilley (1950, p. 49, see also Turner and Verhooden, 1960, p. 287) summed up the problem of the evolution of the calc-alkaline rocks:

> "Many petrologists have . . . sought either the operation of some accessory processes in combination with fractional crystallization or have resorted to some independent process to explain the characters of the normal calc-alkali series."

The hypotheses invoked up to the time of Tilley's summary, and in the following decade, generally relied upon the concept of a magmatic system chemically open to surrounding country rocks or magmas. The hypotheses fall into the general categories:

1) contamination of a magma undergoing fractional crystallization
2) partial melting of sialic crustal rocks
3) mixing of magmas

Mixing of magmas, invoked by Larsen (Larsen et al., 1938) in his study of the San Juan volcanic field, has received little support.

Partial melting of sialic crustal rocks, one of Tilley's "independent processes," fails to provide for the more mafic rock types (e.g. basalt) typical in the association, unless one would argue that locally there is complete melting of basaltic parts of the crust. Even then, the regular order of emplacement of plutonic masses from early mafic to late silicic is the reverse of the order of liquids produced during anatectic melting.

The hypothesis receiving the greatest attention over the years calls for assimilation of sialic crustal material by a fractionating basaltic magma (presumably generated in the upper mantle). The ideo of hybridism has been invoked in a variety of forms for the small composite plutons in the British Caledonides (see general review and abundant references in Mercy, 1963 or 1965). Exhaustive chemical and mineralogical investigation of the Garabal Hill-Glen Fyne complex by Nockolds (see for example, Nockolds and Mitchell, 1946) has, however, left little to be said in favor of hybridism of magmatic contamination by sialic country rocks for that particular suite of rocks. Instead, the data are compatible with a parent magma (Nockolds claims mica-pyroxene diorite) differentiating in an essentially closed system. Sr-isotope measurements by Summerhays (1966) and others lend support to Nockold's interpretation. Essentially the some conclusions may be drawn regarding the evolution of the Guadalupe igneous complex (Best, 1963) because Sr-isotope measurements of four samples of gabbro, quartz monzonite, and granite (performed by C. E. Hedge of the U.S. Geological Survey) yield low initial Sr^{87}/Sr^{86} ratios of 0.7031 to 0.7034 (experimental uncertainty ± 0.0006), thus leaving little possibility for assimilation of much sialic material during differentiation of the magma. Ratios in 53 volcanic

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* Williams (1932) records in the Mount Lassen region a sequence from youngest to oldest: dacite, quartz basalt, dacite, basalt, dacite, rhyodacite and rhyolite, with andesites and basalts constituting several of the oldest flow sequences.

Table 1. Parent magmas of some representative colc-alkaline associations, with comparisons.

	1	2	3	4	5	6*	7*	8*	9*	10
SiO_2	54.4	53.5	56.3	54.9	53.4	49.56	51.7	48.51	49.85	56.2
TiO_2	1.0	0.4	1.1	0.8	1.1	1.53	1.0	1.18	2.52	1.4
Al_2O_3	16.5	18.3	17.3	18.1	19.0	17.88	18.2	17.37	14.08	17.1
Fe_2O_3	1.6	3.2	1.9	3.9	3.2	2.78		1.33	3.06	
FeO	6.4	5.3	6.3	3.8	5.9	7.26	9.1**	8.52	8.61	7.3**
MnO	0.2	0.1	0.1	0.1	0.1	0.14		0.16	0.16	
MgO	6.6	5.5	4.7	5.4	4.0	6.97	5.1	8.70	8.52	5.4
CO	7.8	9.0	7.9	8.6	9.3	9.99	11.1	11.48	10.40	8.7
No_2O	3.5	3.4	3.1	3.4	3.1	2.90	3.0	2.39	2.15	3.0
K_2O	1.7	1.1	1.2	0.8	0.8	0.73	0.7	0.25	0.38	0.9
P_2O	0.3	0.2	0.1	0.2	0.1	0.26		0.10	0.26	
Norm An	38	47	47	48	53	53		62		

1. C, Caledonide
2. L, Mount Lassen
3. SC, Southern California batholith
4. CL, Crater Lake
5. LA, Lesser Antilles (nos. 1 to 5 all from Nockolds and Allen, 1953, Table 8)
6. H, Average High Cascade and Oregon Plateaus (Waters, 1962, Table 5)
7. Aleutians (Hamilton, 1964, Table 1)
8. S, Skaergaard chilled margin (Woger, 1960, Toble 2, no. 4507)
9. T, Average Hawaiian tholeiite (Macdonald and Kotsuro, 1964, Table 9)
10. Liquid fractionate of quartz tholeiite at high pressure (Green and Ringwood, Table 2, no. 3, 1966)

* recalculated to 100%
** total Fe as FeO (+ MnO)

Table 2. Compositions of quenched liquids in the pre-eruption magma chamber of Soufriere, St. Vincent (recalculated water free to 100%)

	Intercumulate		Pumice	
	1	2	3	4
SiO_2	51.51	53.69	56.01	56.19
TiO_2	1.05	1.43	0.99	0.76
Al_2O_3	18.32	15.08	18.34	18.63
Fe_2O_3	2.17	1.95	3.65	3.09
FeO	7.72	8.83	4.86	5.25
MnO	0.21	0.18	0.19	0.05
MgO	5.25	7.33	3.50	3.59
CaO	10.27	8.46	8.20	7.99
Na_2O	2.84	2.53	3.57	3.62
K_2O	0.49	0.52	0.58	0.76
P_2O_5	0.25	-	0.11	0.08

1. Lewis (written communication, 1968, no. T770).
2. Lewis (written communication, 1968; corrected from analysis 3 in Lacroix, 1949).
3 & 4. Lacroix (1949, columns 4 & 5).

rocks from three island arcs are close to 0.704, again indicating minimal contamination with more radiogenic sialic rock (Pushkar, 1968).

The assimilation hypothesis is further weakened by geophysical studies of island arcs, which disclose thin sialic crust in the Lesser Antilles (Officer et al., 1957; see also Donnelly, 1967, and Lewis, 1967) and possibly the Aleutians (Coats, 1962). Elsewhere in this volume, Gorshkov points out that transition from continental to oceanic crust along island arcs is not reflected in the composition of the andesites, hence implying a deeper origin.

Concentrations of trace elements in andesites and calc-alkoline rocks differ significantly from those expected in the contamination hypothesis (Taylor and White, 1965; Taylor, this volume).

If one invokes as a model for the evolution of calc-alkaline associations a fractionating magma essentially closed from and independent of its surroundings, then two restrictive boundary conditions must be specified for the model. The first is the composition of the parent magma and the second is the way in which the elements are partitioned between crystallizing phases and the liquid residuum.

Parent Magma

The compositions of parent magmas of some colc-alkaline associations have been listed by Nockolds and Allen (1953, Table 8), and reproduced here in Table 1. Although there has been some criticism of Nockold's criteria for selection of parent magmas from variation diagrams, no direct means appear to exist for a more rigorous selection. Nockold's compositions (nos. 1 to 6 in Table 1) are fairly uniform, all having high concentrations of Al_2O_3, SiO_2, Na_2O and K_2O and a high $\frac{\text{total Fe}}{\text{MgO}}$ ratio relative to, for example, on overage Hawaiian tholeiite (no. 11 in Table 1). The group may be called high-alumino basaltic andesites.

For the basalt-andesite-dacite series of the Cascades, Waters (1962) has argued for a parent magma (Table 1, no. 7) rich in Al_2O_3 but less enriched in SiO_2, Na_2O and K_2O than the high-alumina basaltic andesites.

Recent experimental studies of natural rocks at high pressures suggest that liquids of high-alumina basaltic andesite composition (Table 2, no. 10) may develop in the upper mantle by partial melting of quartz tholeiite material (Green and Ringwood, 1967). In the proposed model the quartz tholeiite is produced by on earlier episode of partial melting of pyrolite to produce undersaturated basaltic magma which rises to depths of less than 20 km where it undergoes fractionation to the oversaturated material. In view of the current concept of sea-floor spreading, on alternative but perhaps more realistic series of events would be to drag quartz tholeiite oceanic crust beneath the island orc or continental margin via

convective motion in the upper mantle. The 70% melting of the quartz tholeiite to produce andesitic basalt liquid required in the model of Green and Ringwood would yield copious volumes of lava from the down-dragged oceanic crust.

Presnall (1966) has emphasized that many magmatic associations (most are from the Circum-Pacific calc-alkaline suites) include volatile-free compositions very close to the Skaergaard parent, but none include fractionated liquids enriched in Fe to the extent of the Skaergaard. In other words, it seems unreasonable to assert that the proportions of major elements in the Skaergaard parent had any real effect on the unique differentiation trend. The low water content of the Skaergaard parent may well have been unique, however, and this aspect certainly cannot be discounted in explaining its differentiation trend.

Other factors than the composition of parent magmas should be very relevant during crystallization and differentiation of the magma.

Role of Partition Values

Differences in the distribution of major elements between crystallizing phases and residual liquid exert a powerful control on the changing compositions of residual liquids (Newman, Mead, Vitaliano, 1954). Turning first for comparative purposes to the Skaergaard, Figure 3 demonstrates that through 99% of the crystallization of the intrusion, to liquid UZb, the partition of (K + Na) and Si (not shown) between crystalline and liquid phases was about equal. The partition of Fe and Mg favored Mg in the crystalline phases.

Examination of partition coefficients in the calc-alkaline associations is seriously hampered by the lack of analyzed crystal-liquid (glass) pairs. Tilley (1950) presented an AFM diagram, shown here with modifications as Fig. 4, in which were plotted whole rocks and their constituent glasses plus sets of cognate inclusion and host rock. Although these data are of a different nature than the more relevant compositions of crystal-liquid pairs and the textures (commonly panidiomorphic) of the inclusions raise some doubt as to their origin, the plot (Fig. 4) nonetheless suggests, how early crystallized material may be related to residual liquids. More definite and meaningful data have been obtained on ejecta of the 1902 eruption of Soufriere on St. Vincent in the Lesser Antilles (Lacroix, 1949; Wager, 1962; Lewis, 1964) in which quenched equilibrium pairs of crystalline phases (cumulates) and liquid (now glass) have been analyzed.

A rigorous evaluation of the partition of Fe and Mg in calc-alkaline magmas is not warranted from the data shown in Fig. 4, but it may not be much different from that of the Skaergaard. There is, however, an obvious and strong partition of (Na + K) and Si (not shown) in favor of the residual liquids of calc-alkaline magmas -- a marked contrast to the situation in the Skaergaard. Realizing that similar Fe/Mg ratios occur in both the calc-alkaline and Skaergaard trends (Fig. 5), the former trend may be viewed as one "swamped" by increasing concentrations of Na, K, and Si as Fe/Mg increases. It appears then that the critical point regarding the origin of calc-alkaline associations is not so much in the way Fe and Mg are partitioned, but in the fate of Na, K, and Si during crystallization.

Which of the intensive variables -- temperature, confining pressure, fugacity of water (f_{H_2O}), fugacity of oxygen (f_{O_2}), and concentration of chemical components -- might be responsible for this type of partition?

Osborn (1959, 1962) has found that in the system MgO-FeO-Fe_2O_3-SiO_2, the behavior of oxygen during fractionation has a significant bearing on the partition of the elements in the crystallizing and liquid phases. Fractional crystallization at constant total composition (closed system with f_{O_2} at any temperature determined by the equilibrium assemblage of condensed phases) produces a trend in these components similar to that of the Skaergaard. If, however, crystallization ensues at constant or increasing f_{O_2} (open system with f_{O_2} controlled by external factors) then a variation similar to the calc-alkaline trend develops.

The oxygen fugacities (10^{-8} to $10^{-0.7}$ atm) used by Roeder and Osborn (1966, p. 456) to exemplify trends of silica enrichment and iron impoverishment (i.e. the calc-alkaline trend) are unrealistically high for natural basaltic melts. The data presented by Best (1967) suggest a f_{O_2} for the calc-alkaline Guadalupe intrusion that could not have been initially much greater than f_{O_2} in the Skaergaard magma. Carmichael's (1966) study of oxides and mafic silicates in Cascade and other volcanic rocks demonstrates that f_{O_2} decreases during fractionation and concurrent enrichment in SiO_2, the f_{O_2} apparently being buffered by olivine, hypersthene, or biotite-amphibole, rather than by coprecipitating Fe-Ti oxides. Mueller (1967) argues that as calc-alkaline magmas differentiate, f_{O_2} decreases and SiO_2, Na_2O and K_2O are enriched, and the ratio of $\frac{FeO + Fe_2O_3}{MgO}$ increases. These findings

should not necessarily be construed to imply that f_{O_2} does not, as proposed by Osborn, control the partition of elements in a crystallizing magma. In fact, the treatment by Presnall (1966; see also Carmichael and Nicholls, 1967, p. 4674) restates the nature of the control as follows: If fractionation proceeds in a water-poor, closed system at "constant total composition," then on iron-enriched (Skaergaard) trend develops. If, on the other hand, the magma is buffered by abundant water or by condensed phases, the f_{O_2} may increase, remain constant, or decrease during fractionation and iron-enrichment does not develop, provided that Fe-Ti oxides are precipitating in abundance.

Some of the shortcomings of Osborn's synthetic model have been surmounted in a later study in which An_{50} was used as the plagioclase component (compare Osborn and Roeder, 1966). Silica enrichments to 70% at an f_{O_2} comparable to natural magmas are reported (Osborn, this volume). More analytical investigations of ferromagnesian mineral assemblages in Skaergaard-type and calc-alkaline associations are desirable to evaluate these models.

The plutonic blocks in the ejecta of Soufriere, St. Vincent previously referred to all consist of homogeneous crystals of anorthite (generally $\sim$ 50% in the mode) and olivine with aluminous, Ti-rich hornblende, Ca-rich clinopyroxene, and magnetite commonly present in addition. The general homogeneity of the crystals, together with harrisitic and poikilitic textures, suggested to Wager (1962) and Lewis (1964) that the blocks are adcumulates, having formed by settling of crystals to the floor of the magma chamber and continued growth by exchange of ions with the melt overlying the crystal mush. The few percent of glass between the crystals represents the entrapped, and quenched, intercumulate liquid, which in the adcumulus situation had a similar composition as the melt overlying the crystal mush. This liquid (Table 2, 1 & 2) is less "differentiated," i.e. has less Na, K, and Si and Fe/Mg and more Ca and Mg than the pumice (Table 2, 3, & 4) constituting the bulk of the ejecta and presumably representing the liquid in the upper part of the chamber. The pumice has phenocrysts of labradorite, hypersthene and augite. The only hornblende in the erupted material is found in the adcumulate blocks, or was derived from them by fragmentation, suggesting that the magma chamber had a sufficient vertical extent for hornblende to be stable only in the lower portion (Wager, 1962).

The compositionally different liquids in the pre-eruption chamber are significant because their compositions fall in a critical part of the calc-alkaline trend. Whether the junction between the liquids in the zoned magma chamber was abrupt or gradational cannot now be answered, but possibly could be by more analyses.

Of the possible alternatives to account for the different liquids, one involving reaction between andesitic liquid (=pumice) and precipitated crystals to yield a bottom-of-the-chamber liquid (=intercumulate glass) can be definitely ruled out on the basis of reasonable proportions (Wager et al., 1960) of crystals in the crystal mush and known compositions of crystals and liquid. Although relevant analyses are few, it appears possible to subtract 60% to 70% of an average adcumulate block from a bottom liquid to yield the andesitic liquid. This is a reasonable interpretation in view of the broad chemical similarity of the bottom liquid to the average (and possibly parental) basaltic andesite of the Lesser Antilles (Lewis, 1964; Baker, 1968).

The separation of anorthite and aluminous hornblende from basaltic liquid is a very effective means of building up the concentration of Na, K, and Si in residual liquids. The fact that similarly calcic plagioclase (relative to coexistant olivine compositions for a comparative standard) has separated from other mafic magmas of calc-alkaline affinity (Fig. 6; see also Lewis, 1964), suggests that a general phenomenon may be in operation during crystallization of these magmas. Compared to the well-known layered intrusions -- Skaergaard, Stillwater, Rhum, Bushveld -- which crystallized from relatively anhydrous magmas, calc-alkaline rocks have formed from hydrous magmas, as manifest by the presence of hornblende and biotite and the generally explosive nature of calc-alkaline eruptions. Lewis (1964) and Yoder (this volume) argue that the unusually calcic plagioclase is caused by elevated P_{H_2O} (but $<$ P total).

Separation of relatively calcic plagioclase, and possibly aluminous hornblende, from andesitic and dacitic magmas would further the differentiation trend already established in more mafic magma.

Although elevated P_{H_2O} in a crystallizing magma reasonably accounts for precipitation of calcic plagioclase and the strong partition of Na, K, and Si into the liquid it may not be the whole story. Numerous allusions have been made over the years to volatile transfer in bodies of hydrous magma, producing upward concentration of Na, K, Si and of course H_2O. The concept lacks definitive experimental confirmation but studies of compositionally zoned ash-flow sheets suggest the possibility (see Smith and Bailey, 1966; Lipman et al., 1966; Lipman, 1967, and included references). Richter and Moore (1966), in their study of the crystallizing Kilauea Iki lava lake found a transient layer of liquid near the crust-melt boundary containing twice as much K_2O as the initial lava.

Kennedy (1955) has described how the mechanism is established and operates, regardless of whether the alkalies associate themselves with o distinct volatile phose in the magma (when P volotive $\geq$ P total) or with the volotive components in solution. The effectiveness of this transfer when the volatiles ore present as a seporote phose has been demonstrated by Tuttle and Bowen (1958, p. 90).

The hydrous nature of colc-alkaline magmas suggests that the hypothesis of volatile transfer may be generally invoked. Depending upon such factors as geometry of the magma chamber (particularly its vertical dimension), proximity to the surface (deep bodies would hove o stronger gradient in concentration of water, Kennedy, 1955, p. 492), water content of the initial magma and how much water is imbibed from country rocks, the length of time for crystallization, etc., rather variable degrees of transfer and differentiation would occur.

Conclusions

The general chemical and mineralogical properties of calc-alkaline associations are quite generally agreed upon. The interpretive aspects of the associations are far more controversial. The following points may, however, be of value in seeking further data and deciding upon better hypotheses.

1. Parent magmas of colc-alkaline associations ore decidedly aluminous and hove Fe/Mg ratios similar to overage Hawaiian tholeiite and the Skaergaard parent. (No + K) and Si may be higher, however, and could be a controlling factor in the trend.

2. Contamination of basalt magma originating in the upper mantle with sialic crustal rocks as a means of producing the colc-alkaline trend appears to be incompatible with available geochemical and geophysical data, but further investigations ore needed before this hypothesis con be definitely evaluated.

3. The fundamental character of the calc-alkaline differentiation trend is the very substantial enrichment of No, K, and Si in liquid residua. The partition of Fe and Mg does not appear to be greatly different from the Skaergaard trend.

4. Fractionation of unusually calcic plagioclase and aluminous hornblende con accomplish the observed partition of No, K, and Si in colc-alkaline magmas. This may be a fairly general phenomenon and is likely to reflect crystallization at elevated P_{H_2O}.

5. The existence of vertically zoned magma chambers seems certain and whether these ore produced solely by crystal fractionation or by volatile transfer con only be answered by further research.

6. The most lucrative line of petrologic research on the genesis of the calc-alkaline associations would appear to lie in compositional analyses of crystalline phases and associated glass from volcanic rocks (note the apparently unheeded plea by Tilley, 1950, p. 61). From this data the important partition coefficients could be evaluated. Particularly significant in this regard would be the analysis of interstitial gloss in the plutonic blocks (=secretions=cognote inclusions) which, when compared with the composition of the groundmass (glass) of the enclosing lava, would yield information on the nature of chemicol zonation in sub-volcanic magma bodies. Inclusions in lavas of calc-alkaline associations seem to be more widespread than commonly realized, but they certainly have not received attention commensurate with their petrogenetic significance.

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CALCALKALIC ANDESITES: EXPERIMENTAL DATA BEARING ON THE ORIGIN OF THEIR ASSUMED CHARACTERISTICS

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Abstract

Experimental studies at 1 atmosphere on the calcalkalic volcanic series of Paricutin, Mexico, indicate that its andesitic members have plagioclase on the liquidus, whereas olivine is the liquidus phase of the associated high-alumina basalt bombs and lava. Change of liquidus phase is not attributable to a reaction relation of olivine, which appears at lower temperatures in the andesites. Elevated water pressure, effective at the beginning of crystallization of the rock, may have delayed the appearance of plagioclase, thereby retaining olivine as the liquidus phase under the natural conditions of formation.

Atmospheric liquidus temperatures of andesites in several calcalkalic suites do not appear to vary directly with iron enrichment ($FeO + Fe_2O_3/MgO + FeO + Fe_2O_3$) and are excessively high relative to their associated basalts. Hydrothermal experiments indicate that the liquidus temperature can be reduced to reasonable values at moderate water pressures, although anomalies still persist. In contrast, liquidus temperatures at 1 atmosphere of tholeiitic andesites appear to vary directly with iron enrichment.

The high An content of the cores of plagioclase phenocrysts of the circum-oceanic island-arc type of calcalkalic andesite also suggests that elevated water pressures, subsequently reduced, may have been responsible for the initial crystallization of cores of plagioclase more calcic than that expected from the equivalent anhydrous liquid.

Pyroxene reaction relations attributed by Kuno (1950) to the circum-oceanic island-arc type of the calcalkalic series can not be related to the known fractionation schemes deduced from equilibrium studies of pyroxenes. Contamination followed by quenching of metastable pyroxenes is a possible alternative; however, the disappearance of clinopyroxene is most likely the result of a discontinuous reaction relation yielding amphibole.

Strontium isotope ratios of a basalt and andesite from Paricutin, Mexico, are essentially identical and characteristic of basalts, and preclude an origin for this continental-margin type of andesite by assimilation of old sialic crustal material. Internal hybridism by comagmatic sialic material may have played a part.

The change of liquidus phase within the calcalkalic series and excessively high liquidus temperatures obtained at 1 atmosphere, the exceptionally high An cores of phenocrystic plagioclases, the iron fractionation behavior, the generally explosive character of the eruptions, the high alumina content of the rocks, the common presence of phenocrystic hydrous phases, and the experimentally known changes in liquid compositions with water pressure indicate that water plays a dominant role in the formation of both major types of calcalkalic andesites. The frequent occurrence of nonequilibrium petrographic features suggests that the water pressure was highly variable during the crystallization process.

The calcalkalic andesites are believed to be the partial melting product of the parental material under hydrous conditions whereas under anhydrous conditions the product is tholeiitic basalt. Basaltic parentage is, therefore, not required for the calcalkalic andesites.

Introduction*

It is desirable in an experimental study of a rock type, or a suite of rocks, first to define uniquely the rocks on the basis of field and petrographic observations. Next the chemical and mineralogical analyses of the rock are reduced to a critical number of components which are amenable to experiment. These components and often the rocks themselves are exposed to a range of variables deemed most appropriate from field deductions, and the stability ranges of the critical mineral assemblages are outlined and their

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* The following discussion is the substance in part of an invited lecture before the Andesite Conference held in July 1968 at the Central Oregon College, Bend, Oregon, under the joint sponsorship of the Upper Mantle Committee and the Center for Volcanology of the University of Oregon, Eugene, Ore.

physicochemical behavior recorded. Correlation of the laboratory data with field observations is subsequently attempted to test their applicability and to devise more useful experiments. Finally after several such cycles of integration of laboratory and field observations, some quantitative constraints are formulated which it is hoped may lead to an understanding of the genesis of the rock type.

The andesites fail in this well established experimental-field procedure at the first step, definition. Various definitions based on the major minerals observed in so-called andesites, plagioclase, pyroxene(s), olivine, amphibole, and biotite, usually are ambiguous because of the wide range of zoning in the feldspar, the variation in composition and number of the pyroxenes, and the absence in some specimens of certain minerals, such as olivine and the hydrous minerals. Recognition of a rock as andesite is often dependent on assigned arbitrary limits of silica content (e.g. 54-62 percent) of normative feldspar composition (e.g. An_{50} - An_{30}) and color index (e.g. < 30) within each of the major rock series tholeiitic, alkalic, and calcalkalic. The andesites are then known, respectively, as tholeiitic andesite, hawaiite (Macdonald, 1960), and calcalkalic andesite, the last being divided into a continental-margin type and an island-arc type depending on other specific qualitative differences in that series. In short, it is evidently not possible to collect an individual specimen of lava and unambiguously classify it as a particular andesite without regard to its comagmatic suite. One of the most successful operational definitions of the various andesites is outlined by Kuno (1950). Groundmass pigeonite is considered indicative of the tholeiitic series; Mg-olivine and augite (sometimes titaniferous) in the groundmass, the alkalic series; and hypersthene in the groundmass, the calcalkalic series. Unfortunately there are many exceptions and some of these are noted by Kuno. For example, the absence of hypersthene is recognized as a probability in calcalkalic rocks, it being occult in augite. To add to the confusion, hypersthene has been observed in the groundmass of the well established tholeiites (Yoder and Tilley, 1962, p. 354, footnote). Pigeonite may be occult in the common metastable subcalcic augite of the tholeiitic lava series, making recognition of the series indeterminate on this basis. Further, "Hypersthene and pigeonite are entirely absent" in the alkalic series, yet these phases may be occult in the augite of a rock having other features characteristic of the alkalic series.

In spite of the difficulties of unambiguous definition of the andesites, some characteristics of those andesites belonging to the calcalkalic series can be listed which have been proposed as diagnostic.

1. Calcalkalic andesites are generally high in alumina (16-18 weight percent), are normatively high in plagioclase (>50 weight percent), and have quartz in the norm.
2. The cores of the commonly zoned plagioclase are unusually high in An (85-95), and plutonic blocks erupted with the calcalkalic island-arc type of lavas and pyroclastics also may contain plagioclase with a similarly high An.
3. Both olivine and augite are alleged to be in reaction relationship with liquid to produce orthopyroxene in the more siliceous members of the calcalkalic andesites.
4. Hornblende or biotite, or both, are not uncommonly present; however, they may be in various stages of breakdown in some lavas.
5. Iron-magnesium fractionation appears to be of intermediate and very limited range. The iron oxidation ratio is not greatly different from that of basalts.
6. Eruptions are generally explosive and give rise to large volumes of pyroclastics.
7. The volume of calcalkalic andesites is very large relative to other members of the same series.
8. Foreign blocks (xenoliths) are sometimes numerous and may be in various stages of digestion in the continental-margin type of calcalkalic andesite.

All of these general statements are open to criticism, and an effort will be made to bring those experimental data to bear which may not only aid in defining the calcalkalic andesites but also contribute to an understanding of their origin.

Thermal Behavior of Natural Andesites

In the hope that knowledge of the thermal behavior of the rocks themselves will lead to a unique characterization, the four series of natural rocks which were heated at various temperatures in the laboratory are reviewed. The data are few in number and the rocks chosen are not necessarily wholly representative or of a single series. In figure 1, the liquidus temperatures of rocks of the tholeiitic series, mainly from Hawaii, studied by Tilley, Yoder, and Schairer are plotted as a function of $(FeO + Fe_2O_3)/(MgO + FeO + Fe_2O_3)$, iron enrichment (Yoder and Tilley, 1962; Tilley, Yoder, and Schairer, 1963, p. 77-84; 1964, p. 92-97; 1965, p. 69-82). These rocks include picrites, picrite basalts, tholeiites, and

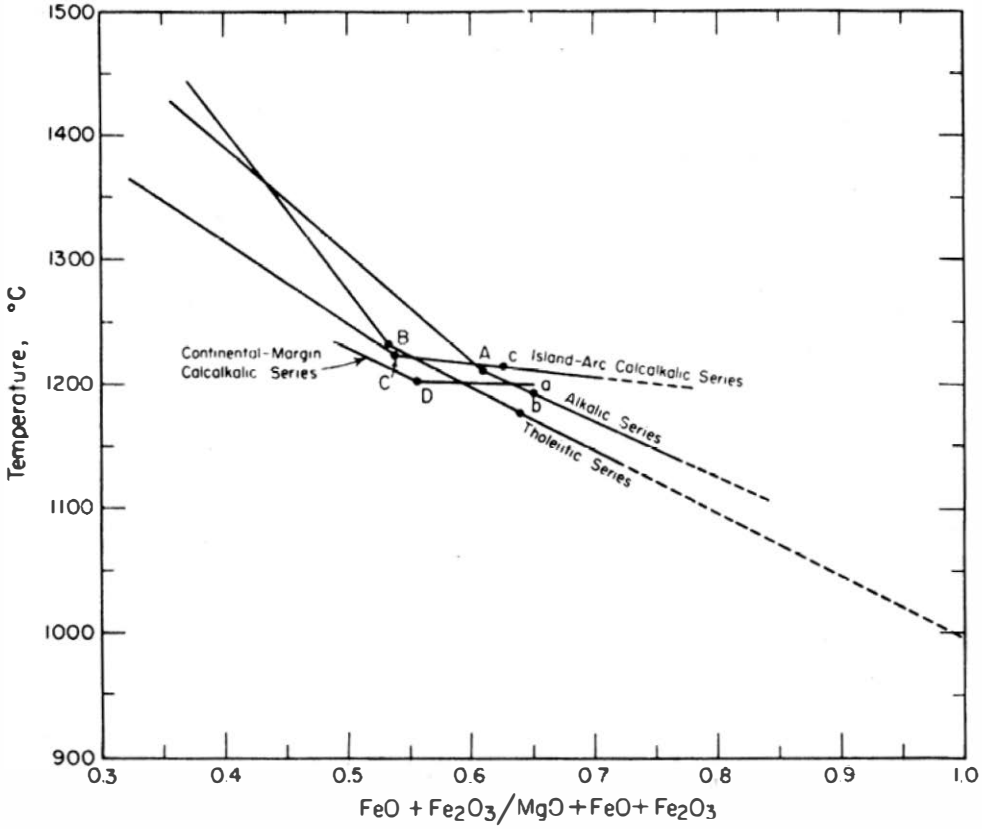

Figure 1. Plot of iron enrichment ($FeO + Fe_2O_3$)/($MgO + FeO + Fe_2O_3$) versus liquidus temperature of rocks representative of four major rock series containing various andesites. Capital letters mark changes in the nature of the liquidus phase; small letters, changes in the character of iron enrichment displayed in figure 2. Based on data from Yoder and Tilley, 1962; Tilley, Yoder, and Schairer, 1963-1967; Brown and Schairer, 1967.

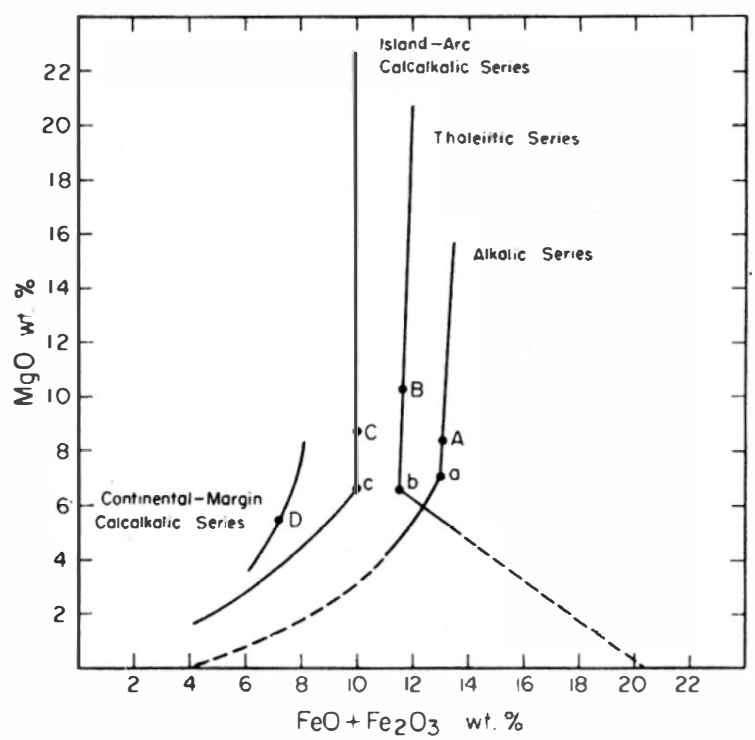

Figure 2. Plot of MgO versus $FeO + Fe_2O_3$ for rocks representative of four major rock series containing various andesites. References and symbols given under figure 1.

tholeiitic andesites. In this series the higher temperature limb is characterized by olivine on the liquidus and the lower temperature limb may have any of the major phases on the liquidus. The individual rock data fall close to the lines and appear to show continuous iron enrichment. The iron enrichment is more clearly displayed in figure 2 where the more magnesia-rich limb shows no change in the total iron oxides whereas the less magnesia-rich limb shows a constant total of magnesia and iron oxides. These data suggest that the higher temperature portion of the series is mainly the result of olivine accumulation. At the lower temperatures the pyroxene and plagioclase are apparently being extracted from the liquid in proportions necessary to preserve the constancy of MgO + FeO + Fe_2O_3. A few rocks near the end of the solid line of the lower limb show strong andesitic affinities (MacDonald and Eaton, 1964, p. 86) and it is believed the tholeiitic andesites would behave thermally in a similar way. Tholeiitic series from other petrographic provinces will probably be somewhat displaced from the example given. It seems clear that the tholeiitic andesites fit well in the scheme of direct fractionation from a tholeiitic parent. In the Hawaii province there is a paucity of lavas immediately beyond an iron enrichment of 0.74. This seems to be the case elsewhere as well, giving some support to those who believe the bimodal frequency of basalts and rhyolites is a result of different modes of origin of each group. The basaltic rocks and their limited derivatives are considered by them as most likely the result of limitations of the fractionation process from a parental magma whereas the rhyolites and their kindred result mainly from the physicochemical constraints imposed by remelting and assimilation of sedimentary materials.

Also exhibited on figure 1 are the liquidus temperatures for rocks of the alkalic series, aceanite, ankaramite, picrite basalt, alkali basalt, hawaiite, mugearite, benmoreite, studied by the same authors cited above. The higher temperature limb is again characterized by olivine as the liquidus phase, the olivine believed to be accumulative for the most part. At point A plagioclase becomes the liquidus phase; however, olivine persists as a later phase. Such a reversal of liquidus phases cannot be attributed to any of the now known variants of the fractionation scheme observed at 1 atm. (Two possible explanations will be presented below.) Figure 2 also indicates that at temperatures somewhat lower than that of the change of liquidus phase, a unique change in the character of the iron enrichment takes place. The mafics are depleted at roughly a constant ratio with preferential subtraction of magnesia. The rocks near the end of the solid line of the lower limb of the alkalic series are described as hawaiites. Those rocks near the end of the hawaiite group and lower in the series have liquidus temperatures which do not vary systematically with iron enrichment. They are usually higher than the dashed extension drawn in figure 1, judging from minimum values observed in the less porphyritic specimens, and always have plagioclase as the liquidus phase. It was concluded by Tilley, Yoder, and Schairer (1965, p. 81) that some other process is imposed on the general iron enrichment, possibly concentration of feldspar by flotation accumulation. The hawaiites, therefore, appear to be primarily the result of fractionation from an alkali basalt parent; however, they are also under the influence of another process involving accumulation of feldspar or feldspar components.

The behavior of the calcalkalic series is displayed in figures 1 and 2, using as an example of the island-arc type, suites mainly from the Salamon Islands and the West Indies, experimentally investigated by Brown and Schairer (1967, p. 462). The thermal behavior and iron enrichment are not unlike those of the alkalic series. The olivine accumulate stage is similar, assuming it is not a composite series similar to Thingmuli, Iceland (Tilley, Yoder, and Schairer, 1967, p. 452).* The change of liquidus phase from olivine to plagioclase is noted at C. The depletion of mafics at roughly a constant ratio of MgO:FeO + Fe_2O_3 is also observed. Most important, the liquidus temperatures of the rocks below c do not vary systematically with iron enrichment, the solid line and its extension indicating values for the groundmass only. The liquidus temperatures for whole rock in general are excessively high and plagioclase is on the liquidus (see footnote next page). Olivine is not found among either the phenacrystic or groundmass phases of the later members of the calcalkalic group presumably because of the reaction relationship outlined by Bowen (1928, p. 78). Those rocks below c include the calcalkalic andesites and indicate that some process in addition to iron enrichment is operating and presumably involves feldspar or its components.

The limited suite of rocks from Paricutin, Mexico, representing the continental-margin type of calcalkalic andesites was studied experimentally by Tilley, Yoder, and Schairer (1966, p. 266; 1967, p. 452). In spite of the increasing iron enrichment, the liquidus temperatures showed a change of only 30° C. The most magnesia-rich specimen, a high-alumina basalt bomb, had olivine on the liquidus, and all subsequent lava samples with greater than 0.5 iron enrichment had plagioclase on the liquidus. The

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* The more magnesian specimens of Thingmuli, Iceland, appear to follow a tholeiitic trend and then abruptly change with the onset of the andesites to a calcalkalic trend; that is, the series may be composite.

most magnesia-rich rock to have plagioclase on the liquidus also contained olivine phenocrysts in hand specimen. These results indicate o direct genetic relationship of high-alumino basalt to the continental-margin type colcolkolic andesites. They also point up again the remarkable feature of o reversal of liquidus phose.

Change of Liquidus Phose

The loss of olivine as the liquidus phose in the tholeiitic series is no doubt due to the well known reaction relationship of Bowen (1928) and to the proximity of the derivative rock bulk compositions to the four-phose "boundary curve" described by Yoder and Tilley (1962) involving the major phases. Small variations of composition about the "boundary curve" would bring about changes in the liquidus phose.

The change of liquidus phase in the alkalic series from olivine to plagioclase obviously cannot be attributed to reaction in that olivine persists in the groundmass throughout the series. It would appear that plagioclase is accumulated in the liquid and the rocks need not necessarily be considered as representing derivative liquids. The erratic variation of the liquidus temperatures could then be attributed to variance in the amount of inherited plagioclase. The iron enrichment would not be influenced by the addition of feldspar. The composition of plagioclase added and the source of the plagioclase ore vital points which will be dealt with below. On the other hand, the erratic liquidus temperatures at 1 atmosphere may be the result of initial crystallization of the rocks at different water pressures where the plagioclase content of the liquid may be greater. The liquidus temperatures obtained at 1 atmosphere would then be interpreted in terms of the prevoiling effective water pressure at the site of origin of the magma (e.g., the higher the observed liquidus temperature at 1 atmosphere, the higher the original effective water pressure), and the feldspars viewed as normal non-accumulative products.

The island-arc calcalkalic series appears to be related in several ways to the alkalic series. The similarity in behavior of MgO versus $FeO + Fe_2O_3$ (figure 2) and the anomalous liquidus temperatures beginning in the andesites suggests that the some process is modifying the general iron-enrichment trend. Here too, an increase in the amount of feldspar, whether inherited or primary, seems necessary to account for the change of liquidus phose.

The relationship of the continental-margin colcolkolic series to high-alumino basalt supports one of the alternative explanations for a change in liquidus phose. The results of a study by Yoder and Tilley (1962) on a high-alumina basalt under various water pressures are shown in figure 3. It is seen that at 1 atmosphere the rock has plagioclase on the liquidus and at slightly elevated water pressures, olivine becomes the liquidus phase. It was on the basis of these and other similar data that Yoder and Tilley concluded that the incoming of plagioclase is delayed by the presence of water. The appearance of plagioclase on the liquidus at 1 atmosphere in the laboratory of an andesite holding modal olivine phenocrysts suggests that water may hove been present during the crystallization of the magma on its way to the surface. On these grounds the modal olivine is in reality the liquidus phose at the site of origin, and plagioclase appears only in the upper reaches of the conduit, becoming the liquidus phose near and at the surface where it appears as a lava flow. The laboratory experiments at 1 atmosphere obviously approximated only the lotter condition. (Trace element partition between plagioclase and two other phases may aid in distinguishing phenocrysts formed at depth from those formed near the surface.) Hydrothermal treatment at P_{H_2O} = 2 kb of some of the specimens from the West Indies brought some order to the random liquidus temperatures (see Brown and Schairer, 1967, p. 467), but anomalies were still apparent. The undulyhigh liquidus temperatures (1250°-1300° C) at 1 atmosphere were reduced as well to values (1000°-1050°C) more in accord with those observed in nature.

Figure 3 is also of interest in that it displays o sequence of mineral appearance in liquid essentially equivalent to that deduced by Bowen (1928) for his subolkoline series now equated with the calcalkalic

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* For this and other reasons the alleged minimum character, relative to other members of the colcalkalic series, of the anhydrous liquidus temperature at 30 kb of a synthetic composition, believed by Green and Ringwood (1966, p. 110) to represent andesite, has only indirect bearing on the origin of magma of andesitic composition. If the rocks collected at the surface, or their synthetic equivalents, do not represent liquids or involve generation under specific important variables (e.g., H_2O), their liquidus temperatures will not directly indicate parent-daughter relationships. The apparent minimum melting character of the synthetic composition studied by Green and Ringwood is also reflected in port by some of the studies at 1 atmosphere herein referred to above. However, those results point up variables not considered in the experiments, and under no circumstance was andesite considered to be o minimum melting compositonal range at 1 atmosphere.

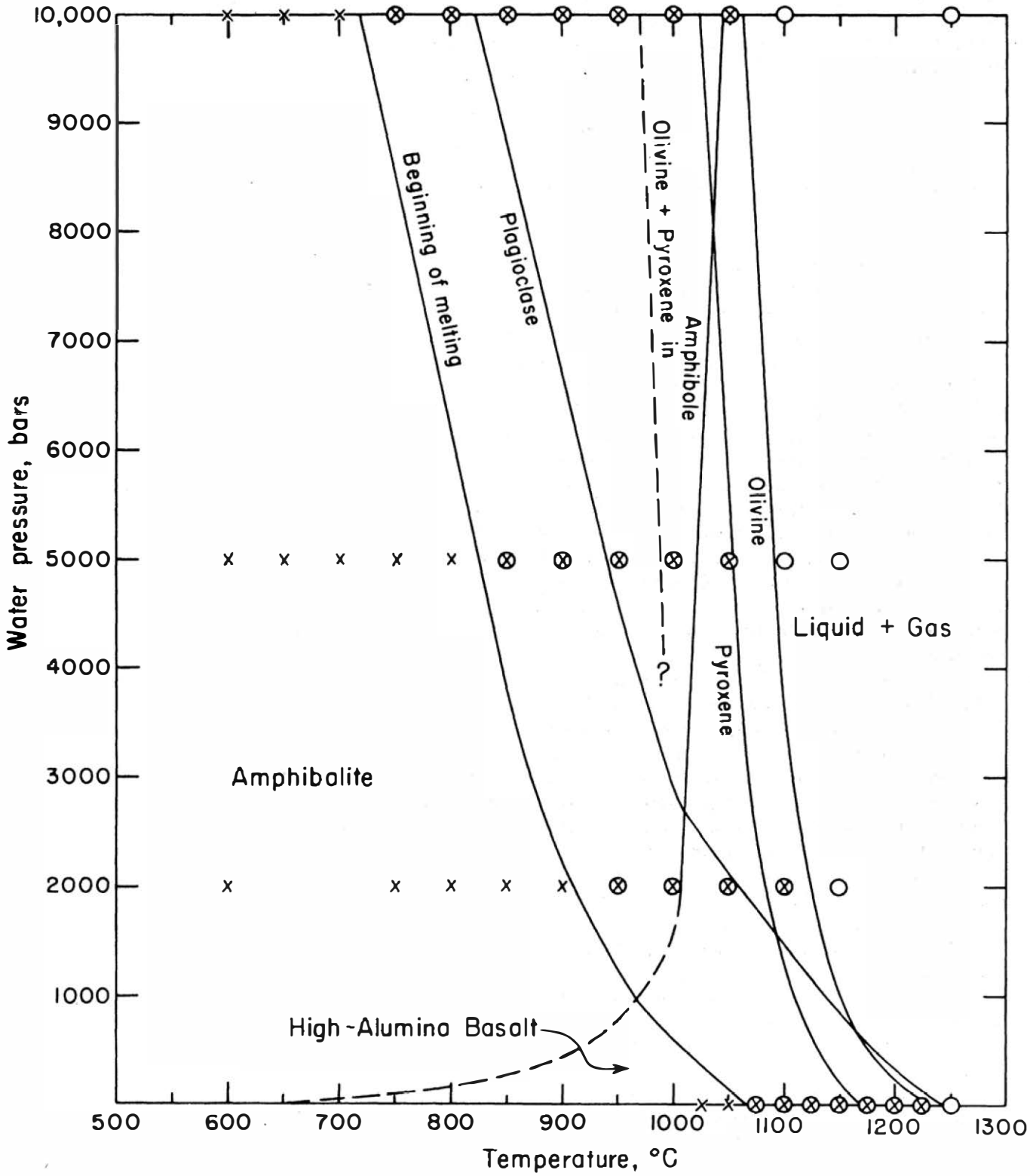

Figure 3. Pressure-temperature projection of a natural high-alumina basalt-water system (Yoder and Tilley, 1962, p. 451, figure 28).

series. For example, at 5 kb water pressure the major phases appear in the following order with decreasing temperature: olivine, pyroxene, and amphibole. The omnipresence of magnetite in these experiments meets the requirements of the reaction series as modified by Osborn (1962). At 10 kb water pressure the sequence would be different and variations in the sequence of crystallization of minerals should be expected if the effective water pressure is variable, especially where the water pressure is less than the total pressure (see Yoder and Tilley, 1962, p. 466, figure 34). Variability of the proportions of phases appears to be one of the subsidiary features of the island-arc type of calcalkalic andesites. If the magma rises slowly to the surface with a concomitant loss of volatiles, the bulk composition of the lava will reflect the influence of the volatiles at the site of magma generation even though they appear at the surface essentially devoid of volatiles and free of hydrous minerals. The breakdown of hydrous minerals is often noted in the andesitic lavas (although often preserved in plutonic blocks held by the lava) and is no doubt due to the nature of their upper stability limits relative to the liquidus of the magma as exhibited in figure 3.

Amount and Composition of Feldspar

If water is indeed an important constituent in the formation of calcalkalic andesites, then certain consequences are to be expected: explosive eruption, unique bulk compositions, hydrous phases, buffered oxidation states, and shifts in element partition. For an example of the last, the feldspar composition is expected to change in the presence of water. In figure 4 is given the change in the albite-anorthite system with low water pressure as compared to that for a very high dry pressure (Yoder, 1969). Only 150 bars water pressure could effect a change at constant temperature in the composition of plagioclase from An 60 to An 74. A substantial dry pressure is required to cause an equal and opposite effect. One of the characteristics of the island-arc type calcolkalic lavas is the very calcic nature (An $\simeq$ 90) of the plagioclase cores. The cores could hove formed at elevated water pressures, and subsequent stages of crystallization at reduced pressures would yield zanes of lower An content without drastically changing the temperature of the magma. (Note in figure 4 the amount of crystallization, concomitant with the change of feldspar composition, which takes place on reduction of water pressure at constant temperature.) Oscillatory zoned feldspars are but one of the many nonequilibrium features of the calcalkalic andesites. The high An cores and zoning of the plagioclase in this view would be the normal products of crystallization under a relatively high and variable water pressure. The assimilation of more basic material or the mixing of partially crystallized magmas of great chemical contrast would not be required to attain the compositional range of plagioclase observed.

The colcalkalic andesites are unusually high in Al_2O_3 relative to the sum of alkalies and lime which is expressed as high normative plagioclase and sometimes normative corundum. High normative plagioclase can be achieved under high water pressures as outlined by Yoder (1954, 1965). In figure 5 is given the diopside-anorthite system dry and at various water pressures. The shift of the "eutectic" from a "gabbro" composition to that of an "anorthosite" is evident. These relations indicate that the plagioclase content of a magma can be increased under elevated water pressures. Dry pressure will produce the same effect, but the temperatures are excessive. Here the emphasis is on generating on initial high plagioclase content as the result of normal physicochemical conditions at the site of origin as opposed to merely "adding" more feldspar by physical means (e.g. flotation).

In general, it appears that elevated water pressures not only can account for the composition and amount of plagioclase, but also aid in the explanation of the apparent reversal of liquidus phase in the series. These effects would occur as the normal consequence of fractionation under equilibrium conditions. The process of feldspar flotation would enhance the development of these features. However, the plutonic blocks rich in olivine, plagioclase, and hornblende erupted with the ondesitic lavas of the West Indies would indicate, if they are cognate, that settling rather than flotation may have occurred in a hydrous environment.*

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* The coexistence of magnesia-rich olivine and calcic plagioclase in the blocks restricts their origin to depths equivalent to pressures less than about 7 kb. At that pressure plagioclase and olivine react to produce two pyroxenes and spinel (Kushiro and Yoder, 1966; Yoder, 1966). If the olivine-, plagioclase-, and amphibole-bearing blocks were indeed accumulates from the andesite magma, then their origin as well would be restricted to those depths.

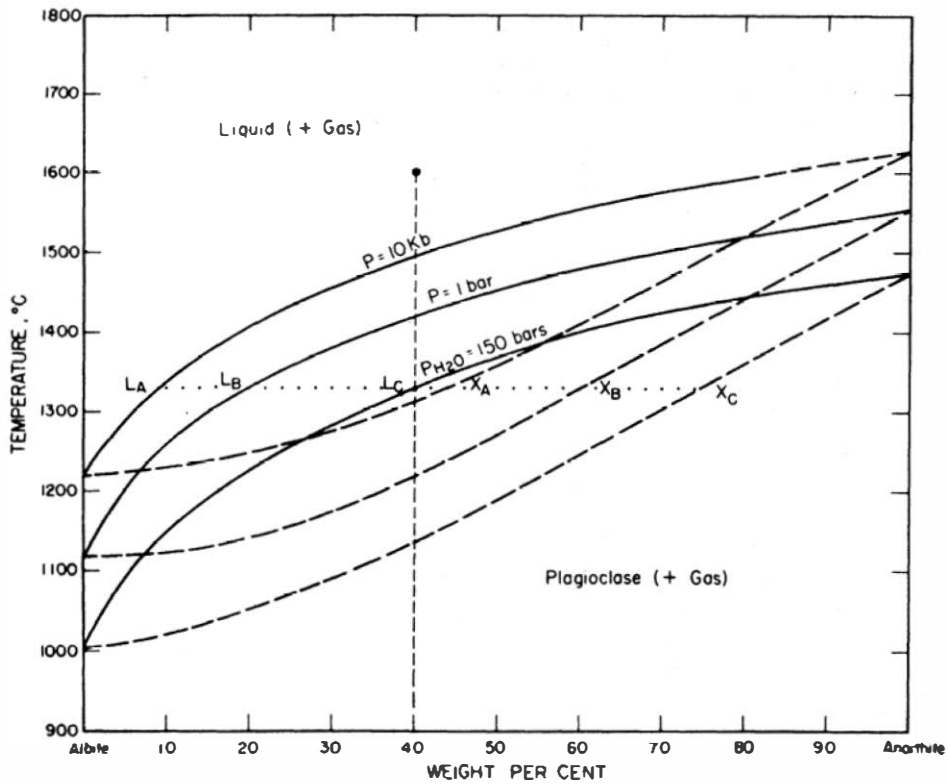

Figure 4. The albite-anorthite system at 1 bar and 10 kb and the albite-anorthite-water system at 150 bars. Adapted from Yoder (1969).

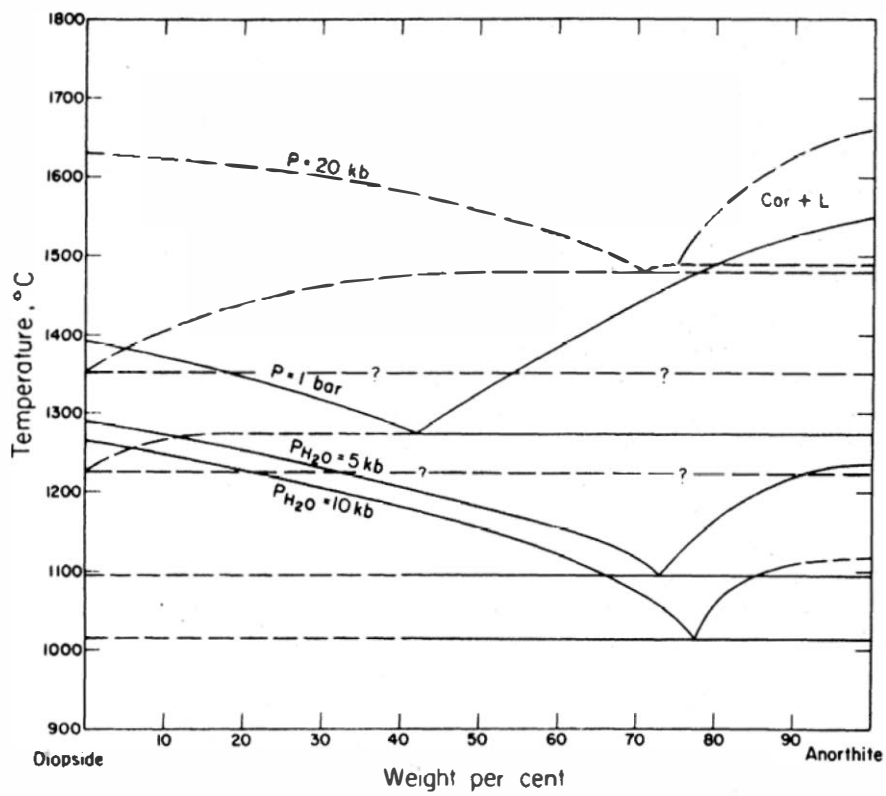

Figure 5. Comparison of diopside-anorthite system at 1 bar (Osborn, 1942, with modifications) and 20 kb (estimated from data of Clark, Schairer, and de Neufville, 1962) with diopside-anorthite-water at P_{H_2O} = 5 and 10 kb (Yoder, 1965). Cor = corundum.

Orthopyroxene Melting Relations

One of the key minerals in the colcolkolic andesites is hypersthene. Its magnesian end member, enstatite, has been studied in the presence of water by Kushiro, Yoder, and Nishikawa (1968) and found to melt incongruently up to at least 30 kb water pressure. The very important implications of this behavior ore displayed in figure 6 in the context of the diopside-forsterite-silico system studied by Kushiro (1969). At 20 kb dry pressure a peridotite, represented in the system by the assemblage forsterite (Fo) + clinopyroxene (Cpx) + orthopyroxene (Opx), begins to melt at 1640° C with a liquid of a composition which if separated would crystallize as olivine and subcolcic augite. The some assemblage begins to melt under hydrous conditions at 1220° C, producing a liquid which if seporoted would crystallize as a two-pyroxene + quartz assemblage. These data indicate that the some parental material could produce a magma capable of crystallizing as olivine-normative rock under anhydrous conditions and a quartz-normative rock under hydrous conditions. These some principles ore valid as low as 7 kb and also when normative plagioclase is present. It is likely that because of the difference in temperature of beginning of melting and the brood expansion of the melting range under hydrous conditions (see figure 3) the normative feldspar in the liquid will be more anorthitic under anhydrous conditions than it would be under hydrous conditions from the same parental material. Pressing this argument further, there is the tempting conclusion that if the normative feldspar in the liquid is sufficiently different, anhydrous partial melting may yieldo magma capable of crystallizing as olivine tholeiite and hydrous partial melting, a quartz-normative colcalkalic andesite.*

Assuming this tentative conclusion is acceptable, the paucity of basalts associated with calcolkolic andesites in the continental margins would be explained. Further, lorge volumes of colcolkolic andesite, relative to other members of the series, would be expected because it, not basalt, is the initial partial melting product. That is, calcalkalic andesite could be considered as the hydrous analogue of the anhydrous flood basalts. The lorge volumes of similar magma ore a direct result of fractional melting at the minimum melting composition wherein the melt is continuously removed from the parental material. Lorge heterogeneities of the mantle will not greatly alter the temperature or composition of magma extruded provided the major mineral assemblage of the mantle remains in the residua. It is suggested, therefore, that the calcolkolic andesites ore the partial melt product of the same parent as the olivine tholeiites which also may produce quartz-normative andesitic (tholeiitic) derivatives, but only by fractionation at low pressure ($<$7 kb). As a consequence, basaltic parentage is not required for colcalkalic andesites (cf. Kuno, 1968b).

Those early-formed high-alumina basalts of small volume rarely associated with calcalkalic ondesites would presumably represent a higher temperature, partial melting product under hydrous conditions. Late-formed olivine tholeiites of small volume may be a product after dehydration of the same source rock. Late-formed explosive dacites and rhyolites might be attributed to hydrous fractionation of the andesite magma toward a point similar to that marked 960° in figure 6. The anydrous, viscous dacites and rhyolites are probably the result of degassing on rise of magma generated at or near the some point. It is to be noted that such a dehydrated magma would develop quartz phenocrysts as it rose or become glossy in a metastable state at a temperature (~ 960°) well below that of the 1 atmosphere "eutectic" temperature (1374°).

Attention has been called to the absence of lovas intermediate between andesite and rhyolite at numerous localities (e.g., McBirney's "divergent" type of volcano; McBirney, 1968, p. 101, and Fig. 2, p. 105). One possible explanation may be forthcoming also from figure 6. The crystallization of the quartz-normative, hydrous, ondesitic magma at depth would provide a suitable parent for small quantities of rhyolite magma on remelting. That is, for example at 20 kb, a magma generated at 1220°, removed and crystallized, would on partial fractional remelting produce a limited amount of liquid at the 960° isobaric invariant point. Some extended time interval would be required with this mechanism to yield a "divergent" series. It appears that H_2O provides sufficient variation to produce "coherent," continuous, or "divergent" series from the some parental material.

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* O'Hora (1965, p. 30, figure 13; p. 35-37) arrived at related conclusions on the basis of an onolysis of o schemotic diagram in which the incongruent melting of enstatite at P_{H_2O} = 10 kb was assumed. No consideration was given to the requirements of composition ond amount of plagioclase in applying the diagram to the generation of quartz tholeiites in contrast to andesites. Further comments on the construction of his diagram are beyond the scope of this paper.

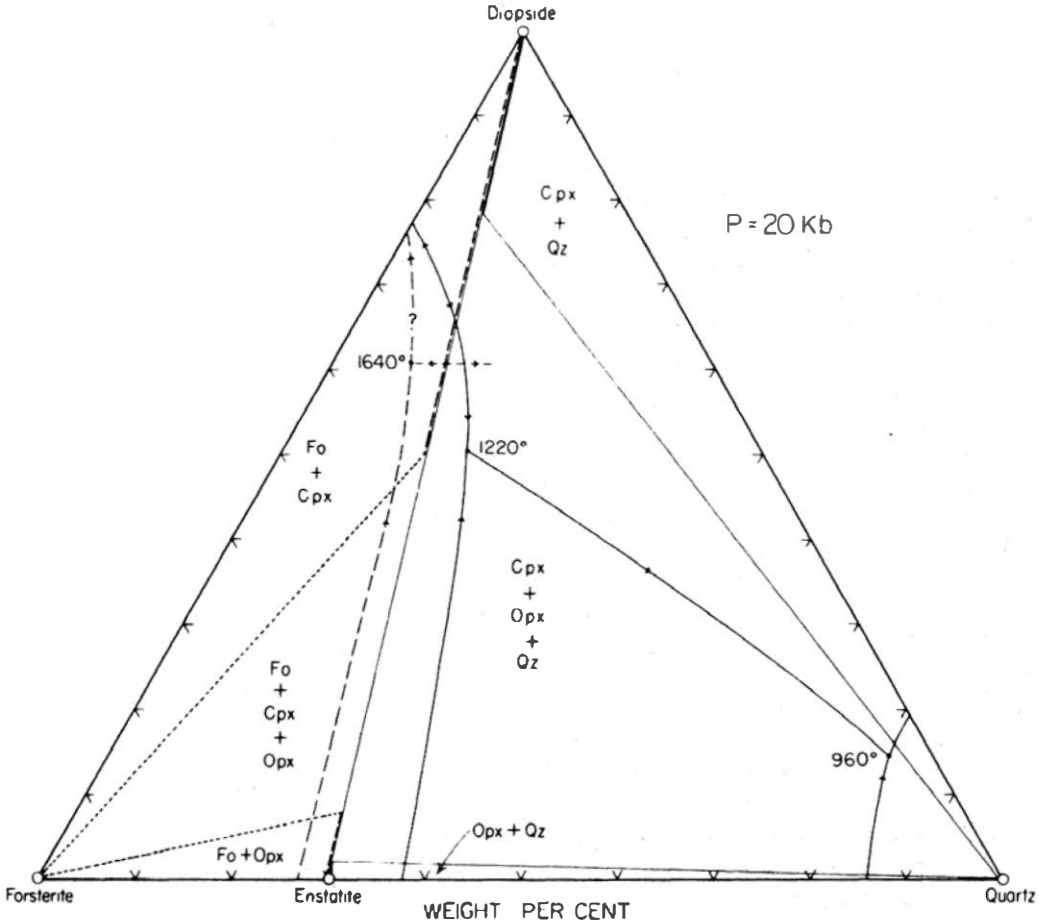

Figure 6. Portions of the diopside-forsterite-SiO_2 system at 20 kb with (solid lines) and without (dashed lines) water, adopted from Kushiro (1969). Solid solution limits at 1640° C are estimated from Davis and Boyd (1966); 1220° C, Kushiro (1969).

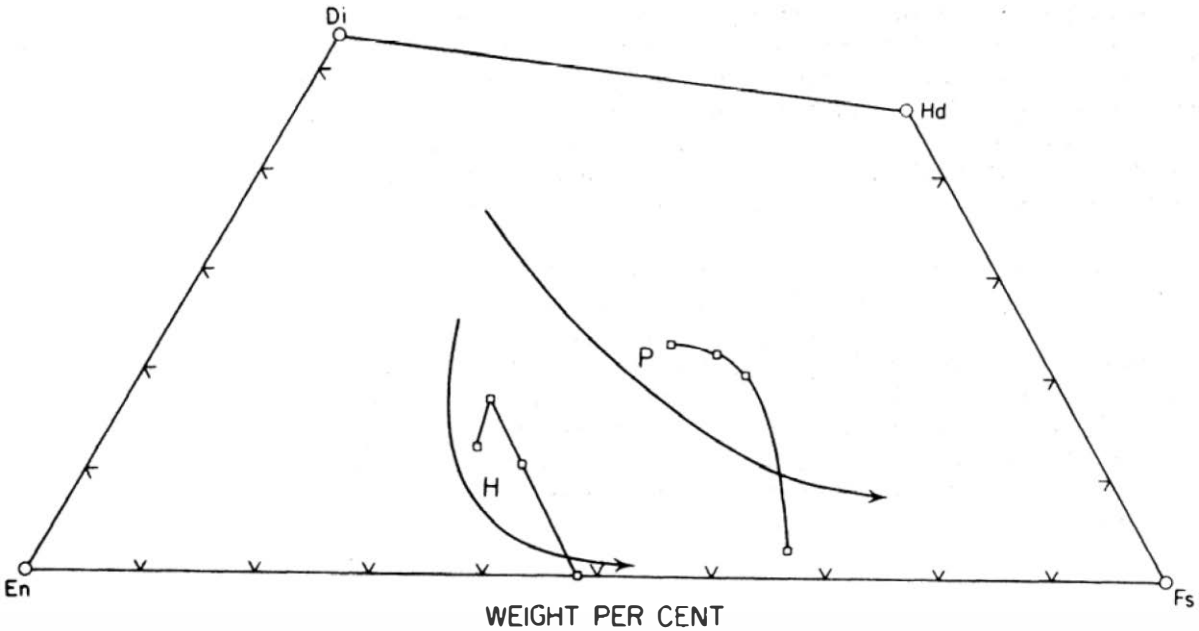

Figure 7. Pyroxene system diopside (Di)-enstotite (En)-hedenbergite (Hd)-ferrosilite (Fs) showing the trend lines for the modal and normative (squares; average) pyroxenes from the hypersthenic rock series (H) and the pigeonitic rock series (P) according to Kuno (1950, 1968a).

Alleged Augite Reaction Relation

Kuno (1950) proposed that augite undergoes o discontinuous reaction with liquid to produce hypersthene near the more siliceous end of the andesites of the "hypersthene rock series" which he equates with the calcalkalic series (Kuno, 1959, p. 44). He illustrated this behavior on the basis of optically determined pyroxenes (Kuno, 1950, p. 994, figures 20 and 22) and with normative pyroxenes (Kuno, 1968o, p. 676, figure 44) in the pyroxene quadrilateral (figure 7), and described the augite as "successively replaced by hypersthene" (1950, p. 994). In contrast, he described (1950, p. 991) and illustrated (1968a, figures 42 and 43) the alleged reaction relation as part of a discontinuous, mafic-mineral series. The eventual appearance of corundum in the norm of rocks later in the series casts considerable doubt on the value of normative plots of these pyroxenes. Hornblende, o major phase before the alleged reaction tokes place, and biotite ore present, and if they contain aluminous end members, diopside would be reduced or eliminated in the norm. The continuous reduction of Wo in the norm should not be attributed to loss of augite by reaction except in the light of the mineralogy of the rock. The plot of pyroxenes, not identified, from which Kuno's hypersthene rock series is drawn is enclosed by a line within which ore included mixtures of pyroxenes and presumably norms of pyroxenes from analyzed rocks as well.

Kuno originally ascribed the "ultimate cause" of this seriesas due to "assimilation of granitic and related rocks" (1950, p. 995) and due in part to alkali loss vía vapor whereby normative anorthite is formed in place of diopside. A decrease in the An of plagioclase, not an increase, is observed in the series. His calculations (1968b, p. 155) indicated that Di/Hy actually increases in spite of the observed decrease in augite relative to hypersthene. Furthermore, removal of alkalies would appear to be an unlikely event in a series which is characterized by a large increase in alkalies, especially K_2O. The petrographic evidence illustrated (1950, p. 974) consists of groundmass hypersthene rims on phenocrystic augite. Reversed relations ore interpreted by him as resorption of xenocrysts of hypersthene by the magma with precipitation of augite. Such mutual rimming has also been attributed to simultaneous growth (Kuno, 1950, p. 991). These observations were interpreted by Yoder and Tilley (1962, p. 353-354) to mean that either assimilation (not a continuous reaction) or oxidation played a major role in the series. This conclusion was refuted by Kuno (1968a, p. 676) on the ground that "no sign of assimilation is to be found in this particular stage" even though he still considered that concentration of water in the magma series may be "connected in some way with contamination by sialic materials" (p. 686). It is difficult to reconcile this rebuttal with the evidence he put forth for contamination of the Hakone rocks and other hypersthene rock series of Japan.

To the best of the writer's knowledge, there is no experimental evidence in synthetic systems for a discontinuous reaction relationship between augite and liquid which produces hypersthene where both phases are present initially in substantial amounts. Those bulk compositions in figure 6 in the Opx + Qz region having an olivine liquidus may exhibit the following relations with decreasing temperature: Olivine crystallizes out first and is joined by orthopyroxene. The olivine reacts out and the liquid courses across the orthopyroxene field until it reaches the clinopyroxene boundary curve. Two pyroxenes crystallize along the boundary curve until the "eutectic" with quartz is reached where clinopyroxene reacts completely with liquid. The final products are orthopyroxene and quartz. Both the olivine and augite react with liquid. No discontinuous reaction relation of augite with liquid to produce orthopyroxene is implied. Continuous reaction of the two pyroxenes is required as they crystallize along the boundary curve as a consequence of the changes in solid solution. Such behavior would reproduce the observation of Kuno, but the parental material could not contain clinopyroxene. There is little reason to doubt, however, that the parental material of the mantle contains both orthopyroxene and clinopyroxene in the region of magma generation.

It is believed on the basis of these arguments that the disappearance of augite in the so-called "hypersthene rock series" is most likely due to its consumption in the formation of hornblende (see figure 3) and does not bear o discontinuous reaction relation with hypersthene of the type proposed by Kuno. Electron microprobe studies of all portions of the various pyroxenes from the calcalkalic series will no doubt resolve the difficulties evident in the alleged augite reaction relation.

Assimilotion

The presence of blocks, inclusions, and xenocrysts undergoing resorption in the ondesitic lovas has given rise to the view that assimilation has been o major influence on the generation of the calcolkolic andesites. Wilcox (1954) believed o combination of fractional crystallization and assimilation of sialic country rock was required to satisfy the chemical relationship between the lavas at Paricutin, Mexico, an example of the continental-margin type of calcalkolic series. Xenoliths of granite and quartz-

monzonite with visible evidence of partial fusion and reaction are found in the lavas. Tilley, Yoder, and Schairer (1967), with the help of T. E. Krogh and G. L. Davis, carried out a test of the extent of contamination by means of strontium isotope studies on early and late lavas of Paricutin. The early high-alumino basalt yielded a $Sr^{87}/Sr^{86} = 0.7043$ and the late hypersthene andesite, 0.7040. The essential identity of the ratios and their correspondence to those of basalts indicate contamination by old sialic crust was not a major factor in the production of these contrasted lavas. The data do not preclude, however, the possibility of contamination by young sialic material, that is, by more sialic camagmatic differentiates of the Paricutin magma itself. The Sr^{87}/Sr^{86} ratios of two inclusions rich in Sr are very close to those of the lavas, whereas two inclusions having low Sr have ratios slightly greater than that of the lavas. These data support the above view; however, other ratios such as K/Rb may yield a more informative test of the role of the inclusions.

Summary

The calcalkalic andesites of the island arcs and continental margins appear to be distinguished from hawaiites and tholeiitic andesites only in the context of their respective series. Their iron enrichment trends, thermal behavior at 1 atmosphere and the nature of their pyroxenes aid in their classification but not unambiguously.

The explosive nature of calcalkalic andesite eruptions yielding large volumes of pyroclastics, presence of hydrous minerals, and common deuteric alteration suggest that H_2O played an important role in their formation. Deductions from simple hydrous systems indicate that elevated and variable water pressures may account for the high normative content of plagioclase, high An of the plagioclase cores and oscillatory zoning in plagioclase.

The behavior of high-alumina basalt under hydrous conditions suggests an explanation for the change of liquidus phase in the calcalkalic andesite series and exhibits the same discontinuous mineral reactions assumed to be characteristic of the calcalkalic series. The large volumes of calcalkalic andesite and the paucity of associated basalts (tholeiitic and high-alumina) is attributed to the change of composition of magma at the beginning of melting of the parental material at high pressure from that of a tholeiitic basalt under anhydrous conditions to that of a calcalkalic andesite under hydrous conditions. Continued partial melting under hydrous conditions may give rise to high-alumino basalt.

The presence of water may also contribute to the maintenance of the slow rate of decrease of oxygen pressure during the fractionation of the calcalkalic andesitic magma according to Osborn (1959). On the other hand, the observed FeO/Fe_2O_3 ratios of the calcalkalic series may be the result of normal depletion of the magma by the crystallizing minerals which control the oxidation state (Yoder and Tilley, 1962, p. 430), especially if the magma originates in the mantle where H_2O is completely dissolved in the liquid and no free gas exists (Yoder and Kushiro, 1969). Evaluation of the influence of H_2O on the oxidation state under such circumstances has not as yet been made.

The excessively high liquidus temperatures obtained by experiment at 1 atmosphere relative to those of the more basic members of the calcalkalic series are substantially reduced under elevated water pressures and are more consistent with the concept of successive derivative magmas. The calcalkalic series will no doubt remain most difficult to define because of the continuum of properties, resulting from the spectrum of H_2O content and partial water pressures, with other major magma series. It is concluded that H_2O is the major factor in determining the composition and behavior of the calcalkalic andesites if the assumed characteristics are valid.

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GEOPHYSICS AND PETROCHEMISTRY OF ANDESITE VOLCANISM OF THE CIRCUM-PACIFIC BELT

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Abstract

Geophysical studies, including gravity, seismic and heat-flow measurements, show marked differences in the nature of the crust and upper mantle in continental and oceanic regions. In some of the volcanic arcs of the circum-Pacific system, the character of the crusts differs markedly from one end of an arc to the other. This is clearly seen in the Izu-Hokone and Kurile arcs. The nature of the upper mantle, however, is uniform in these arcs, regardless of the nature of the crust; it is characterized by abnormally low seismic wave velocities of about 7.3 to 7.8 km/sec. This is probably true of the entire circum-Pacific system.

The ratio of alkalis (on a molecular basis which can be expressed as $Na_2O + 0.7\ K_2O$) to SiO_2 provides a useful means of distinguishing rock series of different types. Regardless of the type of crust along the length of the arc, volcanoes in the some longitudinal belt fall on the same alkali-silica trend, while those along another line only a few tens of kilometers away in a transverse direction are much different. These relations are well shown in the Kurile and Izu-Hokone arcs.

It is clear that the role of assimilation of sialic crustal material in the formation of andesites must be negligible. It is more likely that they represent a primary magma or differentiates of basaltic magma derived from the upper mantle.

Geophysical Peculiarities

Andesite lovas occur in all the island arcs and volcanic chains of marginal zones of continents around the Pacific. Geophysical studies have been carried out in many of these regions. To clarify the problem of andesite genesis it would seem interesting to compare petrochemical peculiarities of andesite lavas with those of geophysical features as well as with the structure of the Earth's crust and subcrustal layers of the mantle.

I shall not dwell upon gravimetric and magnetic data, which are dealt with in the paper presented to the Symposium by H. R. Blank, Jr. We shall only point out that typical gravimetric anomalies of marginal zones of continents (in Bouguer reduction) are caused by a change of the type of the Earth's crust and by certain variations in rocks of the upper mantle under volcanic chains (by the value $\approx 0.1\ g/cm^3$). Gravimetric anomalies of such island arcs as Mariana or Tonga -- where there occurs no change of the Earth's crust type -- are caused by an accumulation of volcanic products and evidently by differing densities of the upper mantle.

A well-known peculiarity of earthquakes should be stressed: the depth of their foci increases gradually from the outer (oceanic) margin of volcanic and island arcs towards the continent thus forming the focal zone of earthquakes (Figure 1). In some arcs of the southwestern part of the Pacific Ocean (for example, the arc of the Solomon Islands) the focal zone dips toward the ocean.

The depth of the focal zone under andesite volcanoes averages 150 to 200 km.

Stresses in the earthquake foci operate mainly in a horizontal direction radial to the arc. The ruptures thus formed strike along the arc with different dip angles (45°-75°) towards the continent. The movements are of a reversed nature when the continental part moves upon the oceanic one; the region of the deep-sea trench is subjected to subsidence.

Conductive heat-flow relations of island arcs are poorly known. In Japan, Kamchatka, the region of the Kurile islands, and in the western United States, it reaches values of 2-3 μ col/sec/cm^2, that is, two to three times the mean value for the Earth. Evidently all the island and volcanic arcs are characterized by somewhat increased heat flow. The dependence of temperature on depth was calculated for Southern Kurile islands (Lubimova, Mognitsky, 1964). A value of 650° was obtained for a depth of 50 km and that of about 1100°C for a depth of 80-85 km.

The radical difference in the structure and thickness of the continental and oceanic crust is well

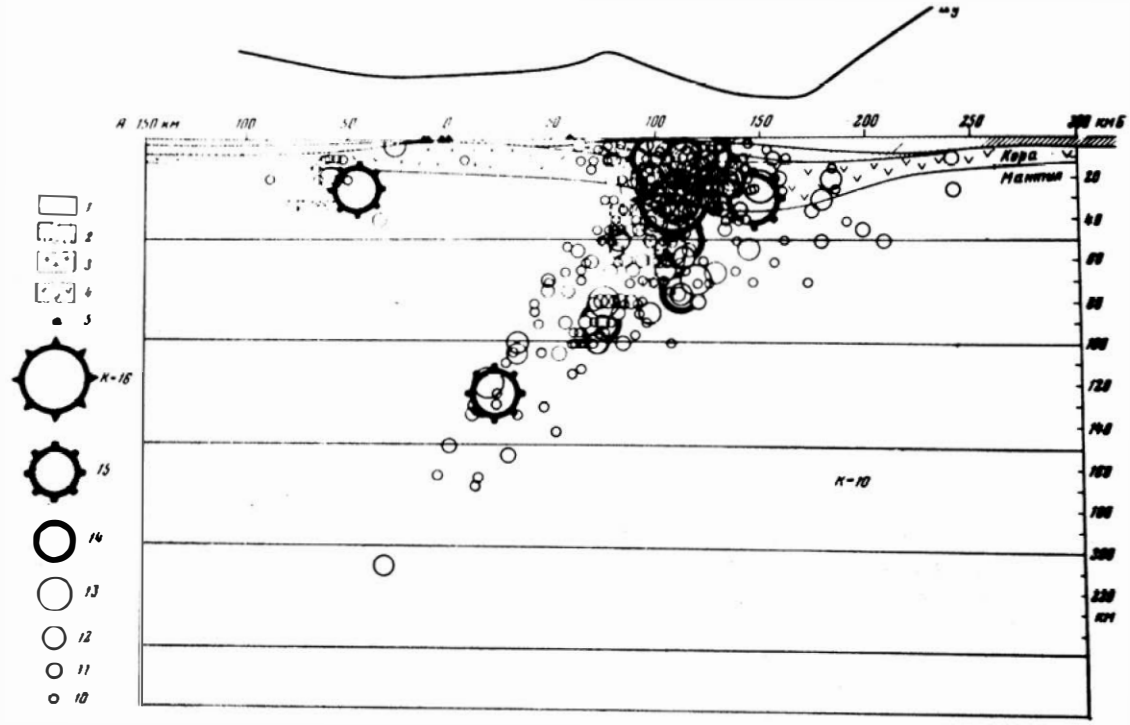

Figure 1. Focal zone of earthquakes at the area of the Kurile Islands.
1. water; 2. sediments; 3. "granitic" layer; 4. "basalt" layer; 5. seismic stations and zone of volcanoes (after Fedotov).

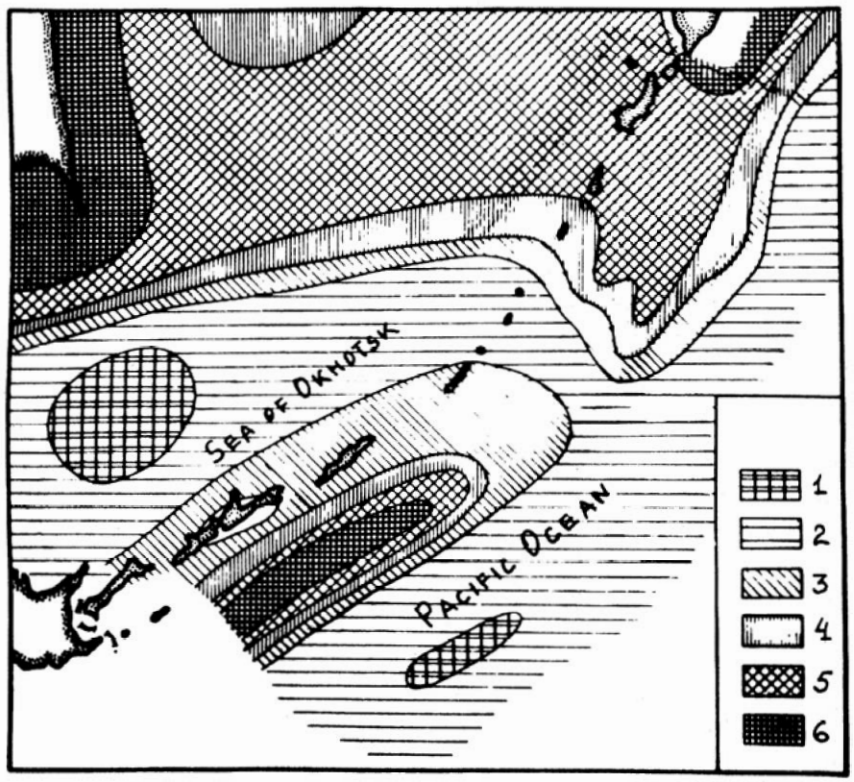

Figure 2. Thickness of consolidated crust in the area of the Kurile Islands.
1. < 5 km; 2. 5-10 km; 3. 10-15 km; 4. 15-20 km; 5. 20-25 km; 6. 25-30 km (after Kosminskaya et ol.)

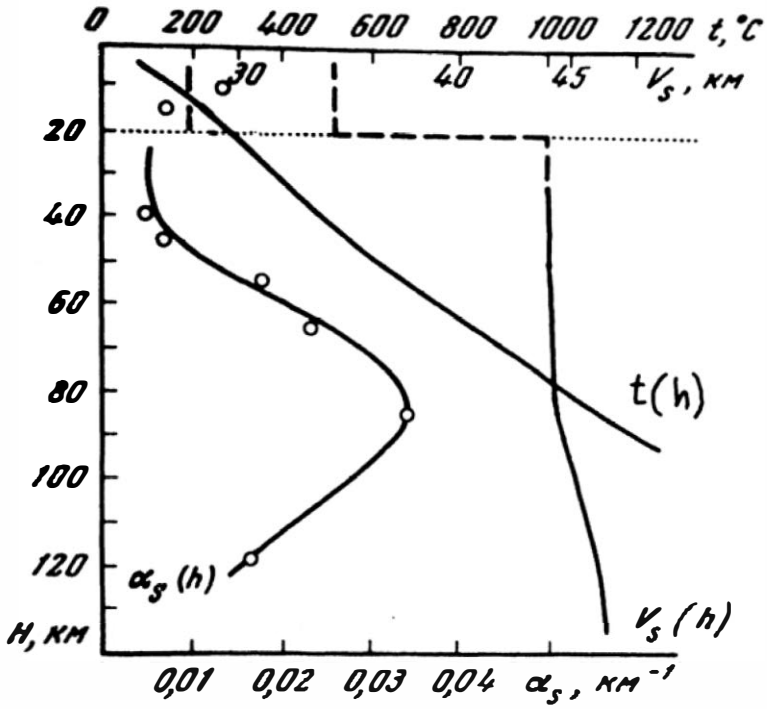

Figure 3. The change of some physical constants with depth in the area of the Kurile Islands.

a(h) - absorption of energy of transverse seismic waves

Vs(h) - velocity of transverse seismic waves

t(h) - the temperature under Kurile arc

(after Fedotov)

known. Oceanic consolidated crust is 5-8 km thick and consists of a single layer, continental crust has a thickness of 35 km on the average and has two layers.

In both cases, seismic velocities Vp at the boundary of the crust and mantle increase sharply "by leaps" from 6.7-7.0 km/sec to 8.0-8.2 km/sec. At deeper levels the velocities steadily increase but there is a rather thick layer at a certain depth in the upper part of the mantle where the velocities Vp fall again to 7.3-7.5 km/sec (Gutenberg, 1954). This layer of reduced velocities, often called the "Gutenberg layer" occurs at a depth of 60 km under the oceans and at a depth of 120 km (twice as deep) under the continents. The lower boundary is at a depth of 200 km in both cases.

The Gutenberg layer may be best explained by the fact that at certain depths the melting temperatures of the rocks and the prevailing temperatures nearly coincide, that is, the horizon ("asthenospheric" layer) is in a state close to melting.

The difference in thickness and position of the asthenospheric layer under the continents and under the oceans indicates that these two tectonic structures differ not only in crustal composition but in the nature of the upper mantle as well.

Quite a different picture has recently been observed in areas of volcanic island arcs: the structure of the Earth's crust in these regions may vary greatly -- from oceanic to continental, but the structure of the upper mantle is well defined and very regular for all the studied regions.

Thus the island arcs such as Tonga, Mariana, Izu, the central part of the Kurile arc and western part of the Aleutian arc are situated on a thin crust of the oceanic type. Volcanoes of Kamchatka, Japan, North and South America are underlain by a thick continental crust.

In same places the character of the Earth's crust varies along the strike of an individual orc. Thus, for instance, the northern part of the Izu-Hakone arc (Hakone volcano) is located on crust of continental type while the southern part (the Izu Islands) -- on oceanic crust; the northern part of the Kurile orc is underlain by continental crust, the central -- by suboceanic (oceanic in fact), and the southern-- by crust of transitional type (subcontinental) (Figure 2).

Though the structure of the Earth's crust in volcanic chains may be oceanic and continental or even vary within the limits of one ond the same orc, the structure of the upper mantle remains everywhere the same and differs from oceanic and continentol types.

In those island and volcanic arcs where detailed investigations were carried out it was found that immediately below the Mohorovičič boundary the velocity of longitudinal waves is 7.3-7.8 km/sec instead of the usual continental and oceanic values of 8.0-8.2 km/sec. Reduced values of seismic velocities of subcrustal ports of the mantle are observed under the continental crust of volcanic regions of the western part of North America (Berg et ol., 1960; Pokiser, 1963; Hodgson, 1963) and under oceanic crust of the Tonga Islands (Raitt et al., 1955).

Reduced values of velocities in the Upper Mantle are also observed for the Aleutian Islands, Kamchatka and Kurile Islands, Japan, New Guinea, Solomon Islands and New Zealand. It con hardly

be doubted that the whole "Pacific fire belt" is characterized by reduced velocities in the subcrustal mantle.

This peculiarity was studied most thoroughly in the region of the Kurile Islands (Fedotov, 1963). It was found that the velocity of longitudinal waves remains constant from the base of the crust (~ 20 km) down to depths of 70-80 km and averages 7.7 km/sec. The velocity V_p increases insignificantly below. Only at a depth of 125 km does the velocity V_p reach a value of 8.1 km/sec. If there is a wave-guide or Gutenberg layer in the upper mantle, it is very vaguely displayed; it "floats," so to speak, from deep in the mantle to the boundary of the Earth's crust. Moreover, at depths of 60-110 km and especially of 80-90 km the absorption of energy of transversal seismic waves increases to a great extent (Figure 3).

The peculiarity of the upper mantle is also indicated by a regrettably small number of studies by magnetotelluric sounding methods. In Kamchatka and the Andes and in some other volcanic regions the layers with high electrical conductivity were found at unusually shallow levels of 40-80 km instead of "normal" continental depths of 120 to 200 km.

Petrochemical Peculiarities

The petrochemistry of volcanic rocks of the Pacific area was analyzed by P. Burri (1926) on the basis of the Niggli method. Later, A. N. Zavaritsky has suggested a new system of petrochemical calculations (Zavaritsky, 1954). This system is very convenient and allows one to analyze graphically a number of parameters of very different types. Recently I have studied the petrochemistry of the Pacific area according to Zavaritsky's method, using recent, more exact analyses (Gorshkov, 1961, 1962, 1967). It was found that one of the most important characteristics is the ratio of the sum of alkalis to silicic acid. Since the system of Zavaritsky is little known beyond the USSR, we shall use a simpler method and consider only the ratio Na_2O+K_2O/SiO_2. This ratio was also considered by Kuno (1966), who has used weight per cent. Since the molecular weights of Na_2O and K_2O differ greatly and may therefore introduce discrepancies and errors of different kind, I shall not use weight per cent but molecular quantities (in a simplified case one may use the sum of $Na_2O+0{,}7K_2O$ and SiO_2 in weight per cent)

I have calculated the mean values for the published modern analyses of volcanic rocks of the Pacific area (Gorshkov, 1967). All the data used are taken from the mentioned work.

The alkalinity of rocks in island and volcanic arcs vary within considerable limits. The least alkaline of the rocks known to the author are the lavas of the Tonga Islands. In double or more complex arcs and in marginal zones of the continents all transitions from less alkaline to more alkaline types of the calc-alkaline family and even alkaline rocks can be observed.

As an example, Na_2O+K_2O/SiO_2 relations for the Tonga Islands, Cascade Range and Bogoslof Island (Aleutian Islands) are shown on Figure 4.

In addition, the data for continental volcanic rocks of East Asia and for Hawaii are plotted on the same diagram.

The line of the Tonga Islands corresponds to the Pele type, the line of the Cascade volcanoes to the Lassen Peak type, while the line for Bogoslof Island resembles the Yellowstone type. Still higher are purely alkaline rocks. The thick line separates the fields of calc-alkaline and purely alkaline rocks. A dotted line shows Kuno's divisions between tholeiitic, high-alumina and alkaline series.

It follows from Figure 4 that the lines Na_2O+K_2O/SiO_2 for island arcs and continental volcanoes form straight or close to straight lines more or less parallel to each other. The direction of the line for the Hawaiian Islands (and other interoceanic islands) differs markedly from the inclination of island arcs and continental volcanoes.

Kuno's line dividing tholeiitic and high-alumina series more or less coincides with the line of the Lassen Peak type. Kuno's line dividing high-alumina and alkaline rocks does not coincide completely with any of our lines and crosses them.

Since our curves may be approximated as straight lines, they may be expressed in an analytical form:

$$y = a + bx$$

where y = the total alkalinity (in molecular quantities), x = molecular quantity of silica, a = the value characterizing initial alkalinity, and b = a coefficient characterizing the rate of growth of alkalinity (equal to the tangent of inclination angle).

The coefficient b for continental rocks varies within the limits 0.05 to 0.20; with oceanic rock it varies from 0.30 to 0.40. The coefficient a indicates the rock's alkalinity. To make a better graphic

image and facilitate calculations the coordinates begin at a point with a molecular quantity of SiO_2 = 700 which corresponds approximately to 42% of SiO_2. Under this condition, a = 3 for the rocks of the Tonga Islands (Pele type), while for the Cascade volcanoes (Lassen Peak type) a = 40, for the Bogoslof Island (Yellowstone type) a $\approx$ 45. With a $>$50 continental rocks belong to alkaline series.

Let us go on with an analysis of peculiarities of petrochemistry of volcanic rocks along the strike and radial to volcanic chains.

We shall begin with the Kamchatka-Kurile arc. It is a double orc. The main volcanic zone covers the eastern shore of Kamchatka and passes on to the chain of the islands of the Major Kurile ridge to the southwest. The western zone passes along the Median Kamchatka ridge of Kamchatka crossing the islands west of the main chain of the Kurile Islands.

Figure 5 shows the points of intermediate compositions of lovas for the Eastern Kamchatka, Northern and Central Kurile Islands. This chain extends 1200 km from the Kronotsky region of Kamchatka to Simushir Island in the Kurile chain and passes from typically continental crust of the Kamchatka region to essentially oceanic crust under the central Kurile Islands. Nevertheless, all points ore closely grouped along the single line E-E on Figure 5. If we consider the plots of overage analyses of the western volcanic zone we see that these points ore clearly grouped along o distinctly more alkaline line W-W. This zone extends more than 1500 km from the Central Kamchatka to Broughton Island and also posses across regions of different types of crust. The distance from the Main to the Western zone north of the Kurile Islands is only a dozen kilometers; hence volcanoes of corresponding ports of the two zones must be located on the crust of one and the some type.

Thus the some petrochemical peculiarities along the arc over o distance of more than 1000 km are observed quite clearly regardless of major changes of the Earth's crust while there is a clear variation of chemistry across the orc at a distance of a dozen of kilometers within the limits of one and the same type of crust.

A similar picture may be observed in the volcanic zone Izu-Hakone. This zone posses from Honsyu with its continental crustal structure for 800 km southward to the Izu-Sitito Islands underlain by oceanic crust. The points of average chemical compositions of volcanic rocks of continental and oceanic parts of the Izu-Hakone zone are also shown on Figure 5. All grouped along one and the same line, H-H on Figure 5, despite o sharp difference in crustal structure. In contrast to this the inner zone of Fuji which is only 20-25 km from the Hokone zone has a more alkaline nature coinciding actually with the E-E line on Figure 5.

The examples of this type could be multiplied. Lateral variations of other arcs hove been considered by Kuno (1966) in connection with different types of island arcs and in connection with the more detailed structure of the Earth's crust and upper mantle by the author (Gorshkov 1961, 1962, 1963, 1967 et al.).

On Andesite Genesis

Andesites ore often considered products of assimilotion of sialic material of continental crust by basalt magma. It should therefore be stressed that andesites ore known in all the island and volcanic arcs and their presence is not uniquely connected with a continental type of crust. In particular, andesites are found in the western part of the Aleutian arc, on the central Kurile Islands, on the Izu Islands (Tori-shima and Aogashima), in the Mariana orc (Uracas Island), in the Tonga arc (Tofua Island) and elsewhere. The two last regions ore at distances of thousands of kilometers from the closest continent.

In these conditions formation of andesites by assimilation of more acid material is clearly impossible. Andesites here ore undoubtedly the product of crystollizational differentiation of primary basalts.

Assimilation phenomena may offer o possible explanation for andesites in continental ports of volcanic orcs, but petrochemical peculiarities along and across island orcs outlined in the previous section indicate that the role of assimilation is probably not significant. Assimilation phenomena should produce a greater diversity of rocks when passing from one type of the crust to another along an orc.

In addition, an analysis of quantitative relations of andesites to other rocks clearly shows that on recent volcanoes in certain island orcs andesites often ploy o volumetrically subordinate role. At a more mature stage of double arcs or continental volcanic orcs, andesites become the prevailing rocks. Sometimes more acid rocks may be dominant. Considering variations in geological time it is possible (for instance on Kamchatka or on the Kurile Islands) to observe a regular variation from massive basalt flows through the andesitic stage to eruptions of siliceous pumice and ignimbrites. Such a variation of rocks may occur many times.

The facts stated above do not allow us to postulate andesites as products of assimilation of sialic

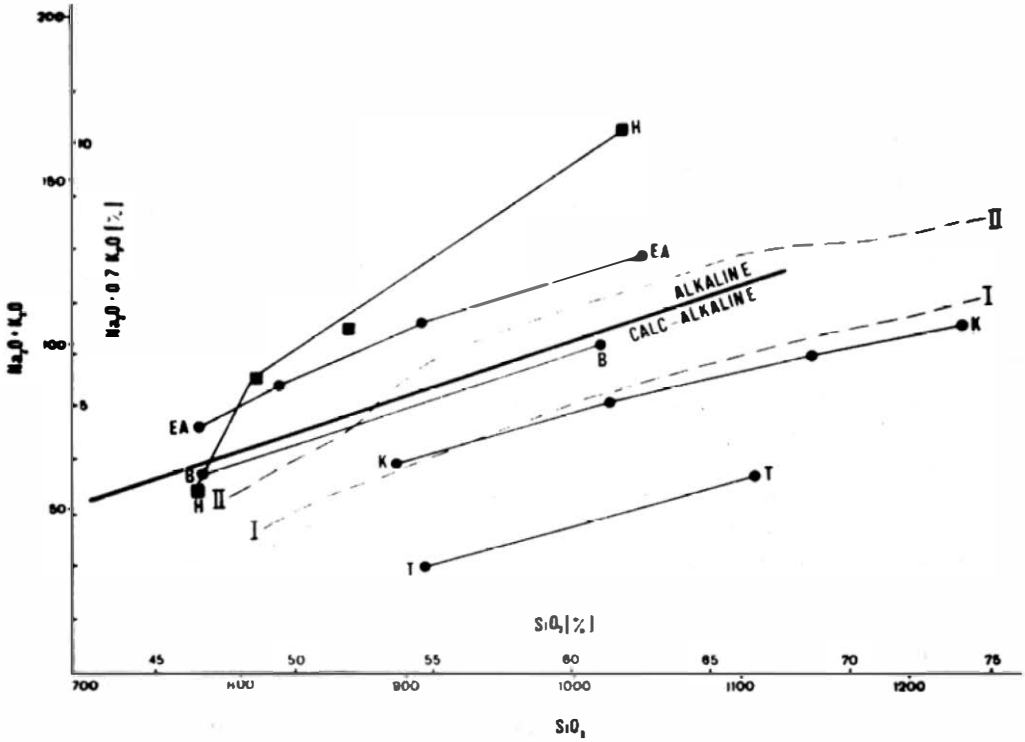

Figure 4. Total alkalies - SiO_2 relation in rocks of some volcanic areas.
T - Tonga Islands. K - High Cascade volcanoes.
B - Bogoslof Island. EA - East Asia. H - Hawaii.

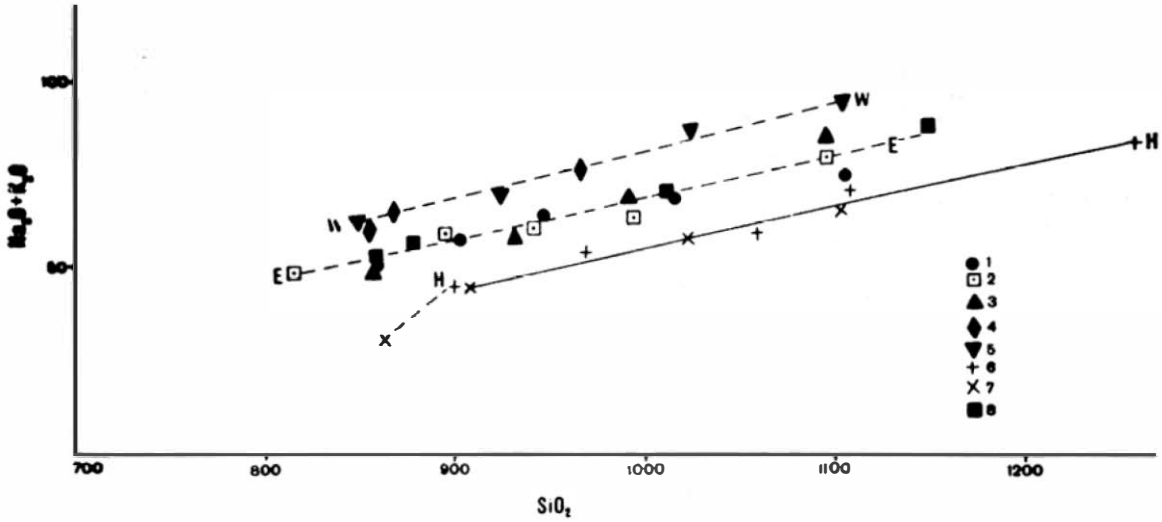

Figure 5. Total alkalies - SiO_2 relations in some volcanic arcs.

1. Central Kuriles.
2. North Kuriles.
3. East Kamchatka.
4. West zone of Kuriles.
5. Central Kamchatka Range.
6. Continental part of Izu-Hakone zone.
7. Oceanic part of the same zone.
8. Fuji zone.

material of the crust. Andesite is one of the members of a common range of volcanic lavas which are generated in the upper mantle. At the beginning basic magmas are generated and andesites are the product of their differentiation. The possibility is not excluded that in further development of differentiation processes in the upper mantle a direct generation of andesites or even of more acid rocks takes place directly in the upper mantle. To clarify this question, geochemical and isotopic studies are needed.

Generation of magma is sometimes related to deep-focus earthquakes in a spatial and causal respect (Kuno, 1959; Sugimuro, 1960). Geophysical data now available, including direct determinations of the depth of volcanic foci (Gorshkov, 1959; Fedotov and Farberov, 1966) indicate that magmas are generated in areas located markedly higher than the depth of the focal zone. Thus for the volcanic zone of Kamchatka the focal zone of earthquakes is located at depths of 151 to 180 km, and volcanic foci and zones of magma generation are established at depths of 60 to 90 km.

To my mind, volcanism and earthquakes as well as other displays of deep tectonics and the type of the structure of the Earth's crust are connected paragenetically. They are caused by one common phenomenon -- by the process of differentiation of the upper mantle. The source of volcanism is evidently the osthenospheric layer (Gutenberg layer), the lower boundary of which does not exceed 200 km. Magma can hardly be generated beyond the limits of the asthenospheric layer, i.e. deeper than 200 km.

The author's conception of the zones of magma generation in different zones of the earth is illustrated in Figure 6.

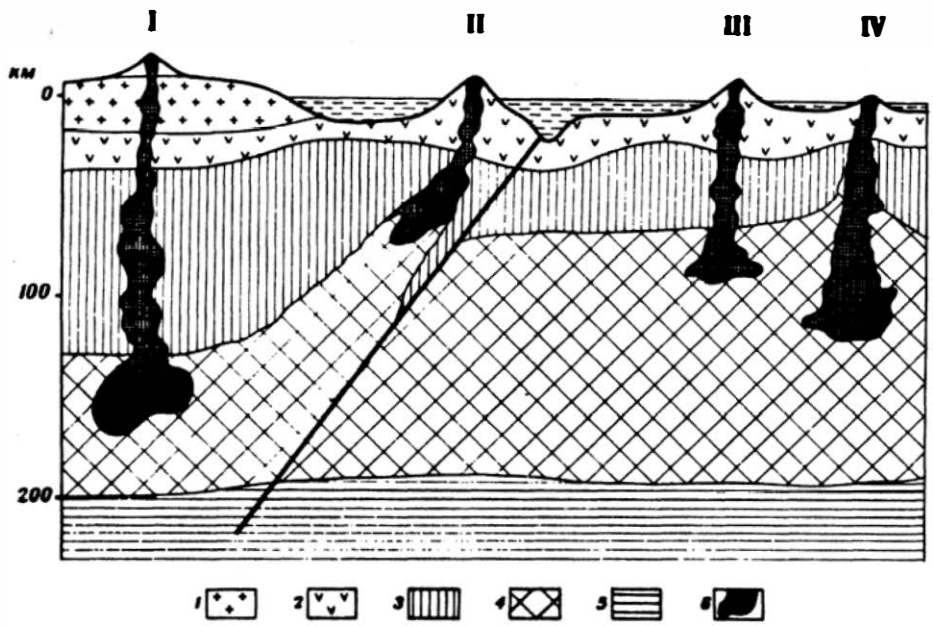

Figure 6. Hypothetical profile across different volcanic areas.

I. Continental volcanoes. II. Island arcs.
III. Oceanic volcanoes. IV. Mid-oceanic ridges.

1. "granitic" layer. 2. "basaltic" layer. 3. subcrustal parts of mantle. 4. asthenosphere layer (Gutenberg's zone). 5. subosthenosphere layer. 6. zones of magma generation and volcanic chimney.

Conclusion

The calc-alkaline nature of lavas and a specific structure of the upper mantle is common for all the island and volcanic arcs.

Both direct geophysical data and petrochemical analysis show that everywhere with very rare exceptions volcanism proves to be a "trans-crustal process." In all regions the volcanic foci are situated beyond the limits of the Earth's crust in the upper mantle. The composition of volcanic lavas does not depend on the composition of crustal rocks; in other words, the role of assimilation of the course of magma towards the surface appears to be very modest. The sources of lava diversity and in particular the localization of andesites are caused by the magma itself and by processes occurring in it as well as by the processes of differentiation of the upper mantle. Thus volcanic rocks may be considered true derivatives of the upper mantle, and volcanism is in its way an indication of the composition and state of subcrustal ports of the mantle.

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SEA-FLOOR SPREADING AND ISLAND-ARC TECTONICS /

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Introduction

Hess' (1962) hypothesis of the spreading of the sea floor and the related hypotheses of Vine and Matthews (1963) and Wilson (1965) have since been supported by compelling evidence from many sources. We shall review* here the evidence relating to that part of the hypothesis which considers the deep oceanic trenches as the sites where the sea floor descends beneath the continental margins. Until a few years ago, the evidence rested mainly on the existence of a narrow zone of seismic activity (Benioff, 1954) dipping toward the continents from a region on the landward side of the trench where a gravity deficiency (Vening Meinesz, 1934) indicated a departure from isostasy of dynamic origin. More recent work appears to provide further support for the findings of Benioff and Vening Meinesz. If the sea-floor spreading hypothesis is accepted, it will have an important consequence for the topic of this Symposium. As the oceanic crust descends beneath the island arcs, its sediments, basalts, and meta-basalt or serpentinite can provide a replenishable source of material for the andesitic magmas which erupt at the surface.

Seismicity

The earthquakes of the island arc and trench systems are known to lie in approximately planar zones dipping toward the continent from a point somewhere near the trench (Benioff, 1954). With the recent increase in the number of seismographic stations, it has been possible to remap the Benioff zones with much greater precision. Sykes (1966) has located earthquakes in the island arcs by a computer program using data from the world-wide standard network of stations. The conclusion of Benioff and others that the earthquakes are concentrated in narrow planar zones has been reinforced. Sykes (1966) finds that the earthquakes beneath the Tonga and the Kuril trenches and island arcs are concentrated in zones probably less than 50 km in thickness. Hamilton and Gale (1968) and Fedotov (1966) find similar results for the North Island of New Zealand and the South Kurils where data from fairly dense local networks are available. The average dip of the Benioff zones is approximately 45 degrees.

Sykes (1966) examined the seismicity of Tonga-Fiji-Kermadec, Kuril-Kamchatka, Alaska, and the Caribbean island arcs. In each region he found that the number of earthquakes decreases nearly exponentially with depth in the upper 200 km. In some areas, particularly Tonga-Fiji-Kermadec, the earthquakes increase in number again below approximately 400 to 450 km before decreasing to zero at approximately 700 km. In Alaska and the Caribbean, no earthquakes below about 300 km in depth were observed. For the earth as a whole, Mizoue (1967) shows that the energy release with depth has a pronounced minimum in the region between about 300 to 400 km and increases again to a maximum somewhere around 600 km.

An increase in the seismic energy released by earthquakes at 350 km to 450 km has been correlated by Anderson (1967) with the olivine-spinel transition thought to account for the seismic-wave velocity increase in that depth interval. It has been suggested that sudden volume change accompanying

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* An excellent review by Isacks, Oliver and Sykes (1968) touching on most of the work discussed here and embodying many of the same conclusions appeared as this paper was submitted. The reader who might wish to pursue this subject in more detail is advised to turn to their comprehensive paper.

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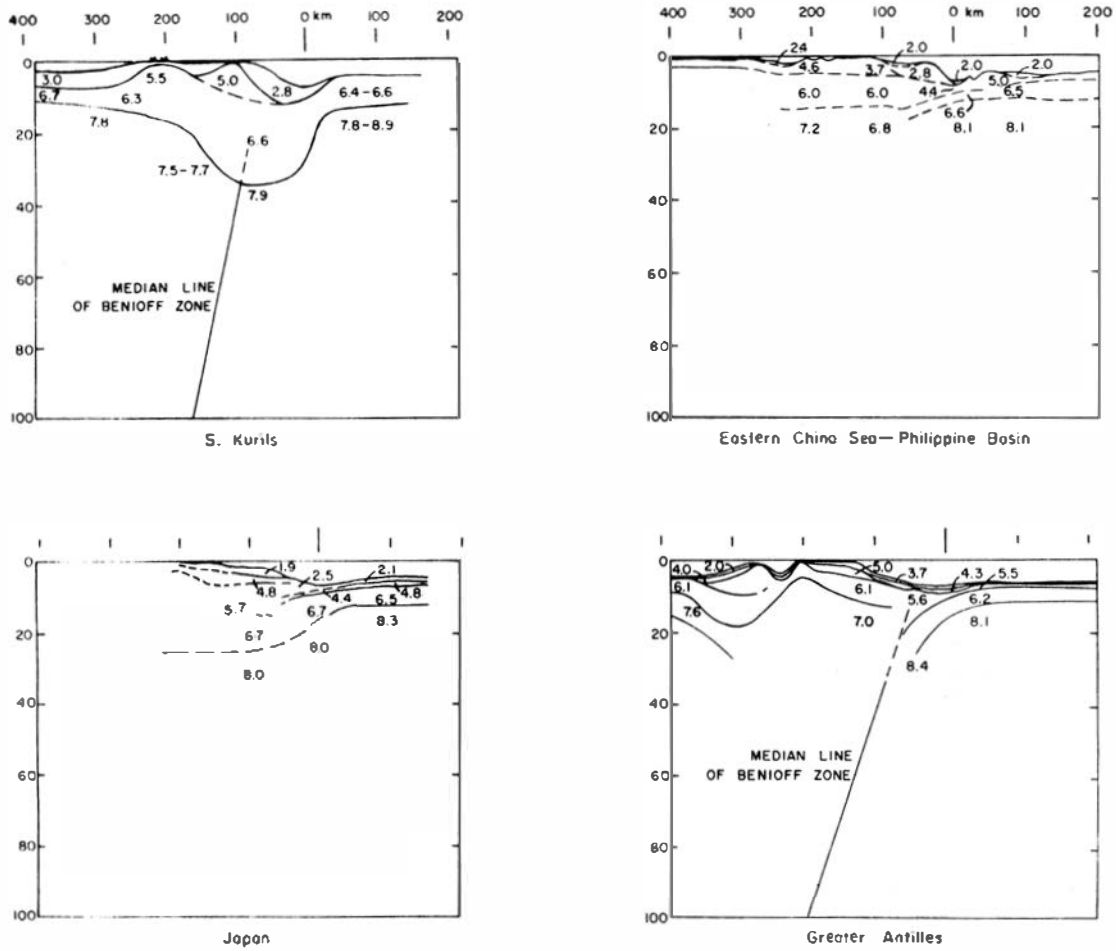

Figure 1. Crustal structure of island arc-trench systems. References are:
S. Kurils (Kosminskaya et al., 1963),
Eastern China Sea-Philippine Basin (Murauchi et al., 1968),
Japan (Ludwig et al., 1966), and
Greater Antilles (Officer et al., 1959).

Beniof zone in S. Kurils is from Fedotov (1966), and in
Greater Antilles from Sykes and Ewing (1965).

a phase transition could account for the seismic energy released (Evison, 1967). However, Sykes (1968) observes that the earthquake source is best represented by a double-couple mechanism in every case where a good solution is obtainable. As Anderson (1967) suggests, the phase change may act more as a triggering mechanism by influencing the tectonic stress field in active regions.

Structure of Crust and Upper Mantle

A significant result from investigations of earthquakes in the Benioff zone is the finding by Oliver and Isacks (1967) that the nature of the mantle is different on either side of the seismic zone. Their studies in the Tonga region show that seismic waves propagating along the footwall side of the Benioff zone have abnormally low attenuation for short-period S-waves compared to normal oceanic upper mantle. Seismic waves traveling through the mantle beneath the island arc on the hanging-wall side of the zone exhibit greater attenuation of short-period S-waves and have somewhat lower velocity than for normal mantle. Fedotov and Kuzin (1963) found that the mantle velocity beneath the South Kuril island arc was also somewhat less than that for normal mantle, about 7.8 km/sec for P-waves to a depth of about 80 km. In addition, they found a greater-than-normal attenuation for S-waves. The existence of the layer having high Q beneath the seismic zones of the island arcs is, as Oliver and Isacks point out, consistent with the notion that convection cells or some other mechanism drag the colder upper part of the oceanic mantle down beneath the island arcs. Aki (1968) has suggested that zones of partially molten rock in the mantle beneath the island arc of Japan can account for the lower P-wave velocity and higher attenuation.

Seismic-refraction studies across trench-island arc systems also suggest that the Benioff zone represents a discontinuity in the crustal structure. As shown in Figure 1, where sufficiently detailed work has been carried out, the structure of the crust near the trench on the oceanward side is typical of oceanic crustal sections determined elsewhere. Between the trench and the island arc the crustal thickness increases, and the layer velocities in many cases vary substantially from those in the oceanic crust at the trench. As is suggested by the figures, the transition from oceanic crust to the thickened crust of more continental character takes place approximately in the regions where the Benioff zone traverses the crust. Thus the Benioff zone represents a major lateral discontinuity in the properties of the crust and mantle at the island arcs.

Tectonics of Island Arc-Trench Systems

Some of the most important information concerning the tectonics of the island arc-trench systems has been produced by studies of the first-motion patterns of earthquakes. Nearly all the seismic radiation patterns studied in recent years for which good focal plane solutions are available (Sykes, 1968) correspond to a double couple at the source. The data from focal plane solutions for island arc earthquakes which we will use in this paper are the poles to the two mutually perpendicular nodal planes and the compression and tension axes. The latter are the directions bisecting the poles to the nodal planes in the dilatational and compressional sectors of the focal sphere, respectively. The compression and tension directions so determined give the maximum resolved shear stress in the slip direction on the nodal planes regardless of which represents the fault surface (Honda, 1957). The diagram in Figure 2 shows the two nodal planes, one of which is the fault surface. The pole to one of the nodal planes is therefore the slip direction; the other is the normal to the fault.

Unambiguous focal plane solutions are still few in numbers for the island arcs. Since 1960, however, the quality and amount of data from reporting seismographic stations has increased substantially and solutions for earthquakes prior to that time have not been used in this report. The solutions since 1960 come from the following sources: Wickens and Hodgson (1967), Stauder and Bollinger (1964, 1966a, 1966b), Stevens (1964, 1967), and Udias and Stauder (1964). In a further effort to improve the quality of the data selected, only the "good" solutions of Wickens and Hodgson (1967) were used. Solutions from other authors were taken only when there was no ambiguity in the orientation of the nodal planes and where the standard deviation of the orientation was small.

The data are presented in the following way. The island arcs for which solutions are available (mostly northern and eastern Pacific earthquakes) are broken down into linear segments, and the solutions for each segment are plotted on the lower hemisphere of an equal area projection. The coordinates for each projection are the azimuth of the linear segment of the island arc and the azimuth of the dip direction of the Benioff zone. All the solutions are then collected on one diagram by rotation to a common orientation for the azimuth of the arc segment and the dip direction of the seismic zone. The areal

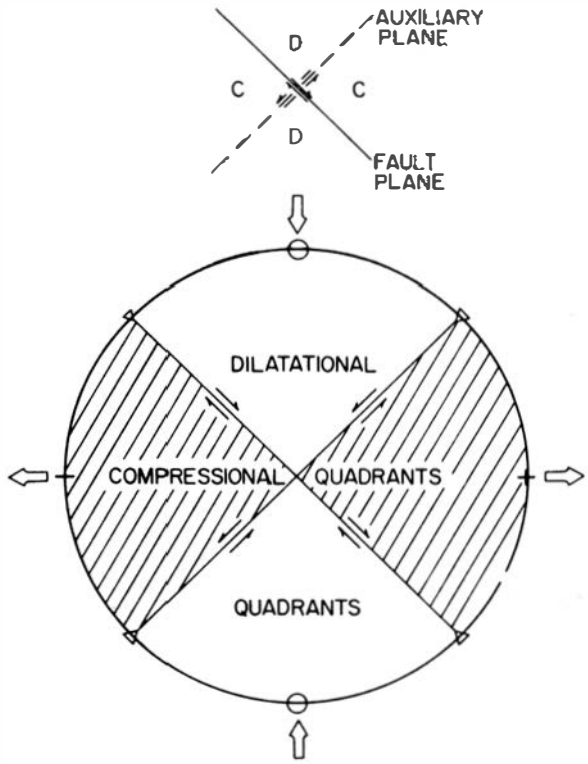

Figure 2. Diagram of nodal planes for double-couple fault plane mechanism. Below: distribution of first motions on equal-area projection. Compression and tension directions shown by north-south and east-west arrows respectively.

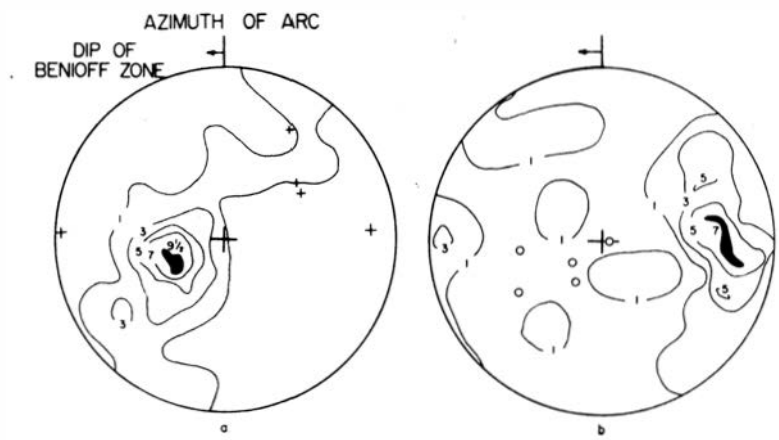

Figure 3a. Tension directions contoured on equal-area lower hemisphere projection for 38 island arc earthquakes, depth < 200 km. + are tension directions for earthquakes, depth > 200 km. Contours: 1, 3, 5, 7, 9 ½% of total poles per 1% area of projection.

Figure 3b. Compression directions contoured for 38 earthquakes, depth < 200 km. O are compression directions for earthquakes, depth > 200 km. Contours: 1, 3, 5, 7% per 1% area.

Figure 4. 76 poles to nodal planes contoured for 38 island-arc earthquakes, depth < 200 km. Δ are poles for earthquakes, depth > 200 km. Lower hemisphere, equal-areo projection. Contours: ½, 1½, 2½, 3½, 4½, 6% per 1% area.

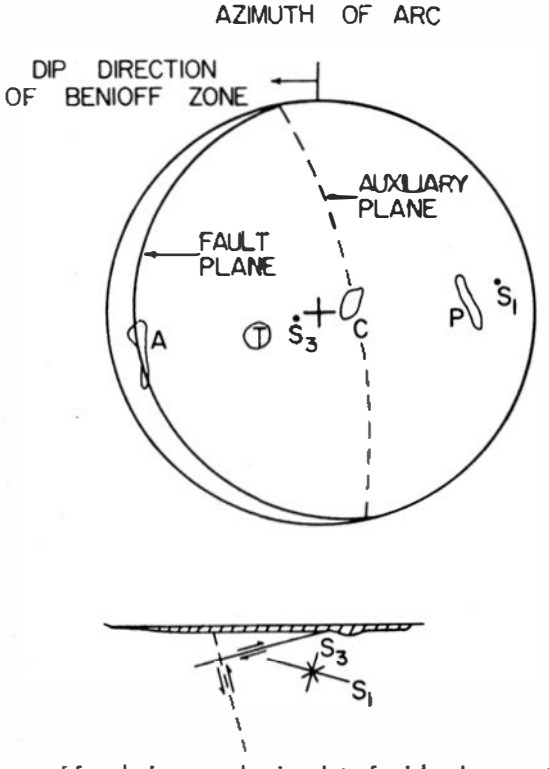

Figure 5. Synoptic diagram of focal plane mechanism data for island arc earthquakes, depth < 200 km. A is slip direction maximum; T is tension maximum; C is maximum of poles to fault planes; P is compression maximum. S_1 and S_3 are greatest and least principal stresses assuming fracture formed at 30° to S_1.

distribution of the earthquakes through which solutions were used is as follows:

Alaska-eastern Aleutians	8
Central Aleutians	4
Western Aleutians	3
Kamchatka	3
Southern Kuril-Hokkaido	9
Northern Honshu	1
Marianas	3
Central American trench	3
Peru trench	4
Peru-Chile trench	5

Thirty-eight solutions were used for earthquakes shallower than 200 km, most of which were shallower than 100 km. Five earthquakes deeper than 200 km were used. The data for the shallow earthquakes were contoured in Figures 3a, b, and 4; the deeper earthquakes are plotted individually.

As shown in Figure 3b, the compression directions for the island arcs and the Central and South American Pacific continental margins define a maximum normal to the azimuth of the arcs for earthquakes shallower than200 km. The maximum is distended along a great circle approximately parallel to the arc and plunges at an angle of nearly 30 degrees in the direction opposite to the dip of the Benioff zone. The tension directions (Figure 3a) plunge steeply toward the dip direction of the seismic zone and approximately normal to the azimuth of the arc. The deeper focus earthquakes are too few in number to give clear concentrations of compressions or tensions. Those shown, however, are consistent with the observations of Aki (1966) that for Japan the compressions tend toward the vertical for deeper earthquakes with the tensions oriented near horizontal and perpendicular to the arc. In agreement with our results, Aki also found thattheshallow-focus earthquakes give compression directions oriented nearly perpendicular to the arc and dipping gently towards the oceanic side of the island arc.

In Figure 4 the normals to the nodal planes for the earthquakes of less than 200-km depth are plotted. The normals fall into maxima with a strong concentration near vertical and normal to the azimuth of the arcs, and a second, more diffuse concentration near horizontal and again perpendicular to the azimuth of the island arcs. The maxima are mutually perpendicular and indicate that the nodal planes lie in sets striking approximately parallel to the arc. As shown in Figure 5, the nodal planes corresponding to the strong maximum dip in the direction of the Benioff zone at about 15°; the other set dips steeply oceanward. The sense of shear on both sets is reverse. If the fault plane is assumed to be that set of planes dipping toward the island arc, the direction for the maximum principal stress, S_1, may be taken to be 30°, corresponding to the experimental fracture angle (Figure 5). The slip direction in the fault plane is given by the normals to the auxiliary planes (Figure 4). The fault movement indicated would therefore be predominantly dip-slip in a reverse sense. Figure 4 indicates that although the fault planes have a consistent orientation parallel to and dipping gently beneath the island arcs, the slip directions have a considerable oblique slip component. This observation may be explained if the slip direction is taken to be the projection on the fault plane of the direction of sea-floor spreading. The directions of spreading are oblique to much of the Aleutian arc and the middle American continental margin based on magnetic anomaly maps and the rigid block hypothesis of Morgan (1968; also McKenzie and Parker, 1967; Heirtzler, et al., 1968; Le Pichon, 1968). Stauder (1968) shows that the focal mechanisms for the earthquakes of the Rat Island sequence define a slip direction oblique to the arc approximately in the direction of spreading for that region.

Plafker (1965) proposed that the changes in elevation and horizontal displacements following the great Alaskan earthquake of 1964 could be attributed to release of near-horizontal compressional elastic strain oriented perpendicular to the eastern portion of the island arc. He showed further that folding in the geologic past indicated a long record of compression perpendicular to this arc. Savage and Hastie (1966) demonstrated that the geodetic changes noted by Plafker were consistent with theoretical strains surrounding a dislocation model of a thrust dipping beneath the Alaskan arc. Focal plane solutions for the aftershocks of the 1964 earthquake (Stauder and Bollinger, 1966b) indicate thrusting on nodal planes dipping gently toward the island arc from the trench or dipping steeply oceanward to the south. The aftershock locations, however, are consistent only with a focal plane corresponding to a thrust fault dipping northward toward the island arc (Stauder and Bollinger, 1966b).

The tectonics of the island arc-trench systems are consistent with Hess' (1962) hypothesis of sea-floor spreading. One apparent inconsistency has been pointed out by Scholl, Von Huene, and Ridlon (1968). They suggest that the pelagic sedimentary cover should be scraped off in the trench at the

contact with the immobile continental plate if the spreading ocean floor descends at the trenches. The Peru-Chile trench, however, is devoid of sedimentary fill over much of its length, and where sediments do occur, they appear to be undistorted. We take the point of view that the spreading sea floor does descend into the trench and beneath the immobile mantle of the island arc or continental margin along the Benioff zone. Where sediments are absent in the trench, we must conclude that they are not subjected to deforming stresses during descent sufficient to scrape them off the oceanic crust. In places where flat-lying sedimentary fill is present, as in the southern part of the Chilean or Hikurangi trenches (Hautz, et al., 1967), we must also conclude that sediment is accumulating faster than it can be ingested.

This conclusion is supported by a comparison of the depth of the Tonga-Kermadec trench with the seismicity. Where the trench is deep (Figure 6) and sedimentary fill thin or absent, the rate of occurrence of earthquakes along a section of the Benioff zone normal to the trench is high; where the trench shoals to the south, the frequency of earthquakes diminishes. If the frequency of earthquakes is assumed to correlate with the rate of sea-floor descent along the Benioff zone, the relationship shown graphically in Figure 6 suggests that thickness of fill in the trench is related to the rate of sea-floor spreading. Of course, other factors such as local rates of sedimentation may be of overriding importance, but a similar, though less well-documented, relationship between the depth of the Peru-Chile trench and the frequency of earthquakes (Gutenberg and Richter, 1954) supports our contention.

To thrust the sediments beneath the crust of the island arc or continental shelf without distortion requires that they escape large shear stresses at the thrust or that debris sliding down the continental slope cover the disturbed region near the trace of the thrust. The former possibility has been discussed by Elsasser (1968). We note that local tensional stresses may act along the upper surface of the descending oceanic plate in the region of the trench for the following reasons. If the Benioff zone is taken to be the contact between the descending oceanic crust and the immobile upper plate in the South Kurils, it must bend about a radius of curvature of approximately 250 km, as shown in Figure 7. The radius is established by connecting the sea floor where it first bends toward the trench to the Benioff plane by a circle. In other areas, such as Tonga-Kermadec and the middle America trench, the radius varies from about 200 to 350 km.

Whatever the thickness of the plate descending along the Benioff zone, the upper surface suffers an extensional strain. For example, taking the plate to have a thickness of 100 km and the surface of zero strain to be midway between the upper and lower surfaces, the extensional strain on its upper surface would be 20 percent. Extension of the upper plate is indicated by normal faulting in pelagic sediments of the oceanward flank of the Japan trench (Ludwig, et al., 1966). Stauder (1968) found that earthquakes occurring beneath the Aleutian trench in the Rat Island sequence gave first motions corresponding to extension in the plate and normal to the arc. In addition, as Elsasser (1968) points out, local tensions normal to the trench would also be a consequence of the downward pull of a denser oceanic layer sinking along the Benioff zone. The likelihood of such local tensional stresses in the vicinity of the trenches may provide an explanation for the lack of compressional structures in the trench sediments.

The bending of the sea floor around a large radius (Figure 7) before descending along the 45° angle of the Benioff zone is also consistent with the results of the first-motion studies. For the shallower earthquakes (Figure 4), one set of the nodal planes dipped at about 15° toward the island-arc side of the trench, rather than at the 45° angle of the Benioff zone. The gentler dip of the downbuckling sea floor in Figure 7 suggests that these earthquakes could have occurred in the upper 30 to 40 km of the mantle.

Heat Flow

The flux of heat from the vicinity of an island arc is best known from Japan. The profile (Figure 8) shows the heat flow in relation to crustal structure and gravity across the trench-arc system (Lee, Uyeda, and Taylor, 1966). A feature of this profile common to other island-arc regions where fewer measurements are available is the set of high values occurring on the continental side (Vacquier, et al., 1966). The lower-than-normal heat flow between the trench and the island arc are also found in the South Kuril Islands (Vacquier, et al., 1966), but the data from elsewhere are too scattered to determine whether the low values are characteristic. If so, the requirement of sea-floor spreading, that descent of relatively cold mantle at the trenches should reduce the heat flow to the surface, would be satisfied.

McKenzie and Sclater (1968) have discussed the origin of the anomalously high heat flow from the inland seas behind Japan, the Kurils, and the Bonin-Marianas arc. They conclude that, in light of the sea-floor spreading hypothesis, only upward migration of magma or shearing along the Benioff zone

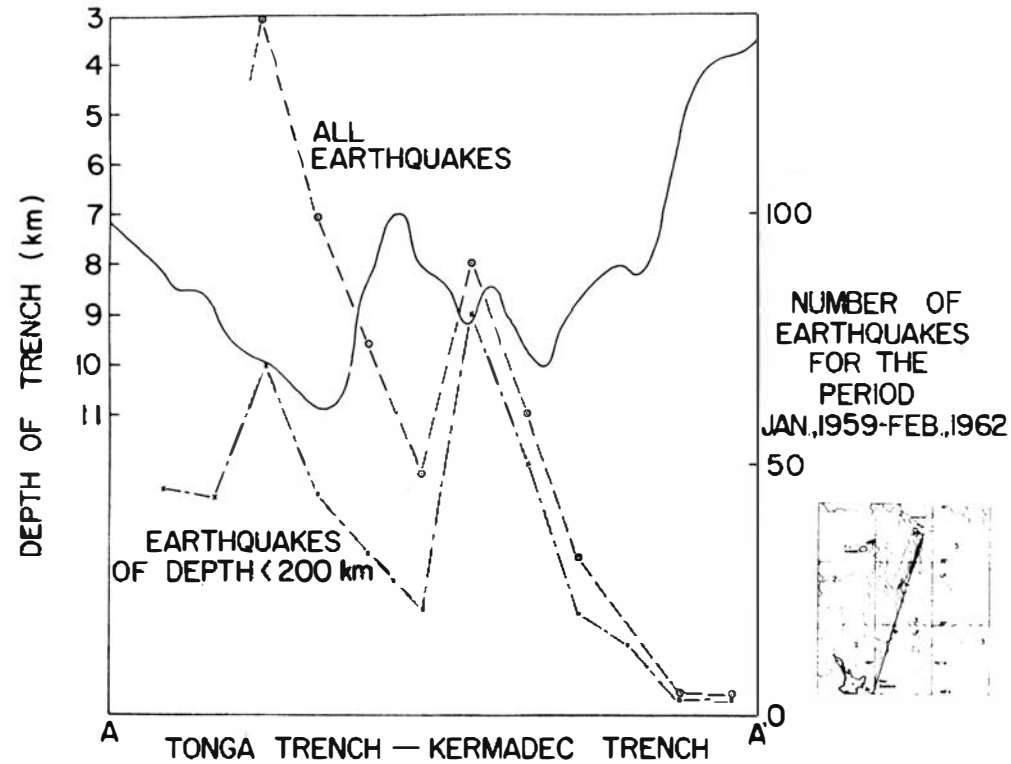

Figure 6. Relation between depth of Tonga-Kermadec trenches and frequency of earthquakes in profiles perpendicular to the trench. Seismic data from Sykes (1966).

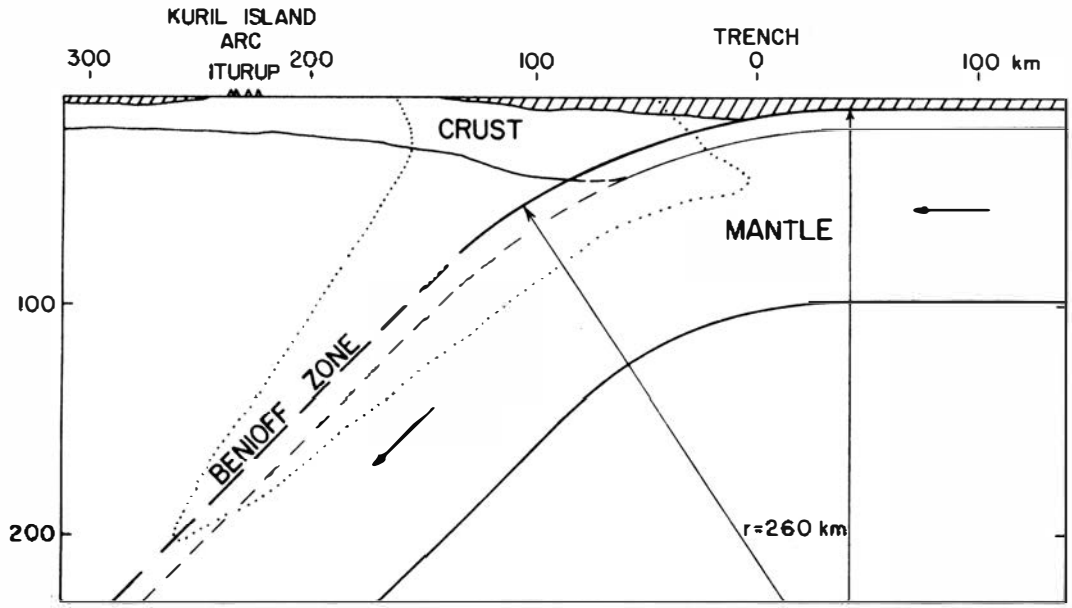

Figure 7. Diagrammatic sketch of bending of oceanic plate descending beneath South Kuril island arc.

could supply the required additional quantity of heat. Both hypotheses ore troublesome, however. There is apparently insufficient volcanic material in the crust of the inland seas to account for the required heating by migration of magma (McKenzie and Scloter, 1968). The time constant for heat to reach the surface by conduction from the deepest ports of the Benioff zone is greater than 300 million years so that for heat generated by shearing to reach the surface a long-term stability of the upper mantle there is required.

A third, equally speculative, possibility for the region of high heat flow arises from the observation of Dickinson and Hotherton (1967) that the K_2O content of eruptives in island orcs increases with depth to the seismic zone below. If their results ore applicable at distances of 300 to 700 km from the trench, then magma rising toward the surface beneath the inland seas should be enriched in radioactive elements compared to regions closer to the trench. This hypothesis requires that most of the rising magma has foiled to reach the surface in order to concentrate the heat sources in the shallow upper mantle and to explain the lock of o thick crust of volcanic origin. The presence of magma in the upper mantle may be the cause of the reduced seismic-wove velocities and Q-volues for the uppermost mantle in the Kurils, Japan, and Tonga (Fedotov and Kuzin, 1963; Aki, 1968; Oliver and Isocks, 1967). None of these three hypotheses is completely adequate, however, and the relationship, if any, between the regions of high heat flow and sea-floor spreading remains unclear.

Conclusions

The hypothesis of sea-floor spreading from the mid-ocean ridges and its descent at the deep ocean trenches down the Benioff seismic zones is consistent with tectonic data. The island orcs and volcanically and seismically active continental margins apparently lie above the descending oceanic crust and upper mantle. Possible consequences of this hypothesis for the origin of earthquakes in the Benioff zones and the generation of ondesitic magmas ore contained in the model outlined below.

The oceanic crust is presumed to consist of a loyer of sediment about 0.2 km in thickness overlying a seismic loyer 2, about 1.7 km thick (Raitt, 1963) of basalt. Basalt in loyer 2 has suitable properties for the generation of the strip-like oceanic magnetic anomalies. Layer 3, about 4 km thick, may consist of serpentinite (Hess, 1962) or meta-basalt, both of which hove been found in dredge hauls from the mid-ocean ridges (Melson and Van Andel, 1966). As the crustal layers descend beneath the hanging wall of the Benioff zone, progressive metamorphism will toke place approximately as follows (Figure 9) :

sediments $\longrightarrow$ pelitic schists + H_2O $\longrightarrow$ anhydrous rock + H_2O

basalt + H_2O or metabasalt $\longrightarrow$ blue schists $\longrightarrow$ amphibolites + H_2O $\longrightarrow$ eclogite + H_2O

serpentinite $\longrightarrow$ olivine + tolc + H_2O $\longrightarrow$ peridotite + H_2)

One sequence of these metamorphic changes with depth is shown in Figure 9. The transformation of basalt to glaucophane schist assemblages is, as Ernst (1965) points out, consistent with the temperatures to be expected near the bose of the thickened crust on the trench side of the island orc where the heat flow appears to be abnormally low.

An aspect of the progressive metamorphic transformations which may be important for the generation of the shallow to intermediote focus earthquakes is the progressive release of water vapor. It has been shown experimentally (Raleigh and Paterson, 1965) that high pore pressure of H_2O in rocks, which under otherwise similor conditions of pressure and temperature would be ductile, renders them extremely weak and brittle. Thus in on environment where dehydration reactions (serpentine $\longrightarrow$ peridotite + H_2O, in experiments) release H_2O at pressures near that of the overburden, the rocks will respond to shear stresses by faulting rather than by flow.

If some water is retained in the crustal rocks during their descent down to the level where partial melting begins, it seems likely that port, if not all, will go into the melt phose. As the experiments of T. Green and Ringwood (this volume) indicate, the presence of water during partial melting of basalt at about 10 kb may give rise to fractionates of the colc-alkaline series. At higher pressures andesite is the low-melting liquid from a dry tholeiite composition. Ringwood and D. Green (1966) hove previously suggested that sinking of eclogite transformed from blocks of oceanic crust provides a source for the

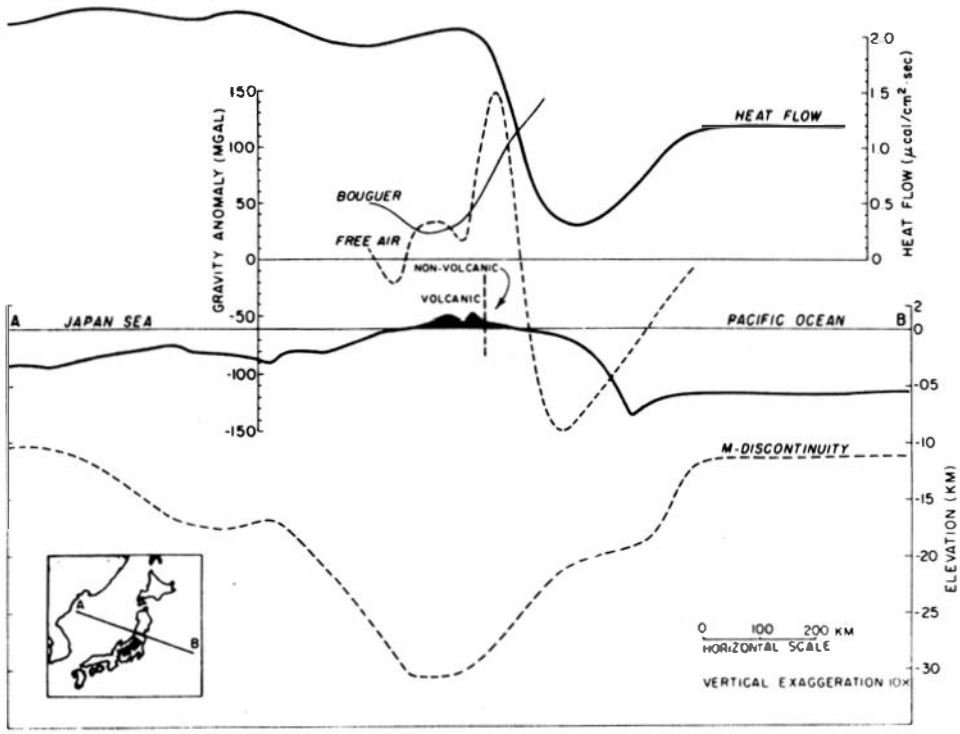

Figure 8. Profile of heat flow, crustal structure, and gravity across Japanese island arc (from: Lee, Uyeda, and Taylor, 1966).

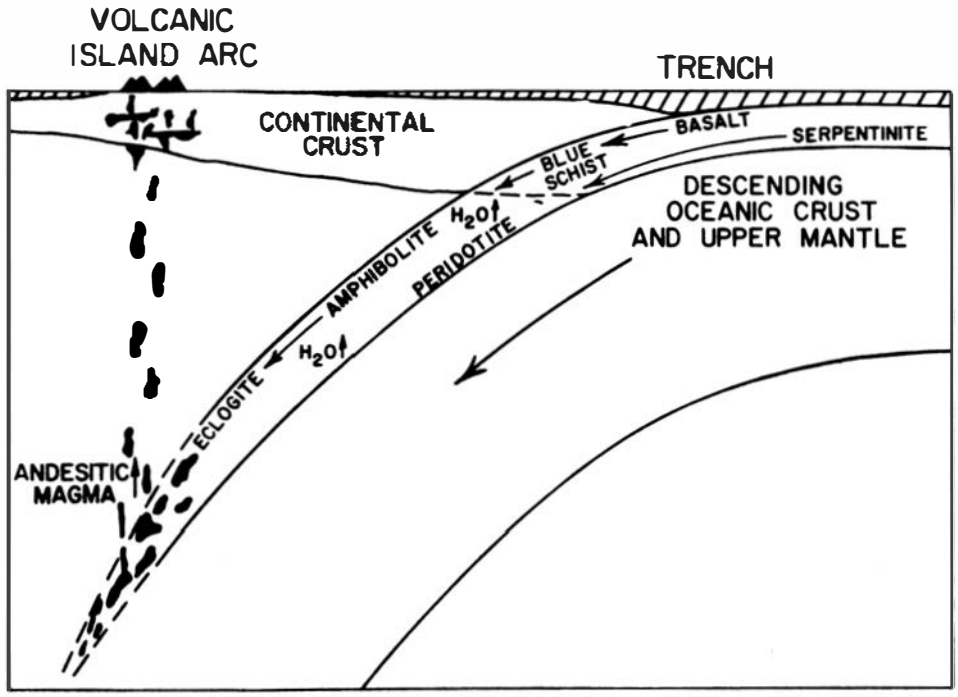

Figure 9. Hypothetical metamorphic reactions in oceanic crust descending beneath island arc. H_2O is released down to level where andesitic magma is generated from oceanic crustal material.

andesites of the island arcs. We consider that the sea-floor spreading hypothesis requires the oceanic crust to be conveyed downward along the Benioff zones to a level where melting occurs. Whether the andesites ore produced by the mechanisms experimentally demonstrated by T. Green and Ringwood (this volume) or by contamination of basaltic liquid with oceanic sediment, the oceanic crust provides a replenishoble source for the andesites.

To extract andesite to form on island orc will require partiol melting of a lorge volume of the mantle. However, Dickinson and Hotherton (1967) showed that K_2O content in ondesitic volcanics is proportionol to the depth to the Benioff zone. This suggests that andesites are derived from a restricted region. Such a restricted zone could not supply the volume of material required unless fresh supplies were added. We suggest that the additions are mode up by oceanic crust rafted downward by the sea-floor spreading mechanism. Thus the new oceanic crust created at the crest of the mid-oceanic ridges may eventually be accreted to the continental nuclei.

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THE COMPARATIVE CHEMICAL COMPOSITION OF CONTINENTAL VS. ISLAND ARC ANDESITES IN ALASKA

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Abstract

Andesitic flows and pyroclastic rocks erupted by Alaskan Peninsula volcanoes during historic time display docitic affinities, and o remarkably small variation in bulk chemical composition. Analyses of prehistoric rocks from active continental volcanoes indicate that chemically similar andesiteshave been erupted since the onset of volcanism.

The six andesite flows erupted by Trident Volcano during the period 1953-60 show some evidence of fractionation from two pulses or "batches" of magma. Admissible evidence is provided by the comparative chemistry of mineral phases of the flows, however, as the range in bulk composition of all flaws is not much greater than that recorded within an individual flaw unit.

Analyzed andesites from the central cane, caldera rim and alder flows of Wrangell Volcano in interior Alaska, are chemically similor to those from the Alaskan Peninsula, although slightly less silicious; and andesites from bath regions ore compositionolly similar to those erupted by the Cascade volcanoes of the western United States.

Aleutian arc andesites contain more iron and calcium than peninsular or interior Alaska variants; a trend shown in andesites from other North Pacific Island Arcs. Although continental andesites are generally more alkaline than island arc variants, Na_2O and K_2O are questionable discriminants for continental vs. island arc andesites in Alaska; but Aleutian andesites appear to be more alkalic than those from most island arcs.

The small variance in bulk composition of continental Alaskan andesites suggests that these magmas are generated under regionally similar physiochemical constraints; and that they are derived from the melting or partial melting of lower crustal racks.

Aleutian andesites display a greater variance in bulk chemical composition, which suggests a more complex petrogenesis. - (R. B. Forbes)

Introduction

In 1965, with assistance from the Notional Science Foundation and the U.S.-Jopon Cooperative Science Program, the Geology Deportment and the Geophysical and Morine Sciences Institutes of the University of Alaska initiated o continuing research program on active volcanoes of the Alaskan Peninsula and interior Alaska.

The new doto presented in this paper represent the contributions of several investigators and collaborating scientists, including chemical analyses by Dr. T. Kotsuro, Deportment of Chemistry, Tokyo Institute of Technology; Dr. H. Matsumoto, Deportment of Geology, Kumamoto University, and Mr. H. Horomuro, Geological Institute, University of Tokyo. Silicate analyses were conducted under the technical supervision of Dr. Kotsuro, at the University of Alaska.

Doto on the petrology and geochemistry of Trident andesites ore from a recently completed University of Alaska doctoral dissertation by Mr. Dipok K. Roy (1967), Geological Survey of Indio; and similar data for the andesites of Wrangell Volcano were token from o master of science dissertation on this topic by Mrs. Jean Furst (1968).

Active Alaskan continental volcanoes and volcanic fields to be discussed in this paper include Mount Wrangell, located on the east margin of the Copper River Basin; Spurr, Redoubt and Iliamna volcanoes, located in the Aleutian Range on the Alaskan Peninsula northwest of Cook Inlet; Augustine, on island volcano near the entrance to Cook Inlet; and several eruptive centers in Kotmoi Notional Monument, including Kotmoi and Trident volcanoes, Novarupta Dome and the ash flow of 1912 in the

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Table 1. Calculated average compositions for andesite and the earth's crust (to 16 km), as compared to a representative Trident andesite.

	Crust (1)	Trident Andesite (2)	Crust (3)	Average Andesite (4)
SiO_2	59.19	60.88	59.07	54.20
Al_2O_3	15.82	16.69	15.22	17.71
TiO_2	0.79	0.54	1.03	1.31
Fe_2O_3	3.41	3.65	3.10	3.48
FeO	3.58	2.91	3.71	5.49
MnO	0.11	0.12	0.11	0.15
MgO	3.30	2.80	3.45	4.36
CaO	3.07	5.77	5.10	7.92
Na_2O	2.05	3.87	3.71	3.67
K_2O	3.93	1.59	3.11	1.11
H_2O	3.02	0.27	1.30	0.86
P_2O_5	0.22	0.13	0.30	0.28
CO_2	0.54	--	0.35	--
		99.97		

(1) Average composition of the earth's crust (to 16 KM) as calculated by Goldschmidt (1933).

(2) Trident andesite (analyst: H. Matsumoto).

(3) Average composition of the igneous rocks (Clarke & Washington, 1924).

(4) Average andesite (Nockolds, 1954).

Valley of 10,000 Smokes.

Wrangell Volcano, located deep within the continental block in interior Alaska, is one of the largest andesitic piles in North America. It is of special interest as it is offset from the main trend of the circum-Pacific volcanic belt.

New and previously unpublished data presented in this paper include chemical analyses of prehistoric andesite flows from the central cone and caldera rim of Wrangell Volcano (Furst, 1968); ejecta from the 1966 eruption of Redoubt Volcano; flows erupted by Trident Volcano during the period 1953-1960 (Roy, 1967); basic and acidic bonds, homogenous core and basic inclusions from Novorupto Dome as extruded in 1912; and prehistoric (pre-Pleistocene) flows from Mount Griggs (Knife Peak).

In the discussion to follow, all andesite data are for analyzed two pyroxene andesites. Data for "hornblende andesites," "basaltic andesites" and other variants were not included in our compilations.

Bulk Chemical Composition of Alaskan Continental Andesites

Table 1 compares calculated average compositions of the earth's crust as proposed by Clarke & Washington (1924) and Goldschmidt (1933) to Nockolds' average andesite (1954), and a representative andesite flow erupted by Mount Trident. The table accents three important points:

1) The gross compositional similarity of Alaskan continental andesites and calculated average compositions of the earth's crust
2) The low SiO_2, high Fe and Co which contrasts Nockolds' average andesite to andesites erupted by circum-Pacific volcanoes

Table 2. Chemical composition and molecular norms; Redoubt, Trident and Wrangell andesites.

	Redoubt #2	Redoubt #3	Trident 1953-54	Wrangell WR2-10a
Chemical Analyses				
SiO_2	59.92	59.72	61.07	59.37
Al_2O_3	17.83	18.20	17.11	17.86
TiO_2	0.65	0.68	0.71	0.63
Fe_2O_3	3.01	3.63	2.43	1.53
FeO	3.13	2.13	3.86	4.56
MnO	0.15	0.14	0.13	0.08
MgO	2.59	2.24	2.95	3.77
CaO	6.70	6.95	6.20	6.10
Na_2O	3.99	4.16	3.71	3.98
K_2O	1.61	1.73	1.40	1.60
H_2O+	0.18	0.30	0.18	0.32
H_2O-	0.05	0.02	0.04	0.34
P_2O_5	0.20	0.21	0.07	0.15
	100.01	100.11	99.86	100.29
$\frac{K_2O}{Na_2O+K_2O}$	.28	.29	.27	.29
Molecular Norms				
Qz	12.15	11.90	14.67	8.96
Or	9.55	10.26	8.34	9.45
Ab	36.00	37.49	33.60	35.73
An	26.12	25.98	26.13	26.14
Di	4.78	5.80	3.55	2.51
Hy	6.88	3.34	9.97	14.39
Mt	3.16	3.80	2.56	1.59
Il	0.90	0.95	0.99	0.87
Ap	0.42	0.44	0.14	0.31
Analyst:	H. Haramura	H. Haramura	H. Matsumoto	H. Matsumoto

Redoubt #2: Cognate hypersthene augite andesite fragment from ejecta of January, 1966, eruptions of Redoubt Volcano.

Redoubt #3: Pumice ejected during explosive eruptions of Redoubt Volcano in January, 1966.

Trident 1953-54: Hypersthene-augite andesite; from a flow erupted by Trident Volcano during the winter of 1953-54.

Wrangell WR2-10a: Hypersthene-augite andesite from the rim of the active crater of Wrangell Volcano.

3) the docitic affinities of Alaskan Peninsula andesites.

Since the Kotmoi eruption of 1912, flows ond ejecta erupted by volcanoes of the northeast Alaskan Peninsula hove been almost exclusively composed of highly siliceous andesites, which show a very interesting convergence in bulk chemical composition. Table 2 compares the bulk chemical composition of the 1953-54 Trident flow ond 1966 Redoubt ejecta to that of the youngest (pre-historic) flow erupted by the octive vent of Wrangell Volcano. There is only a 1.70 wt % range in SiO_2 content shown in these analyses, and the calcium content and the K/No+K ratios are remarkably similar. Inspection of the molecular norms, which ore also listed in Figure 2, further confirms the bulk chemical compositional convergence of the four ondesites.

During our studies of Trident Volcano, we attempted to detect possible short term differentiation in the six flows erupted between 1953 ond 1961. We first examined the variation in analyzed chemical components which was present in samples taken from seven localities on the 1958 flow (Table 3). When these variations were compared to those which were calculated from 17 chemical analyses of andesites token from the six flows, only SiO_2, Fe_2O_3, FeO and CaO variations were statistically admissible as significant compositional changes within the whole suite. These problems ore not further discussed in this paper, but the doto shown in Table 3 should temper our interpretation of silica variation diagrams.

The most important 20th century eruptions of northeastern Alaskan Peninsula volcanoes include:

1) The Kotmoi eruption of 1912; including deposition of the ash flow in the Volley of 10,000 Smokes, and the extrusion of Novarupto Dome.
2) The explosive eruption of Mount Spurr in 1953, which was characterized by the emission of ash charged gas columns, but no lava.
3) The 1953-1960 flows erupted by the new cone of Mount Trident in Kotmoi Notional Monument.
4) The 1966 explosive eruptions of Mount Redoubt, which produced lithic fragments and pumice, but no lova flows.

Table 3. Range in the bulk composition of samples of the 1953-60 Trident andesite flows, as determined for each oxide component.

	LOW		HIGH		RANGE	
	Suite	1958	Suite	1958	Suite	1958
SiO_2	59.84	60.81	63.66	62.48	3.82	1.57
TiO_2	0.51	.51	0.73	.64	0.22	.13
Al_2O_3	16.01	16.03	17.54	17.54	1.53	1.51
Fe_2O_3	1.95	1.95	3.65	3.23	1.70	1.28
FeO	2.91	3.20	4.23	4.23	1.32	1.03
MnO	0.11	.11	0.14	.13	0.03	.02
MgO	2.38	2.42	3.45	3.45	1.07	1.03
CaO	5.51	5.61	6.79	6.35	1.28	.74
Na_2O	3.44	3.67	3.91	3.91	0.47	.24
K_2O	1.31	1.31	1.62	1.62	0.31	.31
P_2O_5	0.07	.12	0.14	.13	0.07	.01

Suite=17 analyses
1958=7 analyses

A flow which was reportedly emitted during the 1963 eruption of Augustine Volcano was apparently a lahar, and it has not been sampled by us. Neither have we studied or sampled a flow erupted by Pavlov Volcano in 1966.

Chemically analyzed samples of flows and ejecta from these various eruptions are plotted on the FMA-CNK diagram shown as Figure 1. Plots for analyses previously given by Fenner (1950) and Wilcox (1955), and the bulk chemical composition of the quartz diorite which forms the subvolcanic basement of Iliamna Volcano (Juhle, 1955) are also shown. Similar quartz diorite also composes the subvolcanic basement of Redoubt and Spurr Volcanoes, to the northeast.

Fenner's work on the ash flow problem and the genesis of Novarupta dome is well known (1923). Although we are principally concerned with andesites in this paper, our findings indicate that the genesis of the dacitic and rhyodacitic phases of the ash flow and Novarupta Dome are also related to the andesite problem. We have, therefore, also plotted Fenner's analyses of Katmai ash and pumice (1926, 1950) and the "light" and "dark bands" from Novarupta Dome (1923). Plots of our analyses of similar Novarupta compositional layers are also on the diagram, and these compositions appear to lie between those of Fenner's samples, thus defining a rather consistent trend which is contiguous with that of the rhyolitic and andesitic pumice and ash which were also collected by Fenner from the ash flow.

These relations are maintained on the equivalent CNK diagram, where a linear trend is defined by an increase in total alkalies at the expense of calcium, without much change in the actual K/Na ratio. Note that the composition of the quartz diorite plots near the calcic end of this curve, and that the bulk composition of the quartz diorite is very similar to that of the 1953 ash from Spurr Volcano (Wilcox, 1955).

In Figure 2 we have plotted the bulk composition of four chemically analyzed Trident andesites and the constituent groundmass glass separated from each of these rocks; and the paired analyses are linked by tie lines. The diagram also includes plots of newly analyzed "basic inclusions" as first described by Fenner in the layered portions of Novarupta Dome, plus a prehistoric andesite flow from nearby Mount Griggs (Knife Peak).

Note that the tie lines describe the same trends as seen in Figure 1, suggesting that the rhyolites, rhyodacites and dacites lie along the same line of liquid descent, and that the derivation of these rocks by fractional crystallization from Trident type andesite magmas is theoretically reasonable. This relationship is reinforced by the CNK plots, in which the tie lines are parallel to the trend seen in Figure 2 as defined by bulk analyses.

In Figure 3 we have compared chemically analyzed samples taken across the east marginal pluton of the Coast Range batholith, to the migmatic gneisses of the west marginal belt collected along the same traverse. The samples taken from the zoned pluton lie along the same trend as that defined by the tie lines (line of liquid descent) and the plots of the series rhyolite to andesite, as previously shown for the Katmai suite.

The more alkaline migmatic gneisses do not plot along this trend, but the two quartz dioritic gneisses are compositionally similar to the Trident andesites.

Figure 4, another FMA-CNK diagram, compares analyzed two-pyroxene andesites from island arc, continental and peninsular tectonic settings around the rim of the northern Pacific. Alaska Peninsula andesites contain less Fe than similar andesites from the Aleutians, Japan, Kamchatka and the Kuriles. The Wrangell andesites plot in a zone which appears to be transitional between the fields defined by andesites from the Alaska Peninsula, the Cascades and Central America.

In the CNK part of the diagram, the plots tend to group in two subfields, as influenced by the higher Na content of andesites from the Alaska Peninsula, the Aleutians, the Cascades and Central America; as contrasted with andesites from Japan, the Kuriles and Ryukyus.

If we examine Na_2O as a function of increasing silica in these same andesites, as shown in Figure 5, the continental andesites define a zone in the Na_2O rich part of the field which approximately parallels the 4 wt. % coordinate of the diagram. While 4 wt. % Na_2O is not an upper limit, the rather abrupt decrease in frequency of plots above this coordinate is intriguing. There is no indication of covariance between increasing SiO_2 and Na_2O in continental andesites; and although the average Na_2O content of Aleutian andesites is similar to that of Alaskan Peninsula andesites, Na_2O shows a tendency to vary sympathetically with increasing SiO_2 content.

When K_2O values are plotted on a similar diagram (Figure 6), one can see a trend toward increasing K_2O with silica for andesites from various settings. Of specific interest, however, is the higher K_2O content of Cascade, Central America and Wrangell andesites as compared to the Alaska Peninsula variants; and the location of the Aleutian plots along the high rather than the low K_2O trend.

In this case, it is questionable as to whether the Aleutian andesites are more or less potassic than

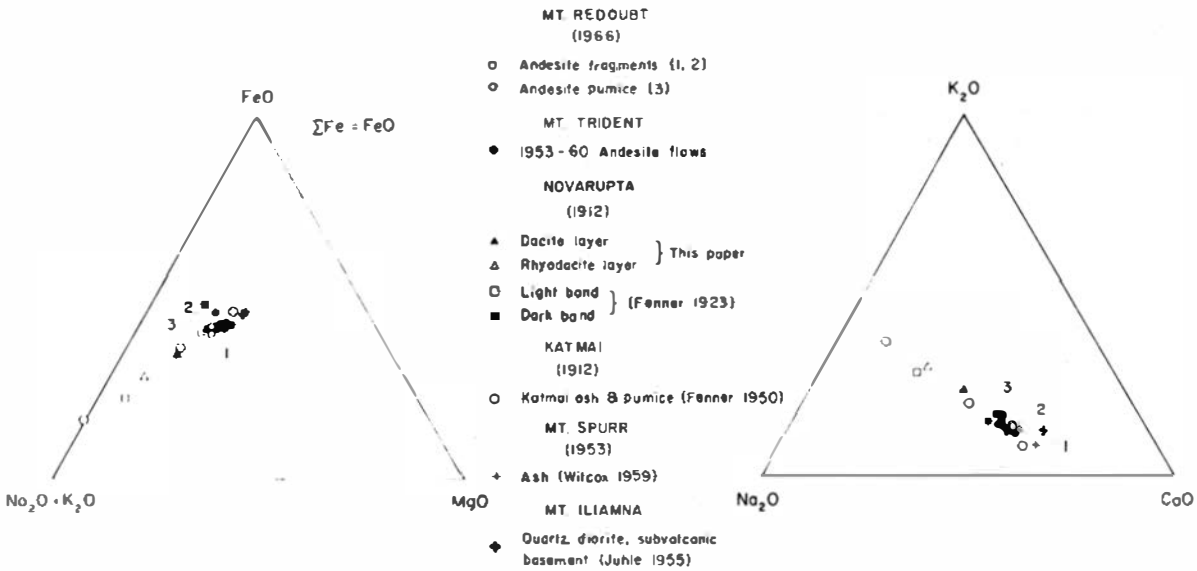

Figure 1. FMA & CNK diagrams showing both chemical composition of historic flows and ejecta erupted by Alaska Peninsula volcanoes since 1912. The mineralogy of the quartz diorite underlying Iliamna Volcano is comparable to that which composes the subvolcanic basement of Mount Redoubt; and the bulk chemical composition is believed to be similar to the analysis plotted on the above diagrams, as taken from Juhle (1955).

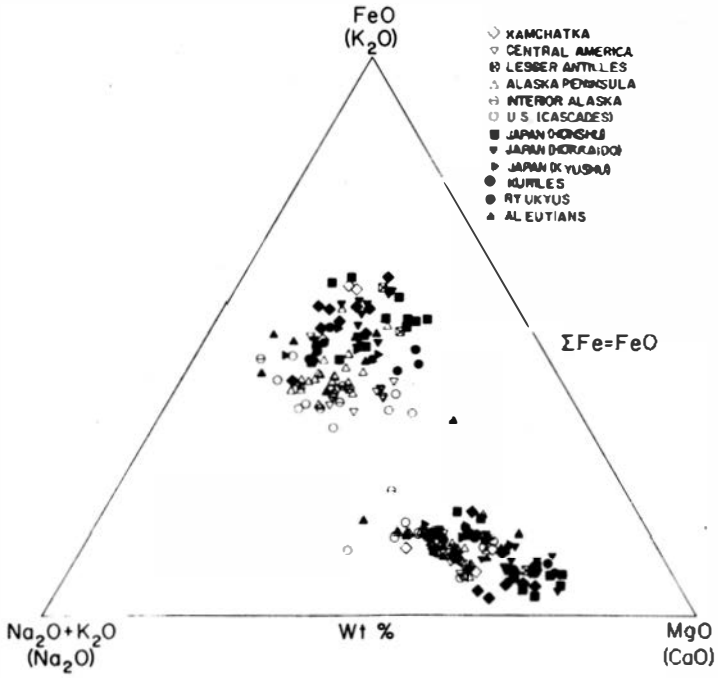

Figure 2. FMA/CNK diagram showing compositions of Trident andesites and constituent glass; compositional layers and basic inclusions from Novarupta Dome, and a basal andesite flow from Mount Griggs.

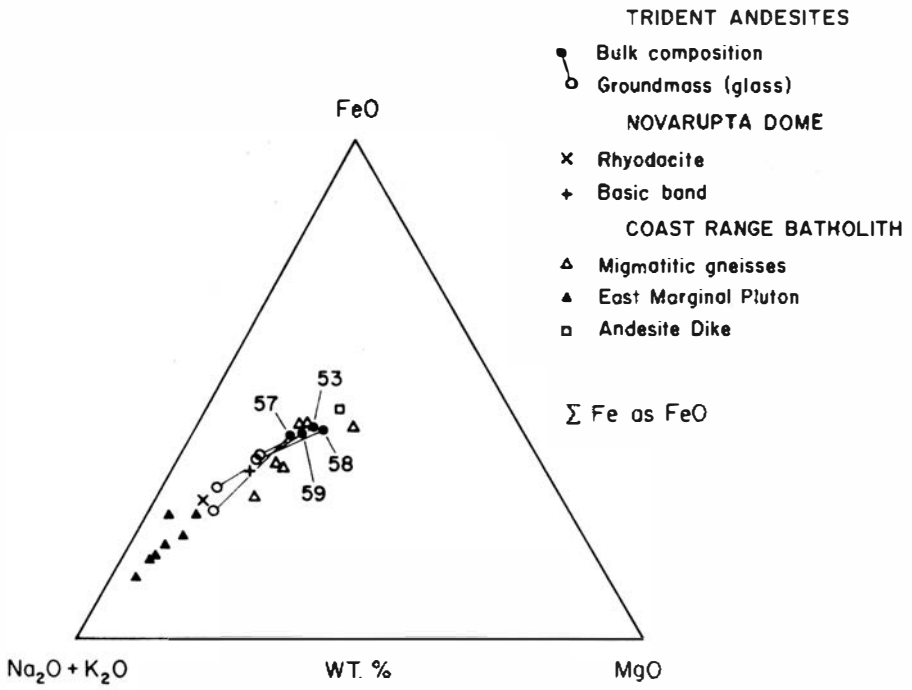

Figure 3. FMA diagram showing line of liquid descent described by tie lines, as compared to compositional fields of magmatic vs. migmatic rocks from the Coast Range Batholith.

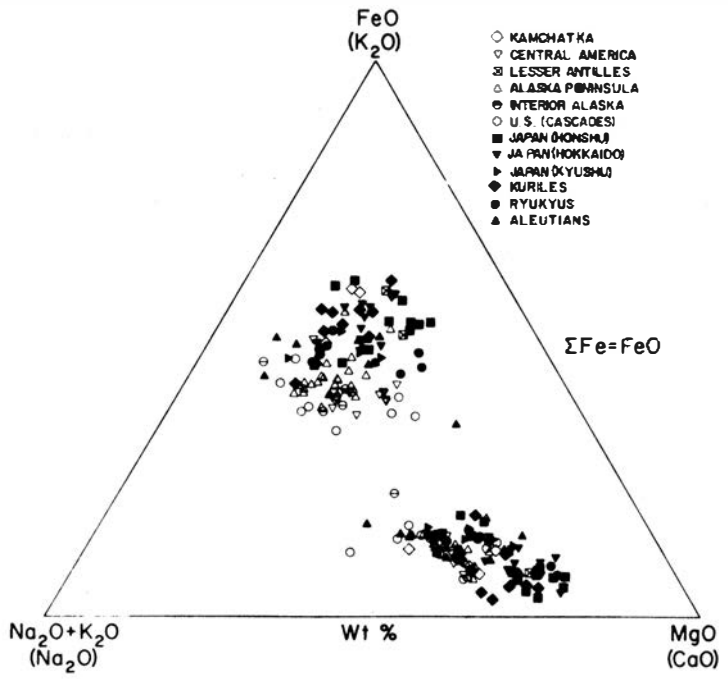

Figure 4. FMA/CNK diagram of chemically analyzed two pyroxene andesites of the North Pacific Rim.

the Alaska Peninsula variants.

Plots of Ryukyu andesites are also coincident with the higher K_2O trend; and when analytical error and sampling difficulties are considered, K_2O seems to be a questionable discriminant for distinguishing island arc versus continental two pyroxene andesites.

The Fe poor trend of continental versus island arc andesites is apparent in the Fe/MgO variation diagram shown as Figure 7. The distinction between Aleutian and Alaskan Peninsula andesites, based on comparative FeO/MgO ratios is not as obvious, but significant.

Summary

Andesites erupted by Alaskan orogenic volcanoes in continental settings from 1912 to the present, are highly siliceous and remarkably similar in bulk chemical composition. Basaltic rocks have not been erupted by these particular volcanoes during historic time; and basalts are not known to exist in important volume in any of these volcanic piles. Chemical analyses of prehistoric flows in these same successions show that the andesites erupted from one vent system tend to be compositionally similar throughout the eruptive history of the volcano or volcanic field, although minor variations in chemical components are of course present.

Basalts appear to have been erupted more frequently in prehistoric and historic time in the Aleutian Archipelago, than from the orogenic volcanoes of the Alaskan Peninsula. This may be of considerable petrogenetic importance, in the argument concerning the origin of andesites in various settings. The variation diagrams discussed above, suggest that Aleutian andesites tend to be more Fe rich than the peninsular variants; and perhaps even more importantly, FeO, Na_2O and K_2O tend to increase with SiO_2 -- variations that could be assigned to differentiation from a basaltic parent. In contrast, however, the Na_2O content of the continental andesites shows an amazing convergence toward 4 wt. %, and little tendency toward sympathetic variance of Na_2O, FeO and increasing SiO_2.

Do these differences in composition and association imply a basaltic parentage for Aleutian andesites (?); and conversely, are the andesites of the Alaskan Peninsula derived from the partial melting or anatexis of lower crustal material? The quartz diorite which composes the sub-volcanic basement of many Alaska Peninsula volcanoes, is compositionally similar to the andesites erupted by these same volcanoes. The genesis of continental andesites from quartz dioritic melts of this same composition requires no manipulation of compositional data, other than remelting pre-existent quartz diorite, or routing the same magma to the surface. Perhaps both quartz diorite and andesites are generated by the anatexis of lower crustal material, which has an average composition similar to that proposed by Clarke and Washington (1924), or Goldschmidt (1933).

Although we are primarily concerned with andesites in this discussion, we believe that our data on the Trident and Novarupta lavas present strong evidence for an andesite parentage for the rhyodacitic and dacitic bands of Novarupta Dome and the pyroclastics of the ash flow in the Valley of 10,000 Smokes. The line of liquid descent which is traced by the whole rock-groundmass glass composition tie lines on the variation diagrams, shows that the rhyodacite and dacite compositions of the ash flow and Novarupta lie on the projection of this trend. Such compositions could be readily formed by simple crystal fractionation of parent magma which had the bulk composition of a typical Trident andesite. The compositions of basic inclusions from the rhyodacites of Novarupta Dome, which are also plotted on the FMA-CNK diagram shown as Figure 2, are basaltic rather than andesitic. These inclusions have diabasic textures, and appear to have a non-cognate origin.

Data for the North Pacific Rim do show that continental andesites are more alkaline than those of the island arcs, but there is a broad overlap in the K_2O content of Alaskan andesites from both settings; and even though continental andesites appear to have a very restricted range in Na_2O content some of the Aleutian two pyroxene andesites have Na_2O concentrations exceeding 4.0 wt. %. If we confine our data to those from two pyroxene andesites in the Alaskan settings, neither K_2O nor Na_2O appear to be statistically reliable as Alaskan geographical discriminants.

We hope that the data presented in this paper will be useful to colleagues who are also involved in various aspects of the andesite problem. The petrogenetic questions raised in this paper cannot, of course, be adequately solved or assessed with the data available to us at this date. We hope to present more detailed analyses of the problems discussed in this paper, as our work continues.

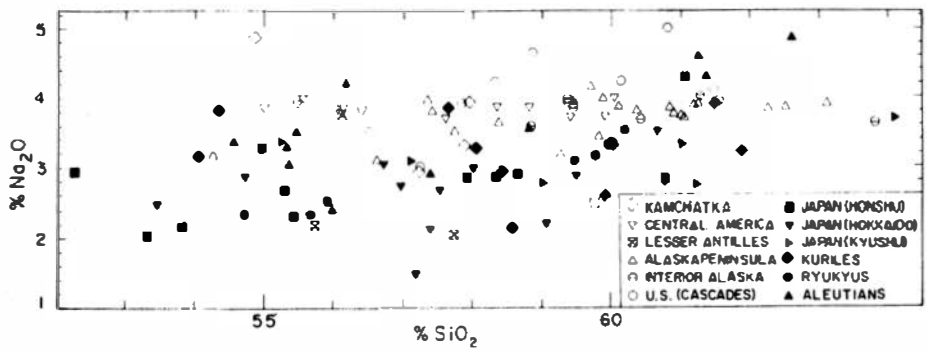

Figure 5. Na_2O/SiO_2 variation diagram of chemically analyzed two pyroxene andesites of the North Pacific Rim.

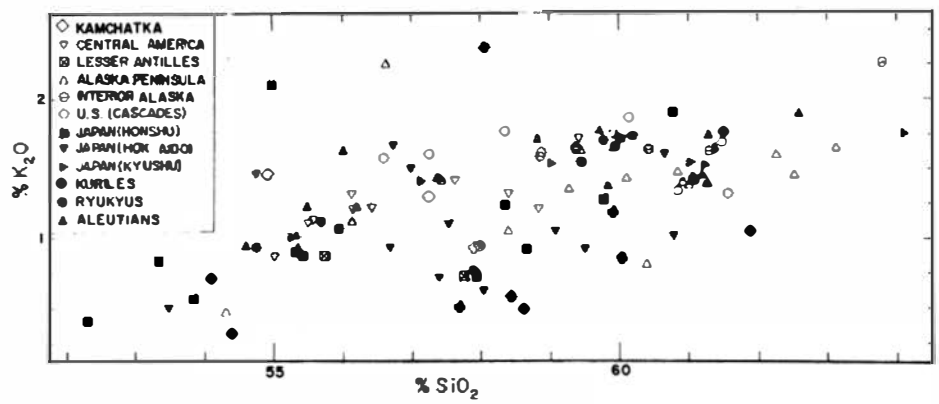

Figure 6. K_2O/SiO_2 variation diagram of chemically analyzed two pyroxene andesites of the North Pacific Rim.

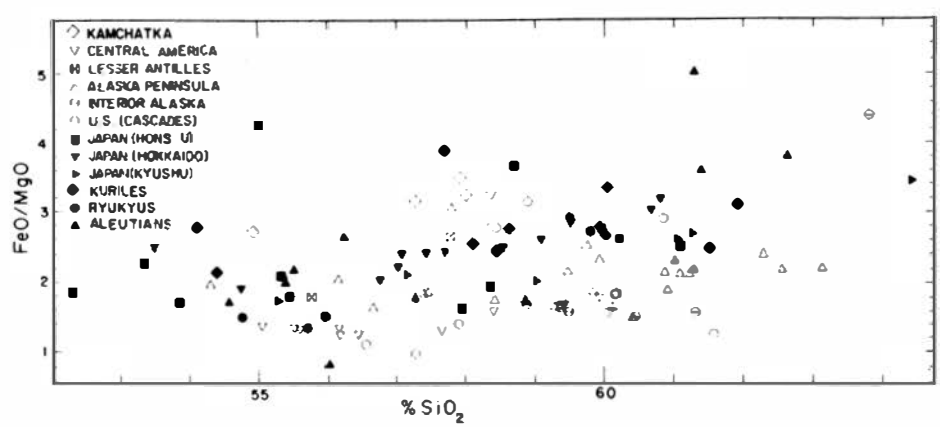

Figure 7. $\frac{FeO/MgO}{SiO_2}$ variation diagram of chemically analyzed two pyroxene andesites of the North Pacific Rim.

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ANDESITES AND ARCHEAN VOLCANISM OF THE CANADIAN SHIELD

W. R. A. Borogor* and A. M. Goodwin*

Introduction

Andesites are widely recognized as the characteristic and most abundant volcanic rocks of the calc-alkaline suite so typical of orogenic belts (Taylor and White, 1965; Taylor, 1967; Green and Ringwood, 1966). They are absent from the oceanic regions, except for the island arcs (MacDonald, 1960) and for this reason are of special interest to students of continental origin. Much of our knowledge of andesites and indeed the calc-alkaline suite as a whole derives from studies in the circumpacific belt where the phenomena of active volcanoes has undoubtedly spurred investigation. In this report an attempt is made to redress the balance to some extent by presenting data from Archean orogenic belts of the Canadian Shield.

At the present stage of research into the origins of calc-alkaline volcanism it is highly desirable to have some quantitative data on average compositions and the distribution of compositions of volcanic assemblages in orogenic belts. Andesites are assumed to be the dominant rock type but can we be sure that this is actually the case; or that this is not just a special attribute of the circumpacific belt? Is it further possible that sampling has tended to favour the upper parts of the circumpacific volcanic assemblage thus biasing the results towards a more siliceous average composition. Volcanic belts in the Canadian Shield have some advantages in this regard. Commonly very thick assemblages of volcanic rocks have been tilted to steep angles and bevelled by erosion so that now they are accessible in all parts and amenable to systematic sampling. In this paper we present the results of our attempts at systematic sampling in four widely scattered volcanic belts of the Superior and Slave Provinces of the Canadian Shield. The data of each volcanic belt are grouped so as to present four aspects of their petrochemistry: 1) the relative abundances of five petrographic classes representing the compositional range of the calc-alkaline series; 2) the average composition of each class; 3) a comparison of compositions and classes in the upper and lower parts of a number of thick sections; and 4) the average compositions. Thus we intend to provide some quantitative measure of the composition of Archean volcanic belts in particular and possibly of some aspects of calc-alkaline volcanism in general.

Some of the studies upon which this report is based have already been published and the reader is referred to these for greater detail (Goodwin, 1965, 1967; Borogor, 1966, 1968).

Geology of Archean Volcanic Belts

Archean greenstone belts of predominant volcanic composition are widespread in the Canadian Shield. Although most common in the Superior Province they also occur in the Slave and Churchill Provinces as illustrated in Figure 1. The belts characteristically strike easterly, northeasterly, and northerly in the Superior, Churchill and Slave Provinces respectively. They vary greatly in size and shape. The largest continuous belt which lies in the southern part of the Superior Province is 400 miles long and 60 miles broad. Of the four belts discussed below one (Yellowknife) is in the Slave Province, two (Birch-Uchi and Lake of the Woods) in the western part of the Superior Province and one (Timmins-Noranda) in the eastern part of the Superior Province.

A variety of volcanic rocks is present in the volcanic belts. Mafic to salic flows and pyroclastics of calc-alkaline chemical affinity predominate but some alkalic rocks are present at Kirkland Lake. Basalt flows and associated mafic intrusions are particularly common in the lower parts of the volcanic

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* Geological Survey of Canada.

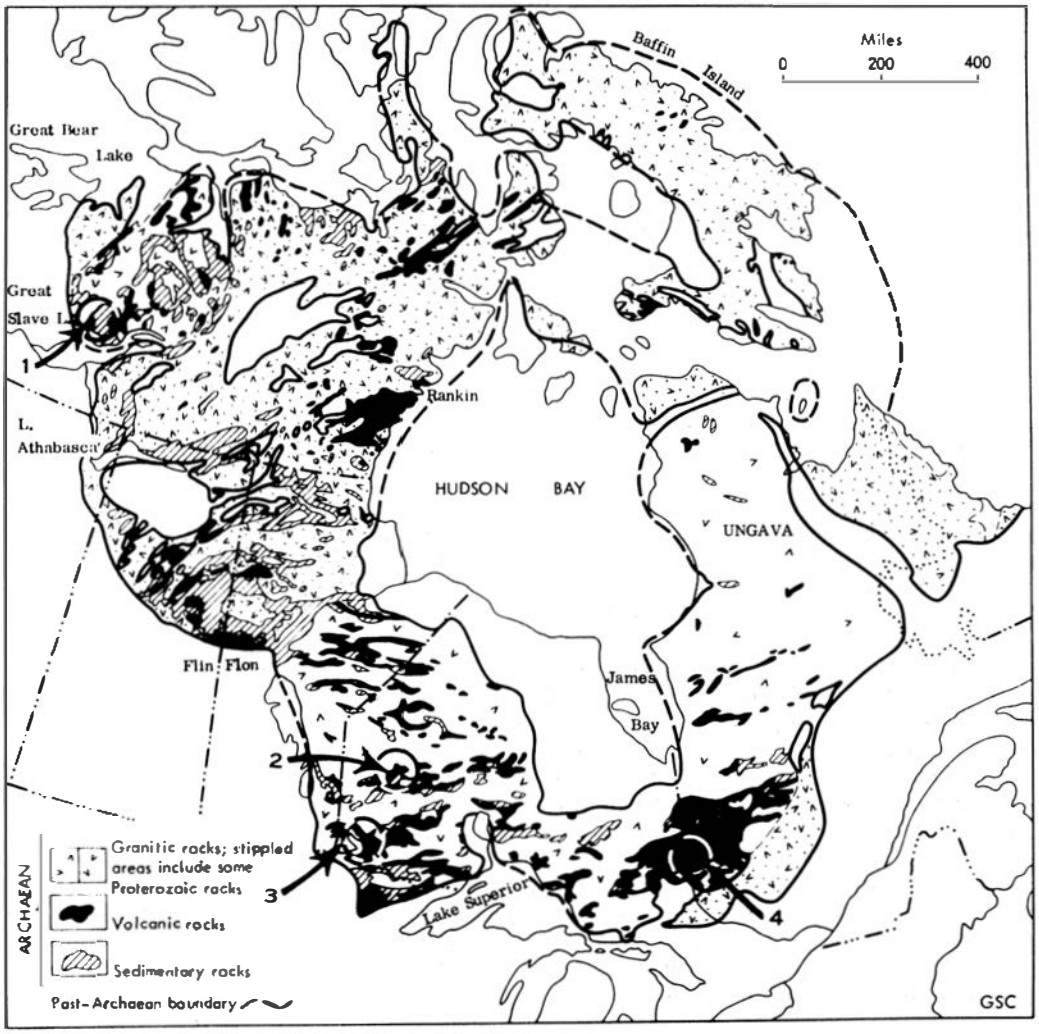

Figure 1. Map of the Canadian Shield showing the distribution of Archean volcanic belts. The four belts considered in this report (encircled and indicated by arrows) are: 1. Yellowknife-Cameron River, 2. Birch-Uchi, 3. Lake of the Woods-Wabigoon, and 4. Timmins-Noranda.

assemblages. Andesitic flows and pyroclastics are intercalated with basalt and, in many assemblages, increase proportionately upwards. Salic rocks, mainly pyroclastic deposits but locally lava flows, are generally present in the upper stratigraphic parts of the volcanic assemblages. Many of the assemblages display a single generalized mafic to salic sequence of this type. Others comprise a mafic to salic sequence together with overlying mafic rocks. Still others contain two or more superimposed mafic to salic sequences. Within the volcanic belts the salic rocks are commonly concentrated in clusters, probably marking ancient volcanic centres, whereas the mafic components are more broadly and evenly distributed. The form and structures of the Archean volcanic rocks are indicative of their accumulation in a predominantly subaqueous environment.

A combination of steeply folded strata and fresh, bevelled surfaces provides excellent cross-sections of the volcanic accumulations to deep stratigraphic zones. As a result nearly complete volcanic

piles are presented for study of their sequential development from birth to death. In this respect Archean volcanic piles offer unique advantages compared with modern equivalents.

Nearly all the Archean volcanic rocks have been metamorphosed to some extent. The intensity of metamorphism varies greatly in different parts of the Canadian Shield and even in different parts of a volcanic belt. It is remarkably slight in many volcanic belts of the Superior Province. Although mineralogically altered these volcanic rocks have retained original textures and structures to a remarkable degree. Thus, in rocks of appropriate composition spherulitic, vesicular, perlitic, pumiceous, ophitic, and porphyritic textures of most delicate form are well preserved in places as are shards, pillows, and columnar structures. Chemical alteration appears to have been slight. The volcanic belts under discussion are typically of greenschist metamorphic grade or lower with the exception of the Yellowknife belt. In other volcanic belts of the Canadian Shield amphibolitic and even granulitic facies are common.

Methods

Each of the volcanic assemblages discussed here was sampled throughout its exposed thickness at more or less regular stratigraphic intervals along two or more section lines. The interval varied somewhat according to our individual interests. One of us (WRAB) was primarily interested in vertical variations in composition and sampled at stratigraphic intervals of 400-500 feet; the other (AMG) was also concerned with lateral variations and sampled at stratigraphic intervals of about 1200 feet in a greater number of sections. Both of us were concerned with obtaining from each section a collection of samples as representative of the section as possible. The positioning of section lines was governed by the need for 1) reasonably thick sections, 2) high proportions of outcrop, and 3) a fairly representative distribution of section lines.

Most of the samples are composite in the sense that they were collected across a limited stratigraphic thickness and are not hand specimens. The stratigraphic thickness represented by a samplewould normally be a matter of a few feet. Care was taken to exclude all weathered surfaces.

The major elements in the samples were analyzed by rapid methods; Si, Al, Mg, Fe (total), Mn, Ca, K, and Ti by X-ray spectrometer and Na, Fe, P, CO_2, and H_2O by chemical methods. The analyses were performed in laboratories at the Geological Survey of Canada, the Ontario Department of Mines, and the Geology Department, University of Manitoba. All trace elements were analysed by spectrograph in the Geological Survey laboratory.

It is difficult to make an assessment of the accuracy of the results. The estimates provided by the various laboratories differ from one another and in any event are applicable to single analyses only. In this paper we are concerned with average analyses where much of the error contained in individual analyses is presumably cancelled out. An unpublished study by one of us (WRAB) on analyses of the Yellowknife belt and of the Duparquet-Aiguebelle sections at Noranda provides an indication of the accuracy to be expected. For each of the Yellowknife and Duparquet-Aiguebelle sections composite samples were made up of equal quantities of a number of samples for which individual rapid-method analyses were available. The samples composing each composite sample were in themselves of fairly uniform composition but the composite samples spanned the range of compositions present. Each composite sample was analysed by classical methods and the results compared with the average of the rapid-method analyses of individual samples forming the composite. In this way it was hoped that cancelling errors would disappear and only the true bias would remain. Some systematic bias was found to be present in both suites. The approximate maximum departures of the rapid from the classical results are as follows: (+ if the classical is larger, - if it is smaller, and + and - where it ranges from larger to smaller in different parts of the compositional range): Yellowknife; SiO_2 -.6 to + 1.0, Al_2O_3 +.7, Fe_2O_3 -.5, FeO -.3, MgO +1.3, CaO -.3 to +.6, Na_2O -.3, K_2O 0, TiO_2 +.2, Duparquet-Aiguebelle; SiO_2 +1.4, Al_2O_3 0, Fe_2O_3 +.6, FeO -.3, MgO - 1.3, to +.5, CaO +.4 Na_2O -.2, K_2O 0, TiO_2 0. Adjustments have been made to the Yellowknife and Duparquet-Aiguebelle analyses used in the present report.

The spectrographic analyses are expected by the laboratory to have accuracies as follows: Sr, Ba, Cr, Zr, V, Ni, Cu, Y, Co, Sc, ± 15%; Zn, Pb, Ga, Sn, Ag, ± 30%. As pointed out above, error in the averages is likely to be considerably less.

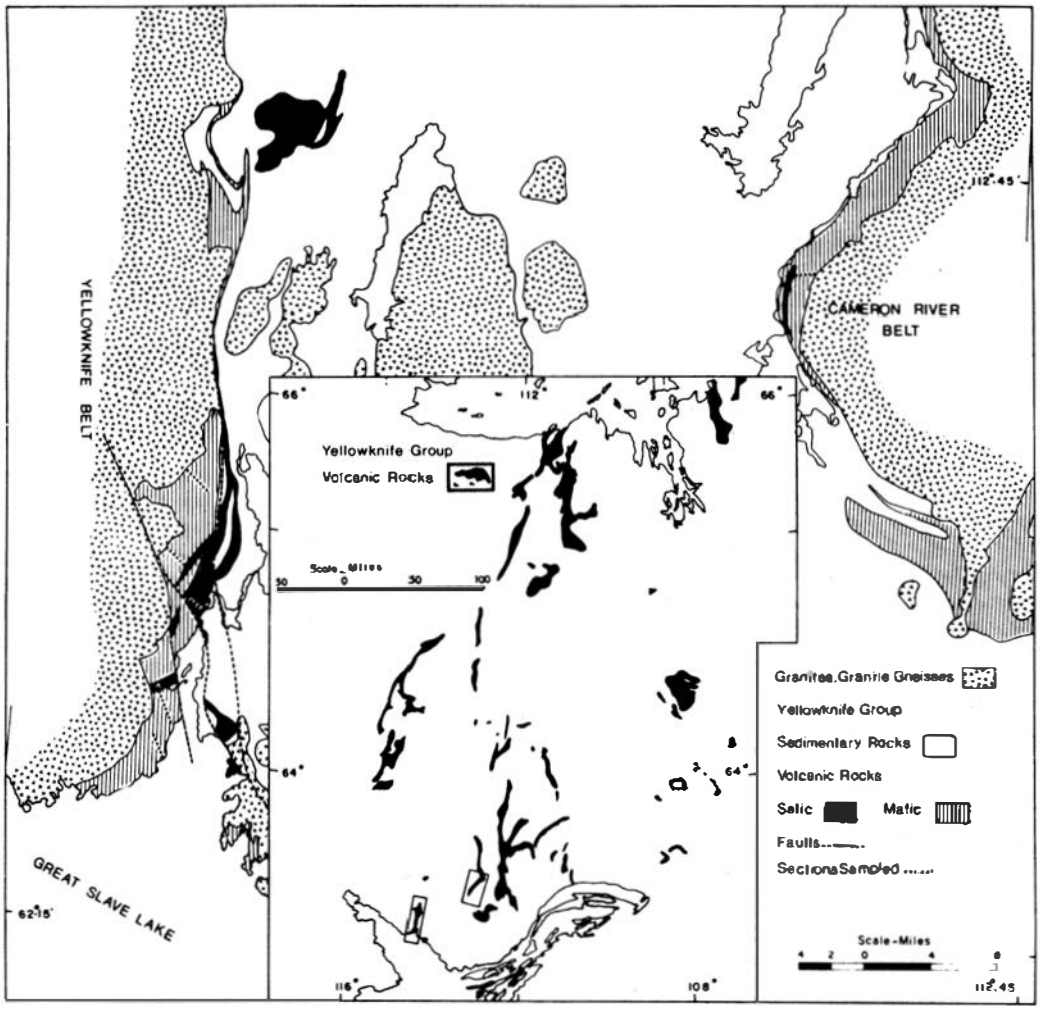

Figure 2. Geological map of the Yellowknife-Cameron River region showing location of sampled sections. The inset map shows the distribution of Yellowknife Group volcanic rocks in the Slave Province of the Canadian Shield. The Yellowknife and Cameron River belts are outlined.

Summaries of Geology and Sampling Procedures in Individual Belts

The Yellowknife Group

The Yellowknife Group, composed of an older volcanic and younger sedimentary formation, is widely distributed in the Slave Province of the Canadian Shield (Fig. 1). The inset map of Figure 2 shows the distribution of the volcanic part of the Group.

The volcanic rocks are generally divisible into two mappable, lithologic types; mafic lavas which form the bulk of the deposits, and felsic lavas and pyroclastics that vary in abundance from place to place but in total form a small fraction of the volcanic assemblage. Pillow lavas are characteristic of the mafic assemblages in most places. Metamorphism in the volcanic rocks is of greenschist or amphibolite grade - more commonly the latter and primary structures vary in their state of preservation from almost undisturbed to complete obliteration.

The Yellowknife and Cameron River volcanic belts (Fig. 2) are among the least disturbed and best known of all the scattered remnants of Yellowknife Group volcanic rocks and are probably closest in composition to the original magma. Both belts were closely sampled. The details of sampling and generalized results have been previously reported (Baragar, 1966) but may be summarized briefly below.

The Yellowknife belt comprises a thick homoclinal succession of volcanic rocks that dips steeply east to southeast and faces in the same direction. Faulting has segmented the volcanic belt but excellent geological work by previous workers* has made correlation between segments possible and enabled one of us (WRAB) to sample a nearly continuous section of volcanic rocks over 40,000 feet thick. The volcanic assemblage is composed of mafic lavas with felsic layers located at about half the thickness of the section and at its top. The upper felsic layer overlies the remainder of the section unconformably and is separated from it by a few hundred feet of sediments. In turn it is overlain by the upper sedimentary layer of the Yellowknife Group. The unconformity is probably of minor significance because elsewhere the upper and lower formations of the Yellowknife Group are invariably conformable. The upper felsic layer is therefore assumed to be part of the same sequence as the assemblage it overlies.

The Cameron River belt consists of a steeply dipping, west-facing assemblage that is about 9000 feet thick. It is composed of mafic lavas except for a single felsic layer and felsic fragmental rocks in the upper part of the section.

Both assemblages were sampled along the section lines shown in Figure 2 at intervals equivalent to about 500 feet stratigraphically. The resulting chemical data showed that in the Yellowknife belt the acidity of the lavas (measured by the differentiation index) increases steadily upward to a culmination in the lower felsic member then repeats the pattern with a second culmination in the upper member. The trend in the Cameron River section is indistinct but tends towards the same pattern.

Birch-Uchi Area

This area which is 80 miles by 40 miles in dimension and located 40 miles east of Red Lake, Ontario lies in the west part of the Superior Province. The Birch-Uchi area is underlain by an older metasedimentary assemblage of the Slate Lake Group and a younger predominantly volcanic assemblage of the Uchi Group.

Slate Lake sediments underlie the southeast part of the area. They comprise a predominantly fine-grained, bedded, arenaceous sequence of greywacke, impure quartzite, arkose, shale and derived schists and gneisses with intercalated and mutually associated banded iron formation, conglomerate and volcanic rocks.

The Uchi Group comprises mafic to felsic volcanic rocks and associated sediments with derived schists. The rocks form a complex synclinorium the axis of which trends northeasterly across the area. Thick stratigraphic sections are exposed in both limbs. The average stratigraphic thickness of volcanic rocks exposed in the fold limbs is 31,000 feet. Felsic volcanic rocks are concentrated along the centre part and top of the stratigraphic sections. On this basis the Uchi Group is divided into lower and upper sequences. Within each sequence basalt predominates in the lower part, andesite content is proportionately higher in the upper part, and felsic volcanics are present at the top. Sedimentary rocks are commonly associated with the felsic rocks. The stratigraphic sequence is fully preserved only in the southern part of the area. To the north the upper stratigraphic parts are missing.

The Uchi volcanic assemblage was sampled along six main section lines as shown in Figure 3. The resulting chemical data confirm the upward increase in acidity of the volcanic components within both sequences and particularly the lower sequence.

Lake of the Woods - Wabigoon Area

This area, approximately 150 miles long and 50 miles wide, is situated 150 miles south of the Birch-Uchi area in the western part of the Superior Province (Fig. 1). The area is underlain by a complex assemblage of volcanic and sedimentary rocks, local mafix masses, and numerous large granitoid intrusions (Fig. 4).

The structure of the area is complex. A pattern of domes has been superimposed upon pre-existing east-trending folds. The domes are occupied by granitic intrusions and the intervening troughs by volcanic-sedimentary rocks.

Volcanic-sedimentary assemblages in the western half of the area were defined originally by A. C. Lawson as belonging to the Keewatin "series." Since that time detailed studies mainly by

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* For the sake of brevity, lists of previous workers in the four areas under discussion have been omitted. This is intended in no way to detract from our indebtedness for this essential work as previously acknowledged in the appropriate publications (see Goodwin, 1965, 1967; Baragar, 1966, 1968).

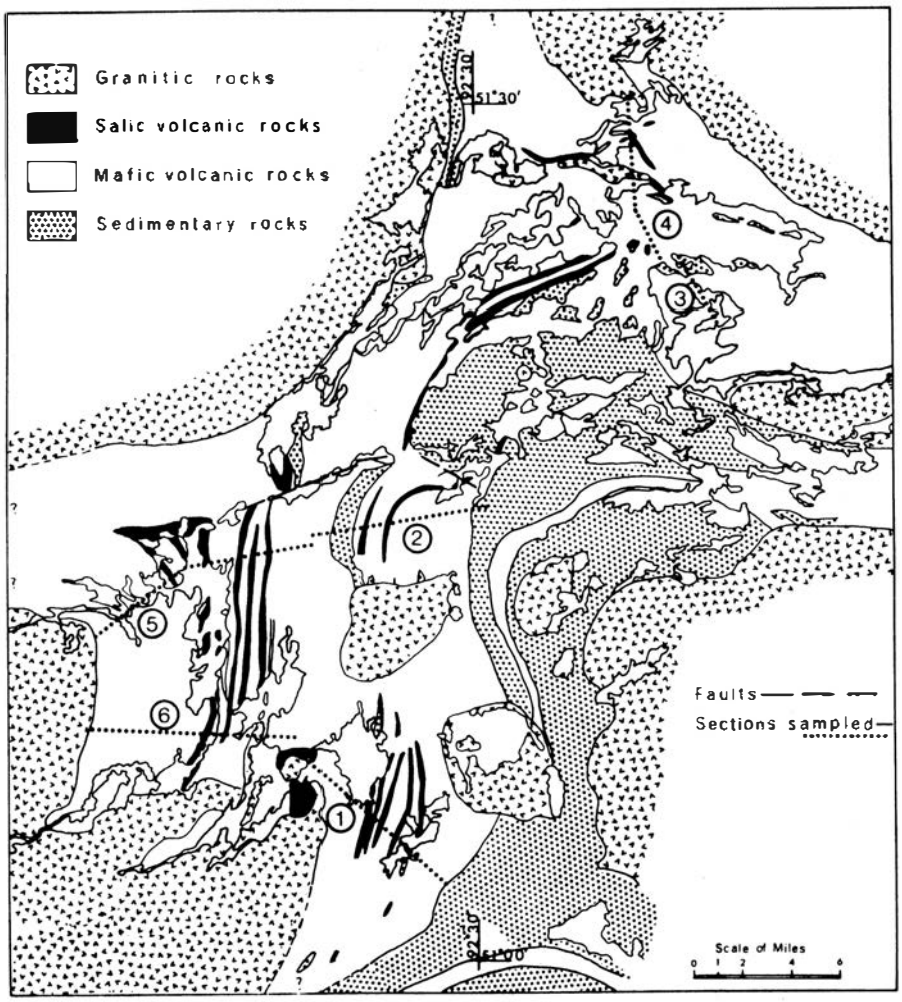

Figure 3. Geological map of the Birch-Uchi Lakes area showing the locations of sampled sections. 1. Uchi Lake, 2. Grace Lake, 3. Springpole Lake, 4. Birch Lake, 5. North Woman Lake, 6. South Woman Lake. Sections 1 and 4 were used in combination to provide compositions for upper and lower parts of the succession. (Table II, Fig. 8.)

geologists of the Ontario Department of Mines and the Geological Survey of Canada have provided the basis for assigning all Archean volcanic and sedimentary rocks of the area to the Keewatin Group.

The Keewatin Group is of diverse, mainly volcanic composition. Mafic flows predominate. Salic volcanic rocks are distributed in irregular clusters as at Shoal Lake, Lake of the Woods and Kokagi Lake (Fig. 4). Sedimentary intercalations include conglomerate, greywacke, arkose, shale and metamorphic equivalents. This leads to the concept of a mixture of volcanic and sedimentary materials deposited contemporaneously in diverse and shifting relationships, a view cogently and accurately expressed by A. C. Lawson (1885, pp. 101-102).

Despite the stratigraphic and structural complexities alternations of lithic types are readily discernible. The typical volcanic sequence contains predominantly basalt in the lower and andesite in the upper parts; salic volcanic concentrations are present at the top. Two such superimposed mafic-to-salic sequences are present in the Shoal Lake - Lake of the Woods part of the area. Elsewhere only one such volcanic sequence is present, the probable equivalent of the lower volcanic sequence to the west.

Stratigraphic thicknesses are between 21,800 and 28,500 feet and average 23,000 feet for the area at large. Thick volcanic sequences were sampled along nine main stratigraphic sections as illustrated in Figure 4. A total of 389 samples were taken along the section lines. The resulting chemical

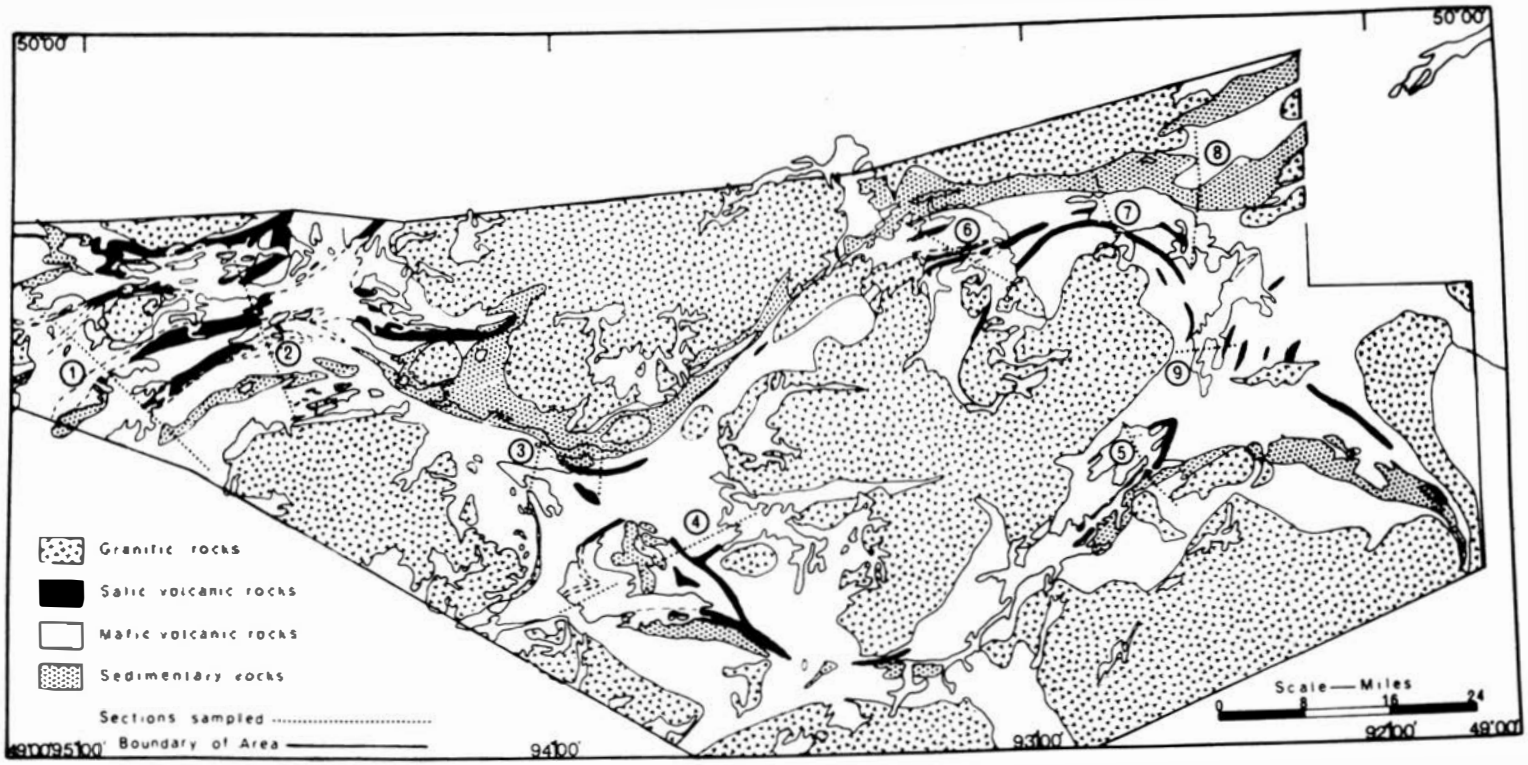

Figure 4. Geological map of the Lake of the Woods - Wabigoon area showing the locations of sampled sections. 1. Shool Lake, 2. Lake of the Woods, 3. Sioux Narrows, 4. Kakagi-Rowan Lakes, 5. Manitou Lake, 6. Eagle Lake, 7-9. Wabigoon Lake. Section 2 provided the compositions for upper and lower parts of the succession (Table II, Fig. 8).

date establish the volcanic classes present in the area and show that within a single volcanic sequence the acidity of the volcanic rocks increases upward.

Timmins - Noranda Area

This area is situated in the southeast corner of the Superior Province (Fig. 1). It is 140 miles long and 35 miles wide and includes Timmins in the west and Rouyn - Noranda in the east. The Kirkland Lake area adjoining on the south is excluded.

The Timmins - Noranda area has been studied by many able geologists of the Ontario and Quebec Departments and Geological Survey of Canada. Archean rocks comprise mainly mafic to felsic volcanic assemblages, sedimentary rocks and younger granitic intrusions (Fig. 5). The volcanic and sedimentary rocks have been complexly folded about mainly east-trending axes. In the central part of the area volcanic strata are distributed about a main east-trending synclinal axis. As a result thick continuous stratigraphic sections of as much as 40,000 feet are exposed especially along the north limb. In the eastern part (Rouyn - Noranda) and western part (Timmins) of the area the fold patterns are more complex and variable. Two major east-trending faults are present in the area. One transects the north part (Fig. 5). The other forms the north boundary of metasediments (Pontiac Group) in the southeastern part.

Thick volcanic assemblages are present throughout the area. Mafic flows predominate. Solic flows and pyroclastics are concentrated mainly near Rouyn - Noranda in the east and Timmins in the west. Several thin continuous intermittently spherulitic salic volcanic zones serve as stratigraphic markers in the north-central part. The volcanic assemblages typically grade from mafic to more salic sequences upward; basalt predominates in the lower and andesite in the upper parts. Solic rocks where present are concentrated in the upper part. Both low-alumina and high-alumina mafic rocks are present; the latter preferentially in the upper part of the sequence.

Sediments are interstratified with volcanic rocks northeast of Rouyn - Noranda. To the west near Timmins a thick sedimentary assemblage overlies volcanic rocks.

Volcanic assemblages of the area were sampled along nine main sections (Fig. 5) at intervals of 500 to 1200 feet. Two hundred and ninety-nine analyses of samples from this area contribute to the chemical data presented in this report.

Classification of Volcanic Rocks

In attempting to determine the proportions of different types in any igneous assemblage the investigator immediately encounters the problems of classification. For us the difficulties are compounded by the fact that our volcanic rocks rarely contain primary minerals, the basis for most accepted classifications. Accordingly, our first step was to adopt normative minerals in place of modal minerals with the hope that the resulting rock divisions would be approximately equivalent to those which would have resulted from the use of modal minerals. This is probably a reasonable assumption. The next step was to adopt a classification that has the largest possible measure of acceptance. Because of the predominance of mafic rocks in the assemblages with which we are dealing our prime concern is with divisions in the intermediate to mafic field. The method of classification finally adopted is illustrated in Figures 6 and 7 and the reasons for its adoption are given below.

Both colour index and plagioclase composition are in wide use as basic elements in the subdivision of intermediate to mafic volcanic rocks. Among users of the plagioclase-based classification there is almost universal agreement that andesites are characterized by andesine and basalts by a plagioclase more calcic than An_{50}, commonly labradorite. There is less agreement among advocates of the colour index-based classification. Kuno (1950, p. 958, personal communication) uses colour indexes of 35-37 and 10 as the mafic and salic boundaries respectively of the andesite field. Rittmann (1962, p. 100) followed by Streckeisen (1967) divides andesites and basalts at a colour index of 40. Moorhouse (unpublished study, 1967) found that a colour index of 27 could be used as the point of primary division for all volcanic rocks represented in Washington's tables. His illustrations indicate that a colour index of 30 would effectively separate andesites and basalts.

In the classification presented in Figures 6 and 7 we have attempted to separate those fields in which classification is fairly unequivocal from those in which it may be debatable. It is assumed that few people would question as andesites, volcanic rocks which contain andesine plagioclase and colour index between 35 and 10 and similarly, as basalts those rocks with plagioclase more calcic than An_{50} and colour index greater than 30. The choice of 30 in the latter case may not be fully accepted but in

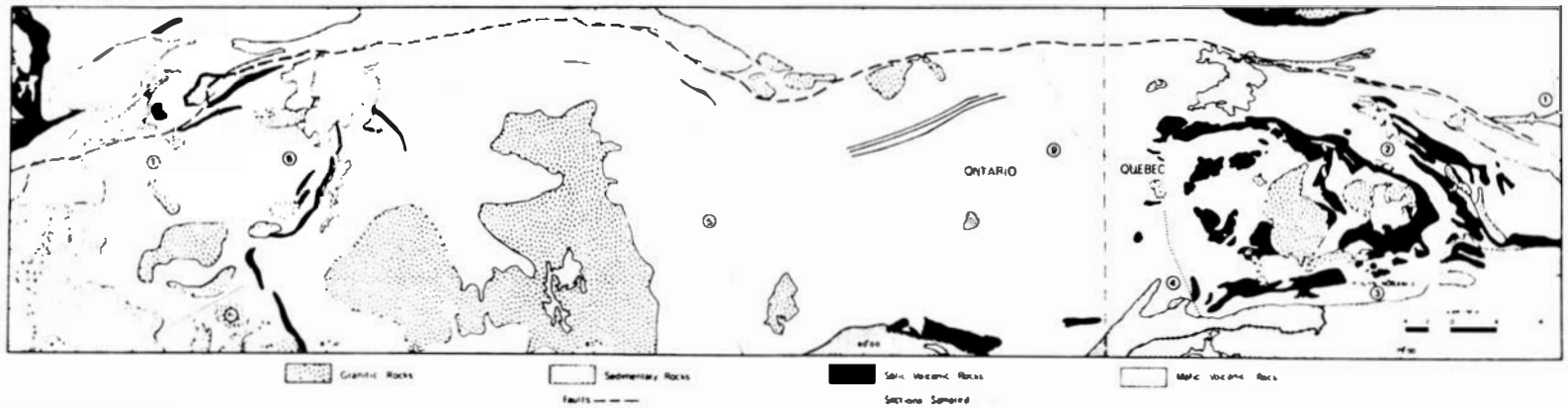

Figure 5. Geological map of the Timmins - Noranda area showing locations of sampled sections.
1. Aiguebelle, 2-4. Waite - Dosserot sections, 5. Kenogomi - Matheson,
6. Redstone River, 7. Tisdale, 8. Delara, 9. Duporquet.

TABLE I. ABUNDANCES OF VOLCANIC CLASSES IN EACH BELT
(in per cent)

	Basalt	Andesite	A	B	Salics
Birch-Uchi	49.5	22.0	8.3	7.2	13.0
Lake of the Woods-Wabigoon	48.1	21.2	14.2	4.6	11.9
Timmins-Noranda	34.4	30.4	20.5	6.7	8.0
Yellowknife	60.3	18.4	5.7	1.8	13.8
Average Archean	48.0	23.0	12.2	5.1	11.7

view of the distribution of our data and the findings of Moorhouse it seems to be a reasonable one. On the other hand, rocks which fall into field A would be classed as either basalts or both basalts and andesites by the proponents of classification by colour index (depending upon whether a colour index of 35 or 40 were used) and as andesites by supporters of the plagioclase method. Field B presents the reverse situation. All other rocks are collectively catagorized as salic rocks and no attempt has been made to subdivide them further. The salic rocks thus defined essentially coincide with those rocks that can be separated from the mafic lavas in the field and mapped as distinctive units.

In the remainder of the report we propose to consider our data on Archean volcanic rocks of the Canadian Shield within the framework of these five categories.

Abundances of Volcanic Classes

The abundances of mafic volcanic classes in each of the four belts shown in Table 1 are basedon stratigraphic proportions established in the field supported by large numbers of chemical analyses. Volcanic units were sampled either at regular intervals along the section lines or in accord with recognizable lithologic changes in the stratigraphic successions. Sufficient dataare available in our opinion to provide a reasonably accurate estimate of relative abundances in the four belts.

It was decided to base the proportion of salic rocks in the belts on previous geological mapping where possible rather than on the proportion of salic rocks in the stratigraphic sections studied in the field which might not be representative of the entire belt. Accordingly the proportions of salic rocks relative to mafic rocks shown for the Timmins-Noranda belt (Fig. 5) and Yellowknife Group (Fig. 2) were determined by planimeter surveys. In each case an attempt was made to compensate for the local dip so as to represent the proportion of salic to total volcanic rocks as they would appear in true stratigraphic perspective. The attempt can only be partly successful as it is based upon incomplete field data but it undoubtedly provides a better estimate than the planimeter data alone. The resulting proportion of 8 percent salic rocks, for the Timmins-Noranda belt and of 13.8 percent for the Yellowknife belt compare closely with an estimated 9 and 12 percent respectively based upon the stratigraphic proportion of salic rocks in the main sections. In the case of the Birch-Uchi and Lake of the Woods-Wabigoon belts it is known that the bands of acidic rocks as previously mapped contain substantial mafic intercalations and that the planimeter surveys therefore exaggerate the proportions of salic rocks. Instead the average salic content of these two belts was estimated on the basis of stratigraphic proportions in the main section lines. The resulting proportions of 13.0 percent salic rocks in the Birch-Uchi belt and 11.9 percent salic rocks in the Lake of the Woods-Wabigoon belt are viewed as reasonably accurate estimates.

The abundances of volcanic classes in the four belts are generally uniform. The order of abundance (with the average percent in brackets) is: basalt (48.0), andesite (23.0), class A (12.2), class B (5.1) and salics (11.7). Thus basaltic rocks (basalt and class A) comprise approximately 60 percent, andesitic rocks (andesite and class B) approximately 28 percent, and salic rocks approximately 12 percent of the volcanic assemblages in the belts. Classes A and B combined are substantially greater in the

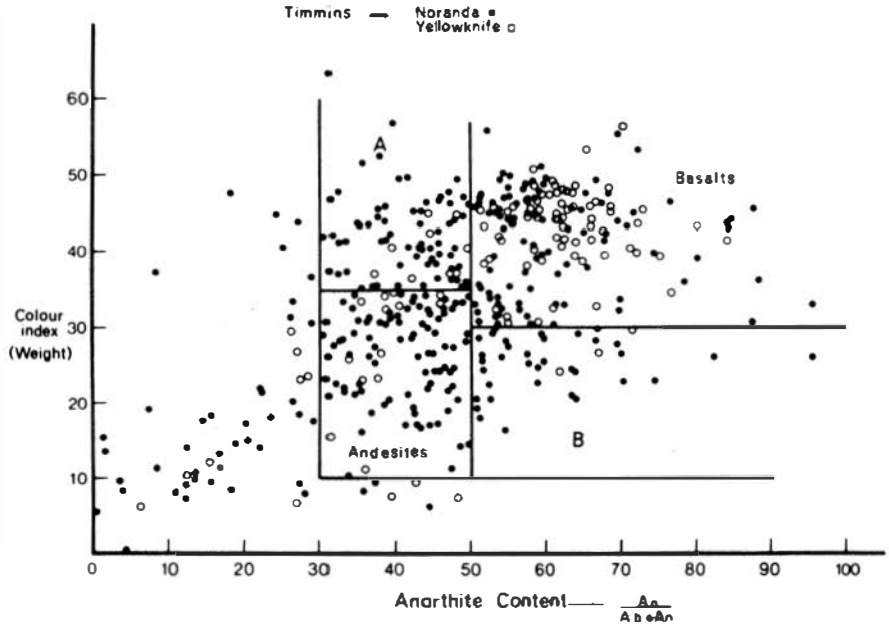

Figure 6. Division of Timmins-Norondo and Yellowknife volcanic rocks into five classes on the basis of the proportion of anorthite in normative feldspar and of the normative colour index.

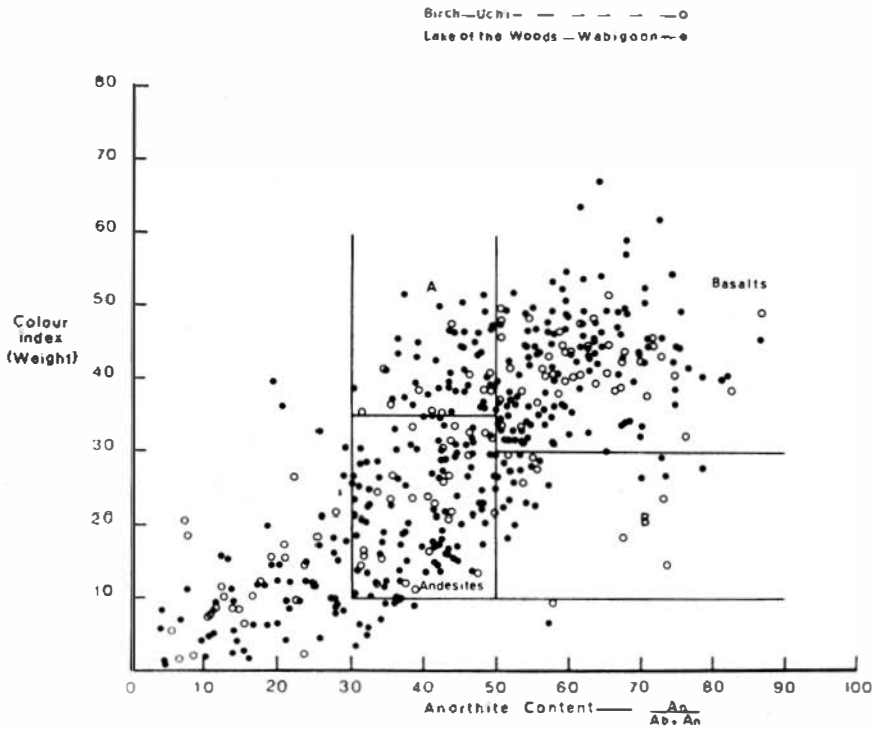

Figure 7. Division of Birch-Uchi and Lake of the Woods-Wabigoon volcanic rocks into five classes. Parameters are the same as in Figure 6.

TABLE II COMPARISON OF COMBINED MAFIC FRACTIONS IN UPPER AND LOWER PARTS OF STRATIGRAPHIC SECTION

	No. analyses	Strat. Thickness feet	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	CO_2	H_2O	% Basalt	% Andesite	% A	% B
DUPARQUET																			
Upper part	60	18,700	53.82	16.89	1.50	5.75	8.42	4.69	2.92	.57	.98	.12	.14	.43	3.47	22	39	1	38
Lower part	45	17,800	52.15	13.73	2.68	8.86	8.83	5.54	2.52	.20	1.46	.16	.27	.72	3.25	53	21	21	5
KENOGAMI-MATHESON																			
Upper part	21	21,800	52.1	17.1	1.7[1]	5.0[1]	7.7	5.1	4.3	.46[2]	1.07	.11[1]	.19	.18[1]	2.8[1]	32	52	16	0
Lower part	22	15,300	49.9	15.7	3.1[3]	10.3[3]	8.4	4.6	3.4[3]	.38	2.04[3]	.29	.21	.8[3]	2.7[3]	54	7	36	3
YELLOWKNIFE																			
Upper part	39	20,400	51.40	14.67	2.46	8.58	8.33	5.75	2.72	.42	1.27		.18	.55[4]		55	24	16	5
Lower part	35	16,800	50.50	15.20	2.96	9.31	9.92	6.83	2.14	.32	.99		.17	.22[5]		95	5	0	0
BIRCH-UCHI																			
Upper part	36	11,200	55.0	15.1	1.83	6.44	6.77	4.60	3.16	.67	.80	.10	.14		(CO_2+H_2O) 4.61	42	52	6	0
Lower part	15	8,300	51.0	14.5	3.23	8.40	7.88	5.83	2.52	.34	.85		.20		(CO_2+H_2O) 4.44	85	12	0	3
LAKE OF THE WOODS																			
Upper part	44	8,500	58.1	15.2	1.71	5.27	6.04	3.62	3.52	1.17	.71		.12		3.64	16	60	21	3
Lower part	55	10,000	51.7	14.4	2.68	8.56	9.62	6.44	2.58	.38	.80		.21			88	3	9	0
AVERAGE OF FOUR ARCHEAN SECTIONS																			
Upper part		15,100	54.4	15.5	1.9	6.4	7.3	4.7	3.2	.69	.95	.10	.15	.43	3.4	35	45	13	7
Lower part		12,900	51.0	14.7	2.9	8.9	9.0	6.0	2.5	.33	1.09	.22	.20	.5	3.0	80	9	9	2

[1] 8 analyses. [2] 20 analyses. [3] 9 analyses. [4] 21 analyses. [5] 15 analyses

TABLE II (Continued)

	No. analyses		Ba	Sr	Y	Zr	Sn	Co	Ni	Se	V	Cr	Ga	Ag	Pb	Zn	Cu
DUPARQUET Upper part	61	18,700	160[1]	150	4	149	1.24	25	92	38	308	152	>43	.151	5.26	91	82
Lower part	47	17,800	73	107	39	161	1.76	30	51	70	410	135	35	.127	1.61	105	106
YELLOWKNIFE Upper part	35	20,400	121	108		51[2]	1.03[3]	5	80		249	135	21[3]	.128[3]	8.15[3]	116[3]	105
Lower part	33	16,800	104	120		44	1.27[2]	25	129		266	167	20[2]	.137[2]	25.2[2]	92[2]	136
BIRCH-UCHI Upper part	36	11,200	331	500		181	2.10	26	68		270	155	29	.13	6.35	90	72
Lower part	13	8,300	131	175		89	1.12	41	74		428	431	24	.13	2.77	108	104
AVERAGE OF THREE SECTIONS Upper part		16,800	204	253		127	1.46	19	80		276	147	31	.14	6.58	99	86
Lower part		14,300	103	134		98	1.38	32	85		368	244	26	.13	9.86	102	119

[1] 60 analyses. [2] 34 analyses. [3] 36 analyses

Timmins-Norondo belt and less in the Yellowknife belt. These differences are noted without attaching particular significance at this time.

Stratigraphic Distribution of Classes and Compositions

The presence of several very thick volcanic sections among those that were sampled in the four volcanic belts has enabled us to compare the upper and lower parts of the stratigraphic successions at a number of places. For this purpose the sections were divided approximately in half and the average compositions and proportions of classes in each half were compiled separately. The very thickness of the sections (± 40,000 feet) probably ensures that a high proportion of the original succession must, in each case, be present. Where two distinct cycles exist (e.g. Yellowknife) the corresponding parts of each cycle were combined to give composite lower and upper parts. The comparisons involve the mafic volcanic rocks only*. The results are presented in Table II and are shown for the major oxides and proportion of volcanic classes in histogram form in Figure 8.

It is readily apparent from the table and the diagram that the proportion of andesite is greater and that of basalt less in the upper than in the lower parts of the section. If Type A is included with the basalts and Type B with the andesites, as discussed in the next section, the difference becomes even more pronounced. In chemical terms the change is marked by an increase in the contents of silica, soda, and potash and a decrease in those of iron, magnesia, lime, and generally titania. Less expectedly perhaps, is the marked increase in alumina content in the upper as compared with the lower parts of the Duparquet and Kenogami-Matheson sections of the Timmins-Norondo belt. A similar but less conspicuous change is evident in the Birch-Uchi and Lake of the Woods sections. The Duparquet section has been studied in detail and the results reported elsewhere (Baragar, 1968). It was shown that the alumina content increases steadily with increasing stratigraphic level for most of the section and is accompanied throughout by progressively decreasing amounts of iron, magnesia, and titanium. The similarity of changes shown by the Kenogami-Matheson section (Table II) suggests that the same pattern may be widespread in the Timmins-Norondo belt.

In summary it can be said with reasonable assurance that Archean volcanic successions in the Canadian Shield show progressive changes upward in the stratigraphic sequence from mafic to more salic rocks. Salic rocks per se seem to predominate in the upper parts of the successions only.

Compositions Characteristic of Volcanic Classes

Average compositions of each class for each of the four volcanic belts together with the over-all average composition of each class are given in Table III. Nockold's (1954) average compositions for the major elements and Taylor's (1964, 1966) and Turekian and Wedepohl's (1961) for the minor elements for some general calc-alkaline rock types are also given for comparison. Triangular plots of the magnesia-total iron-alkalis and lime-soda-potash proportions of the average compositions of each of the volcanic classes together with Nockold's average tholeiitic basalt, andesite, dacite, and rhyodacite are shown in Figure 9. Some observations of interest are as follows.

1. The basalts, andesites and salic rocks (Table III) are similar to Nockold's average tholeiitic basalt, andesite, and dacite-rhyodacite respectively with a few notable exceptions: potash and titania are markedly lower in the basalts and somewhat lower in the andesites; alumina is considerably lower in the andesites and salic rocks; lime is lower in all three types but more markedly so in the andesite and salic rocks; and iron is more reduced in all three types. Although the average of the salic rocks is generally similar to the average rhyodacite, its potash content, which is critical to the definition, is much more like that of the average dacite. Hence it should probably be regarded as dacite.

The trends of the Archean rocks in the plots of Figure 9 are parallel to those of Nockold's average basalt-andesite-dacite-rhyodacite but they are displaced toward lower proportions of iron and potash respectively.

2. Trace elements of the basalts, andesites, and salic rocks differ from those of the average basalt, the average given for 13 New Zealand and Japanese andesites, and the average high-calcium granite in containing decidedly less Sr and Ba but somewhat more Sc and V at all three stages.

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* That is, basalts, andesites, Type A, and Type B.

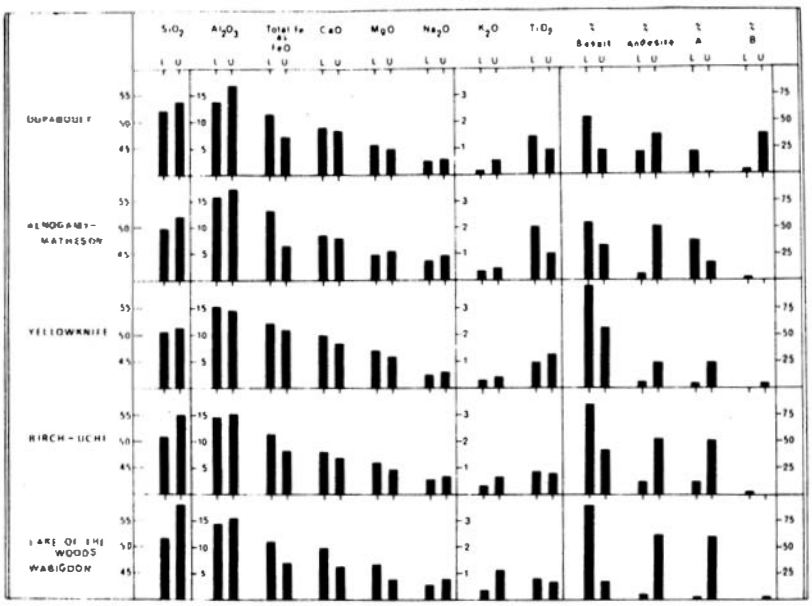

Figure 8. Comparison of major-element compositions and proportion of volcanic classes among the mafic fractions of the upper (U) and lower (L) halves of several thick volcanic sections.

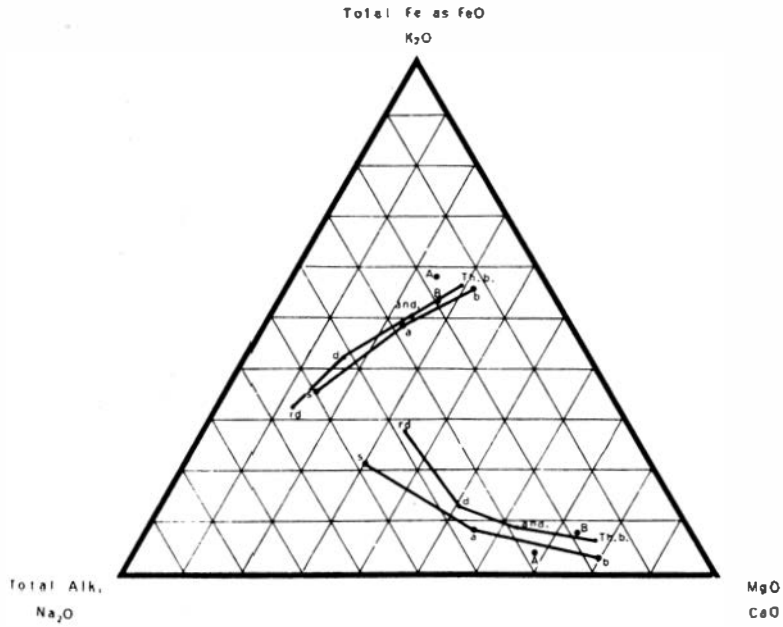

Figure 9. Plots of the average compositions of major volcanic classes determined in this report compared with those of Nockold's (1954) average tholeiitic basalt, andesite, dacite, and rhyodacite (Table III). The upper plots involve proportions of iron, magnesia, and alkalis, the lower plots of potash, lime, and soda. Note that the Archean trends are lower in proportions of potash and iron than the general trends. Nockold's average compositions; Th. b.-tholeiitic basalt, and-andesite, d-dacite, rd-rhyodacite: average compositions of volcanic classes, this report; b-basalt, a-andesite, s-salic rocks, A-Type A, B-Type B.

TABLE III COMPOSITIONS CHARACTERISTIC OF VOLCANIC CLASSES

	No. of analyses		SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	CO_2	H_2O	CO_2 + H_2O
BASALTS																
1. Birch-Uchi	45		48.8	15.2	2.45	8.70	9.18	6.13	2.06	.31	.93		.20			5.24
2. Lake of the Woods-Wabigoon	134	*133 **50 *120)	50.0	14.7	2.70*	8.96	8.93	6.11	2.21	.39	.97	.25**	.21	1.81**	2.01**	4.87*
3. Timmins-Noranda	82	*81	49.9	14.8	2.36	8.20	9.75	6.36	2.07	.25	1.09	.11	.19	.85	3.52*	
4. Yellowknife	61		50.1	15.0	2.76	9.23	9.71	6.62	2.10	.35	1.05		.18	.26		
Average (each belt equally weighted)			49.7	14.9	2.57	8.77	9.39	6.31	2.11	.32	1.00	.18	.19	.97	2.76	5.06
ANDESITES																
1. Birch-Uchi	27		58.8	14.8	1.81	5.47	5.08	3.40	3.37	1.15	.72		.13			4.78
2. Lake of the Woods-Wabigoon	107	*34 **93	59.3	15.3	2.01	5.23	5.23	2.95	3.60	1.12	.79	.28*	.13	2.27*	1.38*	4.14**
3. Timmins-Noranda	85	*84	55.5	15.9	1.78	6.34	6.20	4.33	3.82	.51	1.10	.16	.17	.87	3.03*	
4. Yellowknife	13		56.7	15.5	1.67	6.80	6.05	4.32	4.00	.59	1.40		.15			
Average (each belt equally weighted)			57.6	15.4	1.82	5.96	5.64	3.75	3.70	.84	1.00	.22	.15	1.57	2.20	4.46
TYPE A																
1. Birch-Uchi	11		51.6	13.8	3.07	8.23	7.33	4.56	3.28	.55	1.13		.20			5.78
2. Lake of the Woods-Wabigoon	47	*46 **18 +19 *44	50.0	13.9	2.80*	9.23	7.64	5.47	3.15	.44	1.14	.32**	.20	2.68+	2.44+	5.70*
3. Timmins-Noranda	59	*54	50.7	13.8	2.27	9.45	8.93	5.53	3.39	.28	1.44	.16	.22	1.75	3.36*	
4. Yellowknife	8		50.0	15.4	2.97	10.45	7.93	5.60	3.35	.21	1.59		.19	.41		
Average (each belt equally weighted)			50.6	14.2	2.80	9.34	7.96	5.25	3.29	.37	1.33	.24	.20	1.61	2.90	5.74
TYPE B																
1. Birch-Uchi	9		56.0	15.6	3.08	5.72	6.77	3.17	1.73	1.31	.83		.16			5.33
2. Lake of the Woods-Wabigoon	21	*3	56.8	15.4	2.05	5.87	6.06	3.86	2.45	.96	.80	.19*	.13	4.53*	1.88*	5.35
3. Timmins-Noranda	35		56.6	17.4	1.67	5.30	8.50	3.79	2.61	.67	.94	.13	.14	.68	3.10	
4. Yellowknife	2		50.7	13.9	1.50	5.31	10.26	4.86	1.55	.25	.44		.15	4.00		
Average (each belt equally weighted)			55.0	15.6	2.08	5.54	8.15	3.92	2.09	.80	.75	.16	.15	3.07	2.49	5.34
SALIC																
1. Birch-Uchi	24		69.0	13.5	1.24	3.04	2.22	1.42	4.55	1.44	.54		.08			2.45
2. Lake of the Woods-Wabigoon	80	*37 **77	67.3	14.7	1.23	2.47	2.67	1.73	4.11	1.77	.38	.23*	.07	1.54*	.91*	2.96**
3. Timmins-Noranda	38	*34	65.1	15.2	1.09	4.03	2.77	2.64	4.00	1.82	.63	.12	.10	1.20	1.98*	
4. Yellowknife	10		65.9	15.8	.79	2.52	2.52	1.31	3.56	2.01	.48		.17	.63		
Average (each belt equally weighted)			66.8	14.8	1.09	3.01	2.55	1.78	4.06	1.78	.50	.18	.10	1.12	1.44	2.70
Average tholeiitic basalt (Nockolds, 1954)			50.83	14.07	2.88	9.00	10.42	6.34	2.23	0.82	2.03	.23	.18		.91	
" andesite "	"		54.20	17.17	3.48	5.49	7.92	4.36	3.67	1.11	1.31	.28	.15		.86	
" dacite and dacite obsidian "	"		63.58	16.67	2.24	3.00	5.53	2.12	3.98	1.40	.64	.17	.11		.56	
" rhyodacite + rhyodacite obsidian "		"	66.27	15.39	2.14	2.23	3.68	1.57	4.13	3.01	.66	.17	.07		.68	

TABLE III (continued)

	No. of analyses		Ba	Sr	Y	Zr	Sn	Co	Ni	Se	V	Cr	Ga	Ag	Pb	Zn	Cu
BASALTS																	
1. Birch-Uchi	45		85	196		140	1.05[1]	41	108		391	269	30	.13[1]	3.5	122	106
2. Lake of the Woods-Shoal Lake	36		122	217		133	.75	43	110		384	144	21	.10	3.6	89	91
3. Timmins-Noranda	66	*51	85	124	15*	103	1.61	36	85	66*	362	175	37*	.134	2.4	99	115
4. Yellowknife	58	*55	129	117		43*	1.18	19	110	48	248	161	20	.133	17.4	101	127
Average (each belt equally weighted)			105	164	15	105	1.15	35	103	57	346	187	27	.124	6.7	103	109
ANDESITES																	
1. Birch-Uchi	27		345[2]	330[2]		205[3]	2.18	19	48		210	102	35	.15	8.1	98	58
2. Lake of the Woods-Shoal Lake	17		317	442		193	.87	22	38		162	74	25	.11	7.7	70	51
3. Timmins-Noranda	44	*34	147	142	14*	164	1.59	19	72	43*	258	106	40*	.138	3.2	92	69
4. Yellowknife	13	*13	185	140		78	1.19	13	95	54	176	131	20	.121	9.2	84	63
Average (each belt equally weighted)			248	263	14	160	1.46	18	63	48	201	103	30	.12	7.1	86	60
TYPE A																	
1. Birch-Uchi	11		141	208		199	1.56	35	41		430	65	26	.11	4.0	123	103
2. Lake of the Woods-Shoal Lake	12		272	257		172	.80	44	68		396	204	16	.146	5.3	97	79
3. Timmins-Noranda	33	*22	76	96	24*	151	1.43	43	59	71*	384	130	25*	.120	1.7	125	97
4. Yellowknife	8	*7	68	133		58*	.89	1.27	111	40	306	146	18	.098	5.6	134	134
Average (each belt equally weighted)			139	173	24	145	1.17	31	70	56	379	136	21	.12	4.1	120	103
TYPE B																	
1. Birch-Uchi	9		199	131		422	1.94[4]	19	49		206	77	39	.15	8.4	106	64
2. Lake of the Woods-Shoal Lake	3		280	270		190	.47	20	28		200	53	17	.09	3.3	42	39
3. Timmins-Noranda	28	*24	153	125	21*	187	1.52	23	71	36*	304	154	45*	.121	5.0	91	72
4. Yellowknife	2		58	31		8	.57	0	112	50	215	90	21	.101	11.0	58	125
Average (each belt equally weighted)			172	139	21	202	1.01	16	65	43	231	93	31	.115	6.9	74	75
SALIC																	
1. Birch-Uchi	21		368	218		424	3.44	5	20		54	26	40	.11	6.3	96	32
2. Lake of the Woods-Shoal Lake	9		450[5]	317[5]		210	1.63	6	19		65	51*	25	.13	9.9	50	28
3. Timmins-Noranda	22	*9	399	180	1.7	175	2.03	6	24	19*	106	27	31*	.109	4.5	103	61
4. Yellowknife	8		314	175		61	1.38	1	34		106	47	31	.084	8.4	40	53
Average (each belt equally weighted)			383	222	1.7	217	2.12	4	24	19	82	38	32	.11	7.6	72	44
Average basalt (Taylor 1964)			250	465	25	110	1	48	150	38	250	200	12	.10	5	100	100
Average of 13 andesites (Taylor 1966)[6]			230	350	20	101	.6	33	47	31	173	153	15		7		70
Average high calcium granite (Turekian and Wedepohl, 1961)			420	440	35	140	1.5	7	15	14	88	22	17	.051	15	60	30

[1] 44 analyses. [2] 26 analyses. [3] 24 analyses. [4] 8 analyses. [5] 7 analyses. [6] Thirteen New Zealand and Japanese andesites given by Taylor. Averaged by the present authors for convenience of presentation.

TABLE IV. WEIGHTED AVERAGE COM SITION OF EACH BELT AND TOTAL AVERAGE COM OSITIONS MAJOR ELEMENTS

	No. analyses	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	CO_2	H_2O	$CO_2 + H_2O$
WEIGHTED AVERAGE COMPOSITION OF EACH BELT															
Birch-Uchi	116	54.4	14.5	2.62	7.06	6.84	4.93	2.70	.67	.83		.16			2.84
Lake of the Woods-Wabigoon	389	54.1	14.9	2.37	7.37	7.25	4.81	2.78	.75	.87	.27	.17	1.87[1]	1.79[1]	4.03[2]
Timmins-Noranda	299	53.6	15.3	2.07	7.30	7.78	4.98	3.27	.58	1.13	.14	.19	1.13	3.06	
Yellowknife	97	53.6	15.2	2.25	7.85	7.92	5.40	2.77	.60	1.06		.18	.38		
WEIGHTED AVERAGE COMPOSITION OF COMBINED MAFIC FRACTIONS															
Birch-Uchi	92	52.7	14.9	2.40	7.40	7.52	4.85	2.55	.68	.87		.17			5.17
Lake of the Woods-Wabigoon	309	53.7	14.9	2.44	7.50	7.25	4.76	2.85	.69	.92	.27	.17	2.19[3]	1.88[3]	4.79[4]
Timmins-Noranda	261	52.5	15.3	2.2	7.6	8.2	5.2	3.2	.47	1.2	.14	.20	1.1	3.2	
Yellowknife	87	51.7	15.0	2.5	8.7	8.8	6.1	2.6	.37	1.2		.18	.3		
AVERAGE COMPOSITION OF SALIC FRACTION															
Birch-Uchi	24	69.0	13.5	1.24	3.04	2.22	1.42	4.55	1.44	.54		.08			2.45
Lake of the Woods-Wabigoon	80	67.3	14.7	1.23	2.47	2.67	1.73	4.11	1.77	.38	.23[5]	.07	1.54[5]	.91[5]	2.96[6]
Timmins-Noranda	38	65.1	15.2	1.1	4.0	2.8	2.6	4.0	1.82	.6	.12	.10	1.2	2.0	
Yellowknife	10	65.9	15.8	.8	2.5	2.5	1.3	3.6	2.01	.5		.17	.6		
WEIGHTED AVERAGE COMPOSITIONS OF ARCHEAN VOLCANICS, CANADIAN SHIELD															
Average volcanic rock (Belts equally weighted)		53.9	15.0	2.33	7.39	7.45	5.03	2.88	.65	.97	.21	.18	1.13	2.43	3.75
Average mafic fraction (" " ")		52.6	15.1	2.38	7.80	7.94	5.23	2.80	.55	1.05	.20	.18	1.2	2.5	
Average salic fraction (" " ")		66.8	14.8	1.09	3.01	2.55	1.78	4.06	1.78	.50	.17	.10	1.1	1.5	2.87
OTHER AVERAGES FOR COMPARISON															
Average oceanic tholeiite[7]		49.34	17.04	1.99	6.86	11.72	7.19	2.73	0.16	1.49	0.16	0.17		1.28	
Average tholeiitic basalt[8]		50.83	14.07	2.88	9.00	10.42	6.34	2.23	0.82	2.03	0.23	0.18		0.91	
Average andesite[8]		54.20	17.17	3.48	5.49	7.92	4.36	3.67	1.11	1.31	0.28	0.15		0.56	
Average composition Canadian Shield[9]		65.3	15.9	1.4	3.1	3.4	2.2	3.9	2.87	0.53	0.16	0.08	0.2	0.80	

[1] 172 analyses. [2] 217 analyses. [3] 106 analyses. [4] 203 analyses. [5] 34 analyses. [6] 46 analyses. [7] Engels et al., 1965; [8] Nockolds, 1954; [9] Fairbairn and Eade, 1968.

TABLE IV (continued)

MINOR ELEMENTS (in ppm.)

	No. analyses	Ba	Sr	Y	Zr	Sn	Co	Ni	Se	V	Cr	Ga	Ag	Pb	Zn	Cu
WEIGHTED AVERAGE COMPOSITIONS OF EACH BELT																
Birch-Uchi	116	188	278		252	1.99[1]	32	112		285	307	32	.15[1]	6	121	86
Lake of the Woods-Shoal Lake	60	298	324		184	.84	31	77		285	210	20	.11	6	73	58
Timmins-Noranda	196	131	125	17	151	1.53	27	72	54	309	142	38	.130	3	105	85
Yellowknife	89	160	128		53[1]	1.15[2]	30	96		219	137	21[2]	.122[2]	13[2]	94[2]	106
WEIGHTED AVERAGE COMPOSITIONS OF COMBINED MAFIC FRACTIONS																
Birch-Uchi	90	191	331		286	1.99	31	109		273	264	33	.13	4.8	105	80
Lake of the Woods-Shoal Lake	9	169	234		151	.74[8]	37	78		353	193	21	.11	6.7	92	85
Timmins-Noranda	174	108	120	18[3]	149	1.49	29	76	57[3]	326	152	38[3]	.132	2.8	105	87
Yellowknife	81	135	120		52[4]	1.12[5]	34	106		237	151	20[5]	.127[5]	13.7[5]	103[5]	114
AVERAGE COMPOSITION OF SALIC FRACTION																
Birch-Uchi	21	368	218		424	3.44	5	20		54	26	40	.11	6.3	96	32
Lake of the Woods-Shoal Lake	9	450	317		210	1.63	6	19		65	51[8]	25	.13	9.9	50	28
Timmins-Noranda	22	399	180	2[6]	175	2.03	6	24	19[6]	106	27	31[6]	.109	4.5	104	61
Yellowknife	8	314	175		61	1.38	1	34		106	47	31	.084	8.4	40	53
WEIGHTED AVERAGE COMPOSITION OF ARCHEAN VOLCANICS, CANADIAN SHIELD																
Average volcanic rock (belts equally weighted)		194	214	17	160	1.38	30	89	54	274	199	28	.13	7	98	84
Average combined mafic fractions (" " ")		151	223	18	159	1.34	33	92	57	297	190	28	.12	7.0	101	92
Average salic fraction (" " ")		383	201	2	217	2.12	4	24	19	82	38	32	.11	7.6	72	44
Average oceanic tholeiite[7]		14	130	43	95		32	97	61	292	297	17				77
Average basalt[8]		250	465	25	110	1	48	150	38	250	200	12	.10	5	100	100
Average of 13 a desites[9]		230	350	20	101	.6	33	47	31	173	153	15		7		70
Average composition Canadian shield[10]		1070	340		400		21	23		53	99	14				14

[1] 80 analyses. [2] 91 analyses. [3] 129 analyses. [4] 72 analyses. [5] 83 analyses [6] 9 analyses. [7] 114 analyses. [8] 7 analyses. [9] Taylor and White, 1966. [10] Shaw et al., 1967.

3. Types A and B lie off the trend shown by the major classes (Fig. 9). Comparison of their average compositions (Table III) with those of the other classes and with Nockold's averages indicates that Type A is essentially a soda-rich basalt and Type B a soda-deficient andesite. This can also be seen in Figure 9 where the path from basalt to Type A is essentially an enrichment in iron and soda and that from andesite to Type B mainly an impoverishment in soda. Type A probably includes the spilites which seem to be an element of varying importance but rarely absent in geosynclinal volcanic assemblages. Type B includes high-alumina basalts and andesites which in the Timmins-Noranda belt are fairly abundant (Table III). In view of the significance of their special characteristics the separation of Types A and B as distinctive groups may well be justified.

4. Although the compositions of the four volcanic belts are generally similar to one another in all classes a more detailed examination suggests that they can be divided into two groups; the Birch-Uchi and Lake of the Woods-Wabigoon on the one hand and Timmins-Noranda and Yellowknife on the other. The distinction between the two groups is most pronounced at the andesite stage where silica, alumina, total iron, lime, magnesia, soda, potash, and titania all show a tendency to pair into two sets of similar values. The other classes show a tendency to similar grouping but in fewer oxides: in basalts by lime, magnesia, and titania; in the salic rocks by silica, alumina, and magnesia; in Type A by potash, titania, and lime; and Type B by total iron, lime, and potash. In general, the Timmins-Noranda and Yellowknife group tends to be higher in titania, alumina, magnesia, and lime and lower (except for the salic class) in potash.

Average Compositions of Canadian Archean Volcanic Rocks

The average compositions of the four volcanic belts, and the average of the combined mafic fractions, and salic fraction in each belt are shown in Table IV. The averages are based upon the detailed stratigraphic studies in each belt supported by 901 analyses representative of volcanic units.

The average compositions of the four belts are remarkably uniform. This chemical uniformity is particularly impressive considering that the belts are 1600 miles apart and were studied independently at different levels of stratigraphic detail. The comparatively high volatile content (H_2O and CO_2) is a chemical characteristic of most Archean volcanic rocks.

Similarly the average compositions of the combined mafic fractions (basalt, andesite, class A and class B) in the four belts are essentially uniform. Those in the Yellowknife belt are comparatively low in the salic components (SiO_2, Na_2O, K_2O) and high in the mafic components (Fe_2O_3, FeO, CoO and MgO). The TiO_2 contents are comparatively high in the Yellowknife and Timmins-Noranda belts.

Compared with oceanic tholeiite, Archean mafic fractions are low in Al_2O_3, CoO, MgO and TiO_2 and high in SiO_2 and volatiles. Compared with tholeiitic basalt, Archean mafic fractions are low in Fe_2O_3, FeO, CaO, MgO, K_2O, and TiO_2 and high in SiO_2, Al_2O_3, Na_2O and volatiles.

Compared with average andesite the average composition of Archean volcanic rocks is low in Al_2O_3 (2.2 percent), Fe_2O_3 (1.1 percent), Na_2O (0.8 percent), K_2O (0.5 percent) and TiO_2 (0.3 percent) and high in FeO (1.9 percent), MgO (0.67 percent), and volatiles (3 percent).

Significantly the average salic fraction of Archean volcanic rocks compares closely with the average composition of the Canadian Shield as determined by Fahrig and Eade (1968). The main difference is in substantially lower K_2O content (1.09 percent) and higher volatiles in the Archean salic rocks.

Discussion

1. Compositions of the four volcanic belts are remarkably similar, both in weighted averages of each belt and in the averages of each of the major classes (basalt, andesite, and salic rocks) composing each belt. This suggests that whatever the processes responsible for the volcanism and for the fractionation of its products they acted with uncanny uniformity throughout the Archean of the Canadian Shield. Possibly the compositions are a function of the age of the volcanism or of the tectonic environment of volcanism (eugeosynclinal); in any event the Archean volcanic assemblages do have distinctive chemical characteristics - low potash, titania, barium, and strontium - that mark them off from the general averages of volcanic rocks.

The weighted average compositions of the Archean belts are distinctly not andesitic but are slightly more salic than tholeiitic basalts and more mafic than andesites. If we count Type A as basalt

and Type B as andesite the average distribution of compositions in the four belts is as follows: basalts - 60.2 percent, andesites - 28.1 percent, solic rocks - 11.7 percent. Thus the average composition is predominantly basaltic.

It is not possible to say whether the distribution of classes noted above is a result of crystal fractionation (or the reverse process fractional melting) or of contamination of basaltic magma by the sialic crust or of both. The uniformity of compositions in all four belts might suggest that the mechanism was a closed process that was capable of reproducing chemically identical products in the some proportions repeatedly. If so, the processes of crystal fractionation or fractional melting would be favoured. However, all four belts evolved under similar tectonic circumstances and it is quite conceivable that the distribution of compositions observed represents a consistent level of contamination appropriate to these conditions.

2. The average composition of the major elements of the solic fraction is quite similar to the overage composition of the Canadian Shield (Table IV). Hence it might be tempting to suggest that the sàlic rocks ore simply melt products of the underlying crust. However, the overage composition of trace elements in the solic fraction shows little similarity to that of the Shield, thus, ony such simple explanation must be approached with caution.

3. The fact that the overage composition of these volcanic belts is considerably more mafic than that of the Canadian Shield places strains upon the hypothesis of continental growth by accretion of volcanic belts (Taylor, 1967). If the thesis is to be maintained it must be assumed that these belts ore not typical of those which hove been welded on to the continent or that the continental crust has become progressively more bosic with time.

4. The increase of solic components with increasing stratigraphic level demonstrated for these four volcanic belts has important implications for the sampling of more recent volcanic belts. For example, is it possible to obtain a representative composition for the circumpocific belt by simply compiling on average composition from all available analyses? Such on average might be expected to be heavily weighted towards the compositions represented in the upper stratigraphic levels. If the circumpocific belt shows a similar stratigraphic variation in composition as the Archean volcanic assemblages then that average would be for from a truly representative composition.

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RADIOGENIC TRACERS AND THE SOURCE OF CONTINENTAL ANDESITES: A BEGINNING AT THE SAN JUAN VOLCANIC FIELD, COLORADO*

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Abstract

Lead and strontium isotopic compositions of mid-Tertiary alkalic andesitic rhyodacitic lavas of the San Juan volcanic field, southern Colorado, are compared with available isotopic data on primitive and contaminated basalts, silicic rocks, and upper crust of the Southern Rocky Mountains. These data indicate that none of the volcanic rocks analyzed could have formed by whole-rock melting of upper crustal rocks like those at the earth's surface. One area of alkali andesites could be from the same source as the younger primitive basalts. Intermediate lavas from a second area are isotopically different in both lead and strontium isotope ratios and are similar to those of some contaminated basalts. The isotopic data therefore do not exclude the possibility that andesites in one region may have diverse origins; some bodies, probably the largest, may be representative of their source, which is possibly the lower crust, and others, probably of less volume, may be related to contamination of basalt. Alternatively the isotopic differences could reflect lateral variations in the source. The isotopic data also support the hypothesis that the compositionally diverse volcanics of the Summer Coon volcanic center are formed from a common magma chamber that is slightly heterogeneous in $^{206}Pb/^{204}Pb$.

Introduction

Studies of the radiogenic tracers, lead and strontium, from alkalic andesite-rhyodacite rocks of the San Juan volcanic field have been undertaken in an attempt to place limits on the source of the alkalic andesites and on their genetic relations to more silicic and mafic rocks in the region. Five samples from the early alkalic andesite-rhyodacite lavas of the Conejos Formation have been studied. Two are alkalic andesite (fine-grained and coarse-grained) from Conejos Peak and three samples - basalt, intermediate rock, and rhyolite - are from the differentiated Summer Coon volcanic center (Lipman, 1968), which is of similar age and about 35 miles to the northeast of Conejos Peak.

The San Juan field is particularly interesting, as volcanic rocks of virtually any silica content from 48 to 76 percent (composition from basalt to rhyolite) were erupted intermittently during the Cenozoic. The San Juan rocks are considered in terms of three major volcanic units: (1) early alkalic andesite-rhyodacite lavas, (2) rhyolitic-quartz latitic ash-flow tuffs and genetically related lavas, and (3) late basaltic lavas. The early alkalic andesite-rhyodacite lavas are also compared with data on Precambrian rocks exposed at the surface.

The tracers

Variations in both lead isotopic composition and strontium isotopic composition are used as tracers in this study. These variations come about because the number of atoms of a given isotope in any system such as the earth, the source magma, or a mineral at a given time is equal to the number of atoms of the isotope that was in the system when it formed (T) plus the added radiogenic atoms of the isotope derived from the decay of the atoms of a radioactive parent in the interval up to the geologic time of interest (t). For ^{206}Pb, this relationship is:

$$^{206}Pb_t = {}^{206}Pb_T + {}^{238}U_p(e^{\lambda T} - e^{\lambda t}) \qquad (1)$$

In the radioactive decay term, $^{238}U_p e^{\lambda T}$ gives the number of atoms formed between the time of origin

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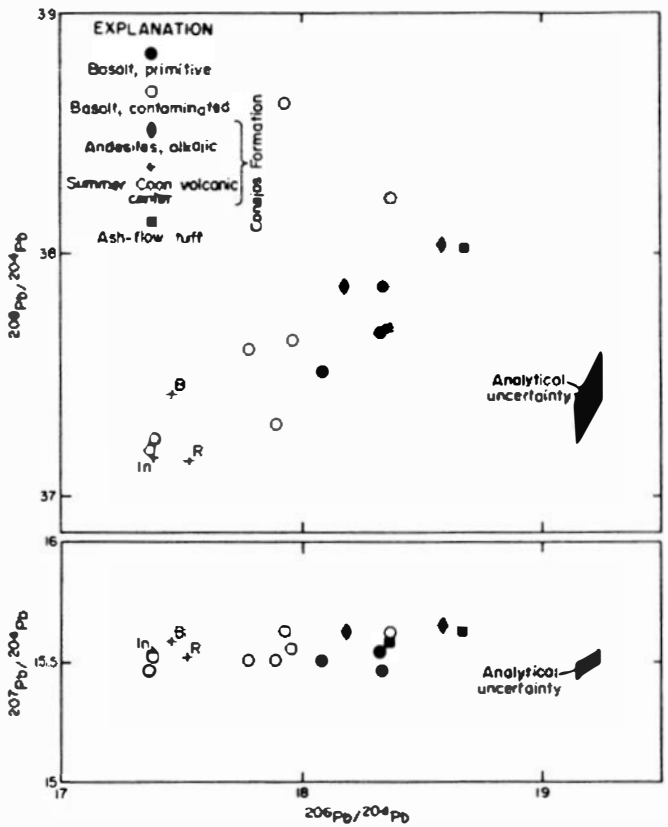

Figure 1. $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ for Cenozoic volcanic rocks of the Southern Rocky Mountains. (B is basalt, In is rhyodacite, and R is rhyolite).

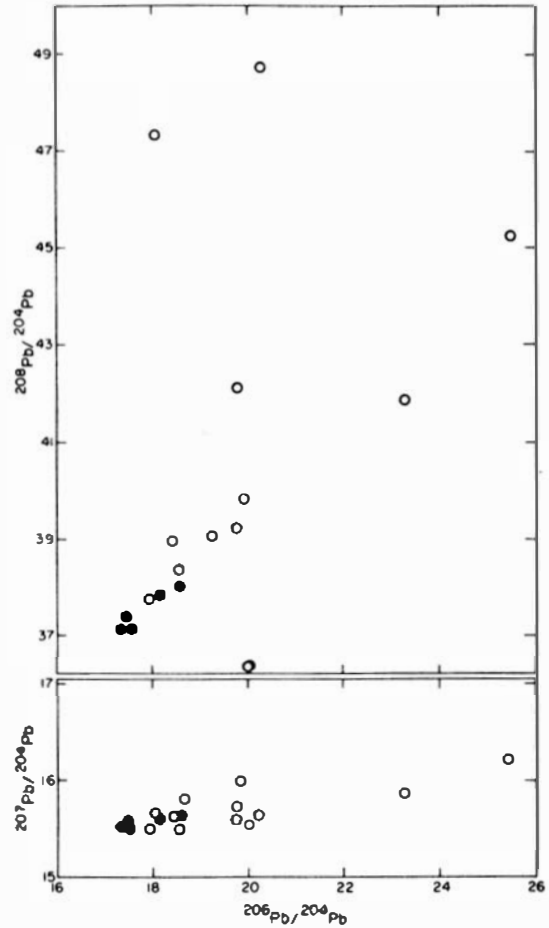

Figure 2. $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ for alkalic andesite-rhyodacite volcanics of the San Juan volcanic field (●) (this paper) and Precambrian crystalline whole-rock analyses (O) (see Appendix A for data and references).

Table 1. U-Th-Pb data for volcanic rocks from the Conejos Formation.
(Data are normalized to Ta, lot 1 filament material and corrected for uranium and thorium decay to 32 m.y. ago.)

Sample	U	Th	Pb	$^{238}U/^{204}Pb$	$^{232}Th/^{238}U$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
				Andesites from Conejos Peak				
Andesite (67L125)	1.37	4.20	8.99	9.73	3.17	18.590	15.66	38.04
Andesite (67L126)	2.11	6.98	12.00	11.16	3.42	18.184	15.63	37.87
				Volcanics from Summer Coon Volcano				
Basalt dike (67L106)	0.55	2.39	7.45	4.64	4.46	17.466	15.59	37.41
Rhyodacite (65L267)	1.71	4.76	18.4	5.76	2.87	17.384	15.54	37.15
Rhyolite dike (65L206A)	1.22	7.31	25.6	2.95	6.21	17.534	15.52	37.14
Analytical uncertainty, in percent of the ratio or abundance.....	3	3	3	5	5	0.29	0.37	0.47

Table 2. $^{87}Sr/^{86}Sr$ and Rb and Sr concentrations for volcanic rocks of the Conejos Formation.

	Concentration (ppm)			Atomic ratio
	Rb	Sr	Rb/Sr	$^{87}Sr/^{86}Sr$
		Andesites from Conejos Peak		
Andesite (67L125)	82	770	0.11	0.7049
Andesite (67L126)	77	820	0.09	0.7048
		Volcanics from Summer Coon Volcano		
Basalt dike (67L106)	29	710	0.04	0.7053
Rhyodacite (65L267)	84	890	0.10	0.7055
Rhyolite dike (65L206A)	99	370	0.27	0.7056*
Analytical uncertainty, in percent	15	15	5	0.04

*0.0003 correction applied for 30 m.y. age.

of the system (T) and the present (p), whereas $^{238}U_p e^{\lambda t}$ subtracts the number of atoms of ^{206}Pb from the present back to the time of geologic interest (t). As the total number of atoms is difficult to determine, equations of the form of Equation 1 are simplified by dividing by isotopes such as ^{204}Pb or ^{86}Sr, that have no radioactive parent and whose number in the system is therefore constant:

$$\frac{^{206}Pb}{^{204}Pb_t} = \frac{^{206}Pb}{^{204}Pb_T} + \left(\frac{^{238}U}{^{204}Pb}\right)_p \cdot (e^{\lambda T} - e^{\lambda t}) \qquad (2)$$

Now we no longer have to know the absolute number of atoms but only a ratio. As different rocks have different ratios of $\left(\frac{^{238}U}{^{204}Pb}\right)_p$, after a time different values of $\left(\frac{^{206}Pb}{^{204}Pb}\right)_t$ result. Equations 1 and 2 are developed for ^{206}Pb but other equations of the same form exist for

$$\begin{aligned} ^{235}U &\longrightarrow {}^{207}Pb \\ ^{232}Th &\longrightarrow {}^{208}Pb \\ ^{87}Rb &\longrightarrow {}^{87}Sr \end{aligned} \qquad (3)$$

The added feature that makes these radiogenic tracers particularly of interest in petrology is that the isotopes, once mixed, are not influenced by temperature and pressure effects to any significant degree and therefore no isotope effects result solely from magmatic differentiation. Empirical and theoretical justification of this lack of temperature and pressure effects may be found in Doe, Hedge, and White (1966) and other papers.

A partial melt may not always be isotopically identical to its source, because U, Th, Pb, Rb, and Sr are heterogeneously distributed among different minerals. Partial melting may therefore not give ratios representative of the whole-rock. More detailed discussions of this phenomenon are given in Doe (1967).

Analytical techniques

The uranium, thorium, and lead concentrations were determined by conventional isotopic dilution; lead isotopic compositions were measured by mass spectrometry. Details of the procedure, modified from Tatsumoto (1966), are given by Doe, Lipman, Hedge, and Kurasawa (1969). Rubidium and strontium concentrations were made by X-ray fluorescence, and the strontium isotopic composition was determined by procedures given by Peterman, Doe, and Bartel (1967).

Data and Discussion

Lead isotopes

The lead isotope ratios in volcanics of the Conejos Formation of Conejos and the Summer Coon volcanic center (Table 1) are shown in Fig. 1 with data on younger primitive (essentially uncontaminated) basalts, crustally contaminated basalts (Doe, 1967; Doe, Lipman, Hedge, and Kurasawa, 1969), and ash-flow tuffs of the Southern Rocky Mountains (Doe, 1967). The basalts are classified as primitive or contaminated according to the presence or absence of quartz or sadic plagioclase xenocrysts and through comparison of their major and minor element concentrations with those of oceanic basalts. Shown on Fig. 2 are the available data on Precambrian and Paleozoic crystalline rocks from North America (Appendix A).

The distribution of data on Fig. 1 shows that all the volcanic rock types are somewhat variable in lead isotope ratios even within a given rock type, and Fig. 2 shows that the volcanic rocks of the Southern Rocky Mountains are less radiogenic than most upper crustal rocks. The alkalic andesites from Conejos Peak, the primitive basalts, and the silicic volcanics all have similar isotope ratios. On the other hand, the contaminated basalts and the rocks from the Summer Coon volcanic center form a different isotopic grouping.

Although the isotopic similarities could be a coincidence, these data suggest some sort of

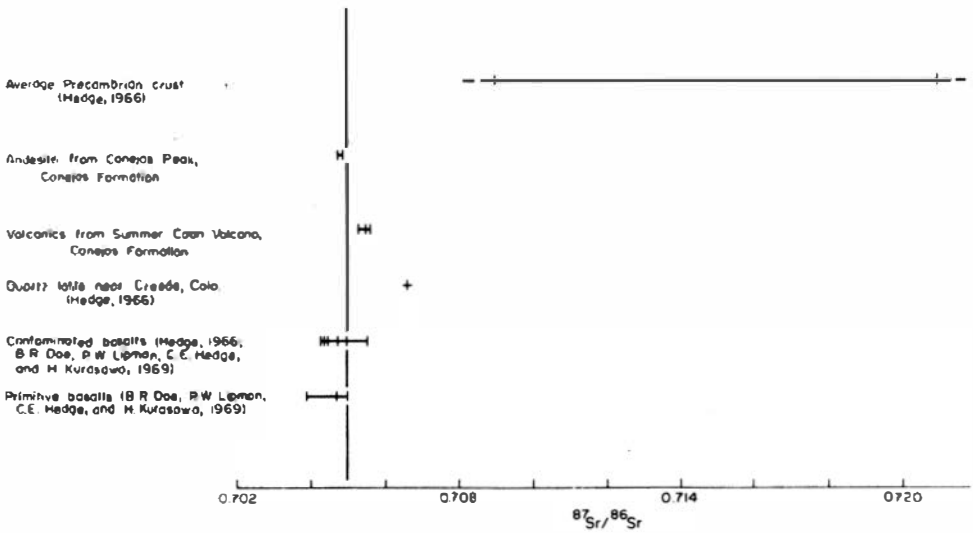

Figure 3. $^{87}Sr/^{86}Sr$ for average Precambrian crust, Conejos Formation and other volcanic rocks of the San Juan Mountains, Colorado, and vicinity. Vertical line is a reference at a $^{87}Sr/^{86}Sr$ of 0.705.

genetic relationship between the origin of the alkalic andesites of Conejos Peak and silicic volcanics with that of the primitive basalts. Processes involving contamination of basalt to form the alkalic andesites of Conejos Peak and the silicic volcanics appear to be unlikely because of the isotopic differences between the contaminated basalts and the other volcanic rocks. Although the isotopic data alone do not exclude differentiation of basalt to form the alkalic andesites of Conejos Peak, the lack of contemporaneous basalt suggests that such a mechanism is unlikely. It is more likely that the alkalic andesites and primitive basalt come from the same source, perhaps the mantle or the lower crust which could be predominantly eclogite facies rocks of andesitic composition (Tex, 1965; Ringwood and Green, 1966) with subordinate volumes of basaltic composition. Such a source with the appropriate isotopic compositions had been proposed elsewhere (Doe, 1968; Doe, Tilling, Hedge, and Klepper, 1969) for volcanics of the Rocky Mountain region and the Boulder batholith.

As in the case of the primitive basalts and the alkalic andesites, the silicic volcanics could also be derived from the same source, although the isotopic data do not exclude differentiation from the more mafic rocks.

The similarity of the isotope ratios between the rocks of the Summer Coon volcanic center and some of the contaminated basalts suggests that the rocks of this volcanic center might have been derived from contaminated basalt. Alternatively the isotopic difference between the volcanics of Conejos Peak and those of the Summer Coon volcanic center could reflect lateral isotopic variations in the source region.

In the differentiated Summer Coon volcanic center, the ratios of the basalt are identical with that of the major unit represented by the rhyodacite samples. The rhyolite, however, appears to be slightly more radiogenic in $^{206}Pb/^{204}Pb$. This small difference may not be of great geologic importance, if one judges from the data on the Boulder batholith (Doe, Tilling, Hedge, and Klepper, 1969), where individual plutons are not perfectly mixed with regard to lead isotopes. We think, from analogy with the plutonic study, that the ratio ranges of the Summer Coon volcanic center are probably within the limits of isotopic "noise" expected for plutons and that the data do not conflict with the interpretation that these volcanics are the result of differentiation from a single source (Lipman, 1968).

Strontium isotopes

Strontium in the volcanic rocks of the Conejos Formation (Table 2) appears similar in $^{87}Sr/^{86}Sr$ to that of the basalts (Fig. 3). As in the case of the lead isotopes, strontium isotopes suggest a close genetic relationship between the alkalic andesite-rhyodacite volcanics and the basalts; however, because crustal rocks are poor in strontium relative to basalts and andesites, strontium is buffered against

contamination effects. Therefore, Doe, Lipman, Hedge, and Kurosawa (1969) interpret all the strontium isotope data in the basalts as nearly representative of their sources.

One value of $^{87}Sr/^{86}Sr$ for a silicic ash-flow tuff (Hedge, 1966) is greater than any of those of the alkalic andesite-rhyodacite volcanics and the basalts; this higher value suggests that genesis of the silicic tuffs is more complex than just differentiation from alkalic andesite-rhyodacite lavas. More data are needed to help resolve the meaning of this difference but $^{87}Sr/^{86}Sr$ is more sensitive to contamination than lead in silicic volcanics as the strontium content is low relative to most upper crustal rocks. (Lead is a more powerful tracer in basalts which are lead-poor relative to the crust.) The strontium data could also be interpreted to imply that the tuff had a different source from the andesite. The tendency of highly silicic volcanics to be more radiogenic than basalts has been noted elsewhere (Gast, Tilton, and Hedge, 1964; Hedge, 1966).

As in lead isotopes, $^{87}Sr/^{86}Sr$ of the Summer Coon volcanic center is different from that of the andesites from Conejos Peak. In the case of strontium, rocks of the Summer Coon volcanic center are slightly more radiogenic than are the andesites of Conejos Peak. Therefore, both lead and strontium support the interpretation that the volcanics of the two localities come from separate plutons. In this regard, the Conejos rocks are different from the Boulder batholith. In the Boulder batholith lead and strontium fluctuate together; either both are more radiogenic or both are less radiogenic. More work is needed to determine the significance of the different behavior between the two regions. Some possible implications are given in Doe (1967). The strontium isotope data do not reflect the $^{206}Pb/^{204}Pb$ isotopic difference found between rhyolite and rhyodacite rock for the Summer Coon volcanic center. As strontium in silicic volcanics is a more sensitive tracer for crustal contamination than is lead, the lack of a strontium difference supports an interpretation that the pluton feeding the Summer Coon volcanic center was slightly inhomogeneous in $^{206}Pb/^{204}Pb$ and that all the volcanics are differentiates from one magma as concluded by Lipman (1968).

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Appendix A: Isotopic ratios of lead from whole-rock samples of various North American Precambrian and Paleozoic rocks.

Rock	Age	Locality	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Reference
Granite	Precambrian	Essonville, Ontario	20.25	15.65	48.73	Patterson (1953)
Granite	Precambrian	Uncompahgre, Colorado	20.04	15.55	36.36	Patterson (1953)
Granodiorite	Precambrian	Silver Plume, Colorado	18.08	15.67	47.33	Peterman et al. (1967)
Granite	Paleozoic	Westerly, Rhode Island	18.42	15.63	38.98	Doe et al. (1967)
Granite	Precambrian	Llano, Texas	18.55	15.49	38.39	Zartman (1965)
Quartz diorite	Precambrian	Llano, Texas	17.93	15.51	37.76	Zartman (1965)
Gneiss	Precambrian	Llano, Texas	23.27	15.89	41.86	Zartman (1965)
Gneiss	Precambrian	Llano, Texas	25.44	16.23	45.29	Zartman (1965)
Gneiss	Precambrian	Llano, Texas	19.78	15.73	42.12	Zartman (1965)
Gneiss	Precambrian	Llano, Texas	19.75	15.60	39.21	Zartman (1965)
Composite	Paleozoic	Western Montana	19.92	16.00	39.84	Murthy and Patterson (1961)
Composite	Precambrian	Western Montana	18.67	15.81	39.06	Murthy and Patterson (1961)

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EVOLUTION OF CALC-ALKALINE ROCKS IN THE GEOSYNCLINAL SYSTEM OF CALIFORNIA AND OREGON

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Abstract

Eugeosynclinal sequences of andesitic rocks are the fragments of ancient volcanic chains beneath which granitic plutons were emplaced in the crust. The sources of geosynclinal sedimentary rocks were mainly volcanic chains, local tectonic highlands made of suprocrustal rocks, and volcano-plutonic orogens within the mobile belt. As the source terranes were largely destroyed by erosion, a full record of their petrology is preserved only in the sedimentary successions. The late Mesozoic sequence of northern California and southwestern Oregon apparently records the evolution of a complex volcano-plutonic orogen on the site of the Sierra Nevada and the Klamath Mountains. The west-to-east increase in modal or normative K-feldspar in the early Mesozoic metavolcanic rocks, the late Mesozoic batholiths, and the Cenozoic volcanic rocks matches the known increase in the alkalinity of island arc lavas from volcanic front to hinterland. The upward increase in detrital K-feldspar in the late Mesozoic sequence may reflect a time asymmetry in petrology parallel to this spatial asymmetry. Petrologic similarities among the Mesozoic plutons and Cenozoic lavas call attention to unresolved questions on the origins and relations of volcanic and plutonic magmas in the mobile belts.

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The chains of andesitic volcanoes that ring the Pacific are part of a circumoceanic orogenic belt that approximates a great circle girdling the globe. The belt as a whole includes the volcanic chains, deep seismic zones, oceanic trenches, young folded mountains, large granitic batholiths, alpinotype peridotite massifs, metamorphic belts with median tectonic lines, and longitudinal strike-slip faults. One way to inquire into the geologic history of andesites is to seek to define the relationships of the volcanic chains to these other features in hopes of perceiving a developmental sequence of events.

Geosynclinal setting of ancient andesites

The Quaternary volcanic chains are surficial accumulations but the intrastructures of older volcanic chains have been carried to great depths by foundering within subsiding belts. For example, the upper Paleozoic and lower Mesozoic metavolcanic rocks of the Fraser Belt in western North America are dominantly andesitic (Dickinson, 1962b) and must represent the wreckage of ancient volcanic chains. Studies of eroded Tertiary sequences show that the eruption of some andesitic lavas can be linked to the intrusion of comagmatic granitic plutons (Fiske and others, 1963, p. 59). We may speculate that many batholiths could have vented themselves to feed surface eruptions, and thus may represent the roots of ancient volcanic chains. On the other hand, we know that volcanic mountain chains are now being destroyed by erosion and that extensive deposits of Tertiary strata flanking Tertiary volcanic chains are composed of debris dispersed from the volcanic centers. The prevalence of volcaniclastic strata in the older eugeosynclinal sequences is also notable (Dickinson, 1962b, p. 1244). To seek a time perspective on andesitic volcanism we may, therefore, consider: (a) eugeosynclinal metavolcanic rocks as fragmentary samples of largely decimated volcanic chains, (b) orogenic granitic batholiths as possible substructures of volcanic piles since destroyed by erosion, or (c) geosynclinal sedimentary rocks as the record of volcano-plutonic complexes partly destroyed by erosion. This paper emphasizes the third approach.

In considering the petrology of the so-called eugeosynclinal assemblages in California and Oregon, one must recognize a clear distinction between two different types of sequences for which different modern analogues must be selected as models (Hamilton, 1966):

(1) Ancient island-arc assemblages like the Permian-to-Jurassic sequence of the Blue Mountains and Sierra Nevada provinces. The intercalated volcanic rocks are largely andesitic or more felsic, and the clastic strata are largely volcaniclastic even though derived in part from polycyclic sources in tectonic highlands as well as from subaerial and submarine volcanoes. Unconformities are common within these sequences and granitic batholiths locally intrude them (e.g., Dickinson and Vigrass, 1964).

(2) Ancient trench or oceanic turbidite apron assemblages like the late Mesozoic Franciscan assemblage of the Coast Ranges province in which the intercalated volcanic rocks are largely seamount accumulations of basaltic pillow lavas, but the clastic rocks are derived mainly from compound sources that included exposured granitic plutons (Bailey and others, 1964).

Where paired metamorphic belts can be recognized (Miyashiro, 1961), the island-arc assemblages belong to the continent-side belts where the T/P ratio is higher than in the ocean-side belts, which are composed of the trench assemblages. Takeuchi and Uyeda (1965) were led by their analysis of relevant heat-flow data to infer that the "hi T/lo P" belts were sub-arc regions and the "lo T/hi P" belts were sub-trench regions in agreement with the suggested tectonic analogies.

Compositions of geosynclinal sandstones

The dominant detrital grains in most geosynclinal sandstones can be grouped into three classes:

(Q) - monocrystalline quartz grains plus polycrystalline quartz-chalcedony rock fragments.

(F) - monocrystalline feldspar grains.

(L) - polycrystalline lithic fragments of unstable, fine-grained rocks.

The framework composition of any sandstone can then be expressed by appropriate percentage subscripts summing to 100; e.g., $Q_{10} F_{40} L_{50}$ (Rodgers, 1950).

The most significant variations within each of these three classes can be expressed by three additional ratios.

(1) C/Q: the ratio of polycrystalline quartz-chalcedony rock fragments (C) mainly chert and metachert from sedimentary and metamorphic sources, to total quartzose grains (Q); monocrystalline quartz grains are mainly plutonic but are partly volcanic.

(2) P/F: the ratio of plagioclase grains (P) to total feldspar grains (F) a reflection of the relative proportions of plagioclase (soda-lime) to alkali (soda-potash) feldspars in the source rocks.

(3) V/L: the ratio of volcanic rock fragments (V) with igneous aphanite textures to total unstable rock fragments (L), which also include clastic rocks, tectonites, and hornfelses; in practice, gradations from volcanic aphanite to metavolcanic tectonite, from felsite to metatuff, from chert to argillite or tuff, and from quartzite to phyllite or schist complicate the assignment of lithic fragments to classes Q or L, and to subclass V.

In geosynclinal sequences of California and Oregon, three general provenance types can be inferred from the composition of the detrital grain populations:

(1) In sandstones derived from active andesitic volcanic fields, L exceeds F in most rocks, Q is low, and V/L is high. Typical examples are the Lower and Middle Jurassic strata of central Oregon (Dickinson, 1962a) and northern California (Sanborn, 1960) within which many sandstones have compositions near $Q_0 F_{25} L_{75}$ with $P/F \sim 1.0$ and $V/L \sim 1.0$. Hydraulic concentration of crystals gave rise locally to associated rocks with compositions near $Q_0 F_{50} L_{50}$. In these volcanic sandstones, mica is rare and grains of pyroxene and/or hornblende are commonly more abundant than quartz. Rock fragments are mainly microlitic andesitic types but include subordinate felsite.

(2) In sandstones derived from tectonic highlands exposing mainly supracrustal volcanic, sedimentary, and low-grade metamorphic rocks uplifted within the mobile belt, L exceeds F in most rocks, Q is moderate; V/L is low, and C/Q is high. Typical examples are (a) the Late Triassic chert-grain sandstones of central Oregon (Dickinson and Vigrass, 1965, p. 18) having compositions near $Q_{60}F_5L_{35}$, with $C/Q \sim 0.9$ and $V/L \sim 0.4$; and (b) the Late Jurassic and Early Cretaceous sandstones of southwestern Oregon (Dott, 1965) having compositions near $Q_{35}F_{15}L_{50}$, with $C/Q \sim 0.6$ and $V/L \sim 0.2$. Late Jurassic strata of the Lonesome Formation in central Oregon (Dickinson and Vigrass, 1965, p. 65) afford an example of rocks containing detritus from mixed volcanic and tectonic highland sources. Their composition is near $Q_{30}F_{25}L_{45}$, with $C/Q \sim 0.6$, $V/L \sim 0.7$, and $P/F \sim 1.0$.

(3) In sandstones derived from deeply eroded orogens exposing mainly plutonic igneous and high-grade metamorphic terranes, F exceeds L in most rocks, Q is moderate, V/L is moderate to low,

and C/Q is low. Typical examples are the Upper Cretaceous sandstones of southwestern Oregon having compositions near $Q_{50}F_{40}L_{10}$, with C/Q~0.05 and V/L~0.7 (Dott, 1965); and sandstones of the same age in the San Joaquin Valley having compositions near $Q_{40}F_{50}L_{10}$, with C/Q~0.05 and V/L~0.1. (E. V. Tomesis, 1966 Stanford Ph. D. Dissertation.) These arkosic rocks commonly contain 5-10% mica flakes of sand size. Eocene rocks of the Umpqua and Tyee Formations in southwestern Oregon (Dott, 1965; Rogers, 1966) afford an example of rocks containing detritus from mixed volcanic and plutonic sources. Their compositions are near $Q_{30}F_{32.5}L_{37.5}$, with C/Q~0.15 and V/L~0.85.

There may also be within the region Paleozoic sandstones composed of quartzose detritus transported into the mobile belt from the craton. Descriptions of pre-Permian metasandstones in the northern Sierra Nevada are suggestive of such a provenance (Stewart-Alexander, 1967 Stanford Ph.D. Dissertation).

Variations in sandstone composition

Most actual sequences of great thickness within the region include at different horizons sandstones whose compositions are indicative of different provenance types. Where it can be shown that the positions of the source regions did not vary, these provenance indicators must reflect the tectonic evolution of the sources. The volume of the sedimentary accumulations is commonly so great as to suggest that large proportions of the source terranes were destroyed during the process of erosion and sedimentation. In these cases, the only remaining record of the upper structural levels of the source regions lies buried in the sedimentary sequences to which they contributed detritus. The record is inverted, for the detritus first eroded is buried deepest.

The late Mesozoic strata of California afford an outstanding example of such complementary erosional-depositional relationships. The combined volume of the Franciscan Assemblage and the Great Valley Sequence, two coeval Coast Range facies derived from the Klamath-Sierra Nevada region, is nearly 5×10^5 cubic miles (Bailey and others, 1964, p. 21, 123). This colossal figure closely matches the estimated volume of material eroded from above the Sierra Nevada region as deduced from the depths of erosion inferred by Bateman and Wahrhaftig (1966, p. 125). Stratigraphic relationships within the Franciscan Assemblage are too uncertain for detailed analysis, but the orderly succession of the Great Valley Sequence permits a detailed evaluation of time-dependent trends in sedimentary petrology during sedimentation. The record within the strata indicates that the source was a complex volcano-plutonic orogen that was torn apart by erosion even as it was built, so that only its roots are now seen.

The Great Valley Sequence of the Sacramento Valley includes about 15 km. of clastic sedimentary strata bedded in the style of turbidite sand bundles intercalated in an enclosing lutite phase (Crook, 1959). The approximate mean composition of the major sandstone bodies in the area between Cache Creek and Lodoga is given in Table 1. The grid of the table is too coarse to illustrate smaller-scale variations. In the Aptian and Albian strata of the Lower Cretaceous, for example, two kinds of sandstones are present: a type ($\sim Q_{55}F_{22.5}L_{22.5}$) derived largely from plutonic sources and a second type ($\sim Q_{20}F_{25}L_{55}$) derived largely from volcanic sources. A similar but less pronounced oscillation of plutonic and volcanic influences can be noted in Turonian strata of the Upper Cretaceous where the

Table 1. Approximate mean modal composition of major sandstone bodies within the late Mesozoic Great Valley Sequence between Cache Creek and Lodoga, Sacramento Valley, California (generalized after unpublished data of R. W. Ojakangas and E. I. Rich, Stanford University); see text for explanation of symbols.

Unit	Stage	Q	F	L	P/F
Guinda	Campanian	40	40	20	0.6
Sites	Turonian	35	40	25	0.65
Venado	Turonian	30	35	35	0.7
"Salt Creek" or "Brophy Canyon"	Albian	35	25	35	0.75
Unnamed	Aptian	50	25	25	0.8
"Leesville"	Valanginian?	45	30	25	0.85
"Blue Ridge"	Berriasian?	25	30	45	0.85
Unnamed	Tithonian	5	20	75	1.0

analogous variants have compositions near $Q_{30}F_{40}L_{30}$ and $Q_{20}F_{30}L_{50}$. These variations appear to record recurrent rejuvenation of volcanism in the source region, and some rocks in the sequence contain recognizable bipyramidal quartz grains and some sanidine grains. The dominant progression from volcanic sandstones in the Upper Jurassic to arkoses in the Upper Cretaceous records the evolution of the volcano-plutonic source from a volcanogenic superstructure to a batholithic infrastructure.

Superimposed on the reversible variations in the proportions of aphanitic and phaneritic igneous detritus is an apparently irreversible decrease in the ratio P/F. This trend is confirmed by the fact that volcanic rock fragments in the Upper Jurassic and Lower Cretaceous sandstones contain only plagioclase microphenocrysts, whereas those in the Upper Cretaceous contain orthoclase microphenocrysts as well. A parallel trend in sandstones of the same age in southwestern Oregon was noted by Dott (1965). The trend appears to reflect what is known of the composition of plutons intruded at different times in the Sierra Nevada region. Plutons emplaced in the Late Jurassic lay mainly west of the quartz diorite line and contain mainly diorite, tonalite, and trondhjemite. The main plutons of granodiorite and adamellite were not emplaced until mid-Cretaceous times, and could not have vented to support volcanism nor been deroofed by erosion during the time the older parts of the sequence were deposited.

Tectonic evolution of volcano-plutonic orogens

The sedimentary record of the Great Valley Sequence suggests that the volcano-plutonic orogens made of andesitic eugeosynclinal sequences intruded by granitic batholiths may undergo a generic evolution in time and space that can be reconstructed by analogy with what is known of modern island arc systems. If they were ancient arcs, one may infer that they possessed the geophysical and petrologic asymmetry of modern arcs, which have dipping seismic zones beneath them and display a zonal gradation in petrology. The least alkalic lavas would be erupted at the volcanic front with successively more alkalic lavas toward the hinterland (Sugimuro, 1967). The nature of the quartz diorite line (Moore, 1959) and the presence of analogous petrologic gradations among the Jurassic lavas of the Fraser Belt (Dickinson, 1962b, p. 1252), suggest that a similar spatial asymmetry in petrochemistry existed within the Mesozoic eugeosynclinal belt. The time-dependent decrease in P/F noted for late Mesozoic sandstones derived from an evolving orogenic arc in California suggests the possibility of a time asymmetry in addition to the spatial asymmetry.

If emphasis on the increased potash content in successively younger increments of a volcano-plutonic orogenic belt is correctly placed, then three alternative interpretations present themselves. If levels of potash content in arc magmas are set by conditions of partial melting along the inclined seismic zone in the mantle beneath the arcs (Dickinson and Hatherton, 1967), then increased potash content would reflect a migration of the surficial volcanic chain relative to the seismic zone, or vice versa. If potash contents of arc magmas are controlled by crustal contamination of mantle-derived basaltic magmas or zonal melting of the lower crust, then increased potash would presumably reflect a growing thickness of crust or a more effective mobilization of crustal material. If potash contents of arc magmas depend upon anatectic processes within the crust (Fiske and others, 1963, p. 91), then an increase could reflect melting of different parts of a growing geosynclinal prism.

The inferred increase in potash content with time cannot be valid on a wholesale regional scale, but can only apply arc by arc. For example, lower Tertiary sandstones of western Oregon with P/F $\sim$ 1.0 (Rogers, 1966) rest on Upper Cretaceous sandstones with P/F $\sim$ 0.5 (Dott, 1965). The Upper Cretaceous sandstones were derived mainly from Mesozoic plutonic sources that had undergone deep erosion, whereas the lower Tertiary sandstones were derived largely from the juvenile volcanic arc of the ancestral Cascade Range.

Plots of $\%K_2O$ vs $\%SiO_2$ (Fig. 1) for selected volcanic and plutonic suites in California and Oregon illustrate important similarities and differences. Among the late Cenozoic lava suites, there are systematic variations that may reflect the tectonic position of the different volcanoes. In the plot shown, it is clear that the levels of potash content in the lavas of the Medicine Lake Highlands are consistently higher than in the lavas of Crater Lake. Lavas of Lassen Volcanic National Park display intermediate levels that partly overlap both.

As shown in Figure 1, the potash contents in the Crater Lake suite are similar to those in the early Cenozoic Western Cascade lavas of Oregon and in the Late Jurassic plutons in the Sierran foothills. Potash contents in the lavas of the Medicine Lake suite are similar to those in the Cretaceous plutons of the Sierran crest. The significance of these relationships remains in doubt, but their existence emphasizes the likelihood of linkages between volcanism and plutonism within the mobile belt. As one

cannot examine the volcanic and plutonic parts of an igneous suite at the same structural level, the time perspective of sedimentary petrology may be the best means of bridging this gap.

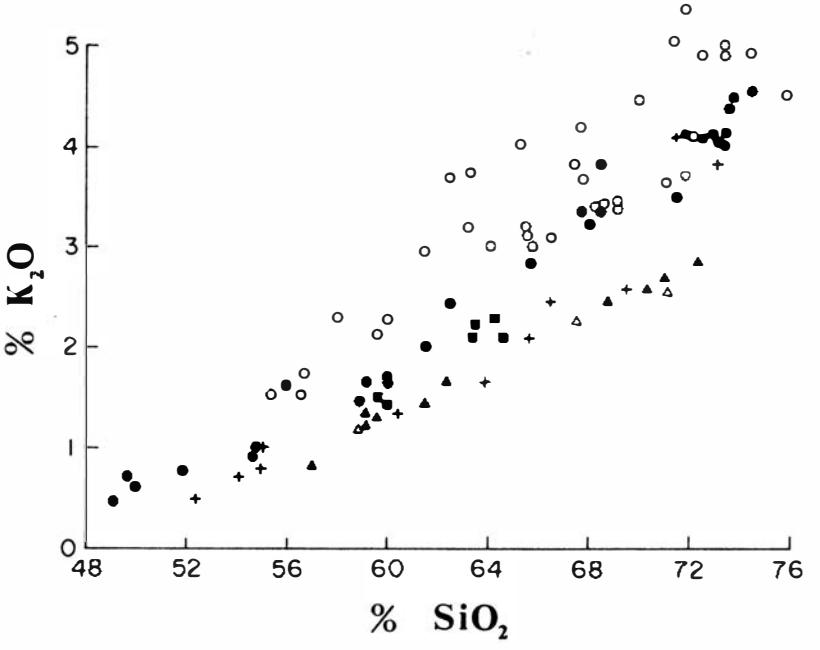

Figure 1. Partial Harker variation diagram of % K_2O vs. % SiO_2 (after recalculation to 100.0% free of volatives and exclusive of analyses with > 2.0% volatiles) for selected Cenozoic lava suites (solid symbols) and Mesozoic pluton suites (open symbols) from Oregon and California. Lava suites include Lassen (squares, Williams, 1932), Medicine Lake Highlands (circles; Anderson, 1941), and Crater Lake (triangles: Clarke, 1904, p. 256-258). Pluton suites include northwestern foothills (triangles; Hietonen, 1951) and central Sierran crest (circles; Bateman and others, 1963 and Clarke, 1904, p. 231-234). Crosses are intrusive and extrusive rocks of the Western Cascade suite (Peck and others, 1964).

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SOME PRELIMINARY OBSERVATIONS ON COMPOSITIONAL VARIATIONS WITHIN THE PUMICE- AND SCORIA-FLOW DEPOSITS OF MOUNT MAZAMA*

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Abstract

Pumice blocks of markedly different lithology are intimately associated with one another throughout the scoria-flow deposits and in the upper parts of the underlying buff pumice-flow deposits of Crater Lake National Park and vicinity. About a third of these pumices are phenocryst-poor and have bulk chemical compositions and refractive indices of the glass phase almost identical to those of pumice blocks from the lower part of the pumice-flow. The remainder show wide variations in bulk chemical composition, amount, size, and proportions of phenocrysts, and in the index of refraction of the glass phase. Banded pumices and aggregates (crystal cumulates?) of plagioclase and mafic phenocryst euhedra bound together by small amounts of vesiculated glass are common. The amount and nature of the phenocryst fraction is more important than glass composition in producing the differences in bulk chemical composition of the individual pumice blocks. An upward change toward more mafic average pumice-block compositions may take place within the scoria-flow deposits. The available data are consistent with mixing of a gradationally zoned magma during ascent and eruption, and mixing of various pumice types within an eruption column and in pyroclastic flows.

Introduction

Howel Williams, in his classic study of the pumice and scoria flows produced by the climactic eruption of Mount Mazama (Williams, 1942), appears to have been the first to recognize systematic vertical compositional variations within pyroclastic-flow deposits. More recently, vertical compositional zonation has been recognized within many ash-flow deposits of both subalkaline (e.g. Ratté and Steven, 1964; Ewart, 1965; Martin, 1965; Lipman and others, 1966; Lipman, 1967; Byers and others, 1968) and peralkaline composition (Noble and others, 1964; Noble, Chipman, and Giles, 1968; Noble, Sargent, and others, 1968). With the recognition of the prevalence of compositionally zoned ash-flow sheets has come the realization that such rock units provide perhaps the best opportunity for studying the high-level differention of magmas of silicic and intermediate composition.

Field Observations

The senior author spent several days during the summer of 1967 studying and sampling the pumice- and scoria-flow deposits in and near Crater Lake National Park. Field study of compositional variation was limited to visual estimation of the size, total amount, and relative proportions of the phenocryst species in individual pumice blocks[1/] – probably the only way that compositional variations in the non-lithic fraction of pyroclastic deposits can be studied in outcrop.

Early in the field study it was recognized that pumices of grossly different phenocryst content are intimately associated with one another through much of the vertical extent of the deposits. In both the upper part of the pumice-flow horizon and the entire overlying scoria flow, the phenocryst content of individual pumice blocks ranges from less than 5 percent to more than 90 percent by weight. (The

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1/ The term "pumice block" is here applied to any vesicular glassy block of appropriate size regardless of color, vesicle size, or phenocryst content.

Table 1. Chemical data for composite pumice-block samples.

	A49	A111	A147-XP	A147-XM	A147-XR
SiO_2	65.4	65.3	67.4	62.5	55.2
Fe as FeO	2.57	2.51	2.63	3.96	5.67
CoO	2.17	2.25	2.22	3.98	7.33
K_2O	2.41	2.39	2.49	1.76	0.90
No. Blocks	12	10	4	4	4
	A147*	**A194**	**A241-XP**	**A241-XR**	**A241***
SiO_2	61.7	61.6	65.5	58.4	60.6
Fe as FeO	4.09	3.89	2.70	4.87	4.19
CoO	4.51	4.20	2.36	5.53	4.54
K_2O	1.72	1.80	2.42	1.37	1.70
No. Blocks	12	12	5	11	16
	S44	**S77**	**S116-XP**	**S116-XR**	**S116***
SiO_2	66.6	67.2	65.3	57.8	61.6
Fe as FeO	2.44	2.39	2.46	5.37	3.92
CoO	2.16	2.20	2.25	5.88	4.07
K_2O	2.35	2.27	2.26	1.10	1.68
No. Blocks	6	5	7	7	14
	C20-XP	**C20**	**C145-XP**	**C145-XR***	**C145**
SiO_2	64.8	62.5	65.8	58.3	60.1
Fe as FeO	2.66	4.09	2.80	5.47	4.84
CoO	2.39	4.47	2.67	6.02	5.22
K_2O	2.38	1.82	2.41	1.32	1.58
No. Blocks	7	17	5	16	21

A, specimens from Annie Creek (west bank at lat. 42°49'5" N.); S, specimens from Sand Creek (south bank at long. 121°59'20" W.); C, specimens from Castle Creek (south bank at long. 122°14'55" W.). Numbers indicate height in feet above stream level. Suffixes XP, XM, and XR indicate composite samples of low, medium, and high phenocryst content, respectively. Asterisk indicates values calculated from other data obtained on specimens from the same level.

terms "pumice flow" and "scoria flow" as here used are based on color, the transition being drawn at the more or less gradational upward change from buff to gray.) The proportion of mafic phenocrysts to plagioclase varies from block to block, as commonly does the size and the length to breadth ratio of the hornblende prisms. Banded pumices and clots of phenocrysts (crystal cumulates?) held together by a very small quantity of vesiculated glass and glass fibers are not uncommon.

Pumices in the lower half to two-thirds of the buff pumice-flow horizon do not exhibit this marked variability; they contain 10 percent or less of phenocrysts, mainly plagioclase, and apparently lack any trace of compositional banding.

Sample Collection

Pumice blocks were collected from various arbitrarily selected levels within the flow deposits at three separate localities (Table 1). The pumices were cut from the outcrop and bagged as removed with no preliminary sorting. The samples from a given level were obtained from within vertical and horizontal distances of 2 and 5 feet, respectively. From 5 to 21 blocks were collected from a given station (Table 1), depending on the heterogeneity of the pumice-block population.

Laboratory Study

Partial chemical analysis: Equal weights of material were removed from each pumice block, and those from the same collection locality combined to form composite samples. For several stations the blocks were divided into subgroups on the basis of visually estimated phenocryst content and composite samples representing these subgroups were prepared.

Duplicate pellets of the composite samples and U.S.G.S. standards G-2, AGV-1, GSP-1, and BCR-1 were prepared using standard lithium tetraborate plus lanthanum oxide fusion techniques (Rose and others, 1963). These pellets were then analyzed for silicon, iron, calcium and potassium using a Norelco vacuum X-ray spectrograph equipped with pulse height analyzer. Working curves were constructed from data obtained by analysing the standard pellets prior to and following the analysis of the composite samples. The absence of significant instrumental drift was verified by analyzing one of the standard pellets at least every 20 minutes. Half of the samples were analyzed for iron, calcium and potassium twice, on separate days, to give an estimate of instrumental precision, while the variation in values for the different pellets of the same sample gives an estimate of sample preparation precision. The total relative deviations are $SiO_2 \doteq 1\%$, Fe as FeO = 2%, CaO = 2%, and $K_2O \doteq 1.5\%$.

Refractive index of glass: The refractive index of the glass phase of certain of the pumices was determined in sodium light using new Cargille oils. Although measurement was hampered by the fine vesiculority of the glass and the common presence of numerous fine inclusions, nearly all of the values (adjusted to 25°C) are believed good to $\pm$ 0.002 at the 95 percent confidence level.

If, as seems likely, the glasses of the pumice- and scoria-flow deposits approximate a two end-member series with respect to their chemical composition, refractive index should provide a reasonable estimate of position within the series. We have used a working curve constructed utilizing refractive index data on the glass of four of the pumices studied by McBirney (1968) [1/] to infer the chemical compositions of our glasses.

Results and Discussion

The partial chemical analyses are given in Table 1 and are summarized in Figure 1 utilizing the parameter ($1/3\ SiO_2 + K_2O$ - Fe as FeO - CaO), an empirical parameter similar to one proposed by Larsen (1938). The data corroborate and extend the results of the field study. Very little, if any,

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[1/] We have determined the following values for n_d at 25°C: 1, 1.502_5; 4, 1.507; 5, 1.523; and 6, 1.524, all $\pm$ 0.001. The glass of pumice 3 was too vesicular to measure accurately but the index of refraction lies between 0.502 and 1.510. No material from specimen 2 was available for measurement.

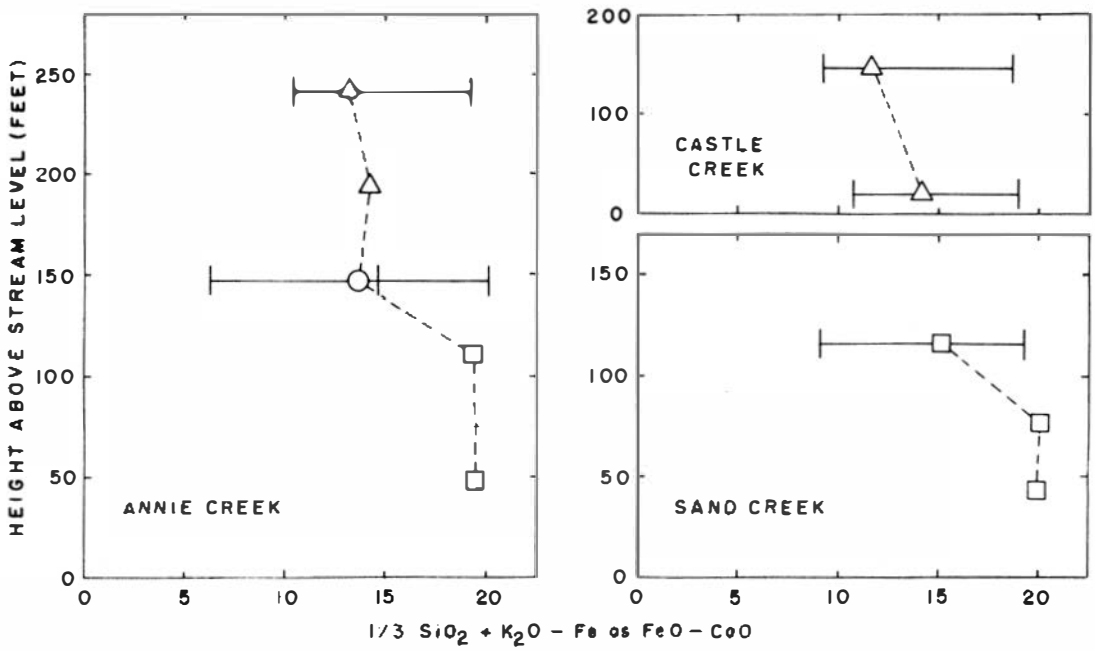

Figure 1. Plot of the parameter (1/3 SiO_2 + K_2O - Fe as FeO - CoO) against height above stream level for the composite samples. Horizontal lines connect composite samples (vertical bars) at stations for which two or more composite samples were prepared. Dashed lines connect average pumice-block compositions of the stations. Square indicates station in pumice flow; triangle, station in scoria flow; and circle, station in transition zone.

variation in average pumice composition is apparent within the lower part of the pumice flow. The refractive index values for the pumices from stations S77 and A111 (Figure 2) are almost within the limits of error of the individual measurements, indicating very little or no variation in the composition of the glass phase.

The differences in the chemical composition of the various subgroup composite samples (Table 1, Fig. 1) and the wide range in glass refractive index (Fig. 2, Fig. 3), however, show that the ranges in both whole-pumice and glass composition within individual sample localities in both the scoria flow and the upper part of the pumice flow are nearly as great as the range within the entire deposit. The most felsic pumices from the upper part of the pumice flow and from the scoria flow are at most only slightly more mafic than the pumices from the lower part of the pumice flow. The composite samples of crystal-poor blocks closely approximate the most felsic pumice compositions present at the particular horizons. However, the range in crystal content and in the refractive index of the glass of the more crystal-rich blocks, as well as analyses of single scoria blocks from the literature (Williams, 1942; McBirney, 1968), indicate that composite samples of more crystal-rich blocks are appreciably less mafic than certain of the individual blocks present in the samples.

Finally, the chemical data for the Castle Creek and Annie Creek sections suggest a general upward progression toward more mafic average block compositions within the scoria-flow interval.

McBirney (1968) has shown that variations in the chemical composition of six pumice blocks from different levels of the pumice- and scoria-flow deposit in Sand Creek reflect variations both in the chemical composition of the glass phase and in the percentage and composition of the phenocryst fraction, with the latter being the more important. The relative importance of the two factors may be shown graphically by plotting a compositional parameter for pumice blocks against the same parameter for the glass fraction of the blocks (Fig. 4). Such data from a suite of pumices in which variation in pumice chemistry is produced solely by the phenocryst fraction would define a vertical line on Fig. 4, whereas data from a suite in which there is no variation in the amount and nature of the phenocrysts would generate a line with a positive slope of slightly less than 45°.

The data for the more mafic composite samples of the present study plot consistently to the left of McBirney's points 5 and 6. This could result if McBirney's pumices have somewhat mafic glass

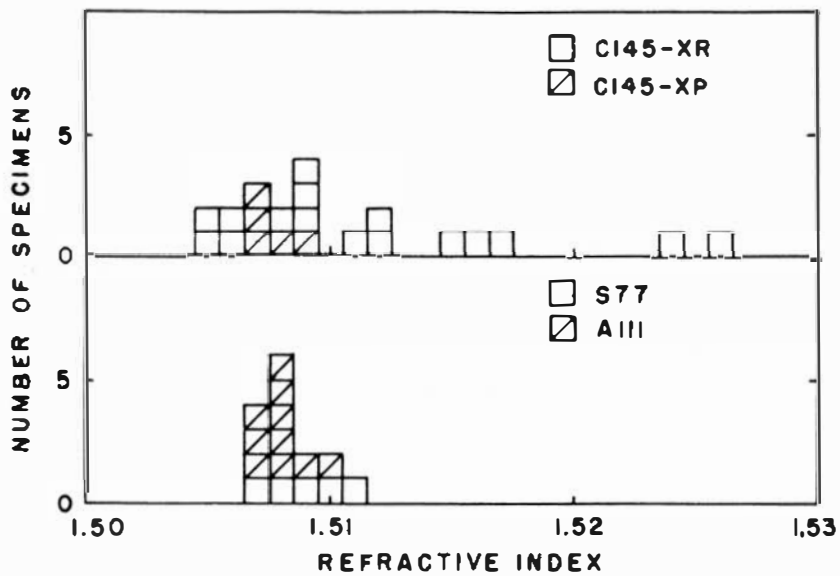

Figure 2. Variation in refractive index of the gloss phase of individual pumice blocks of certain composite samples.

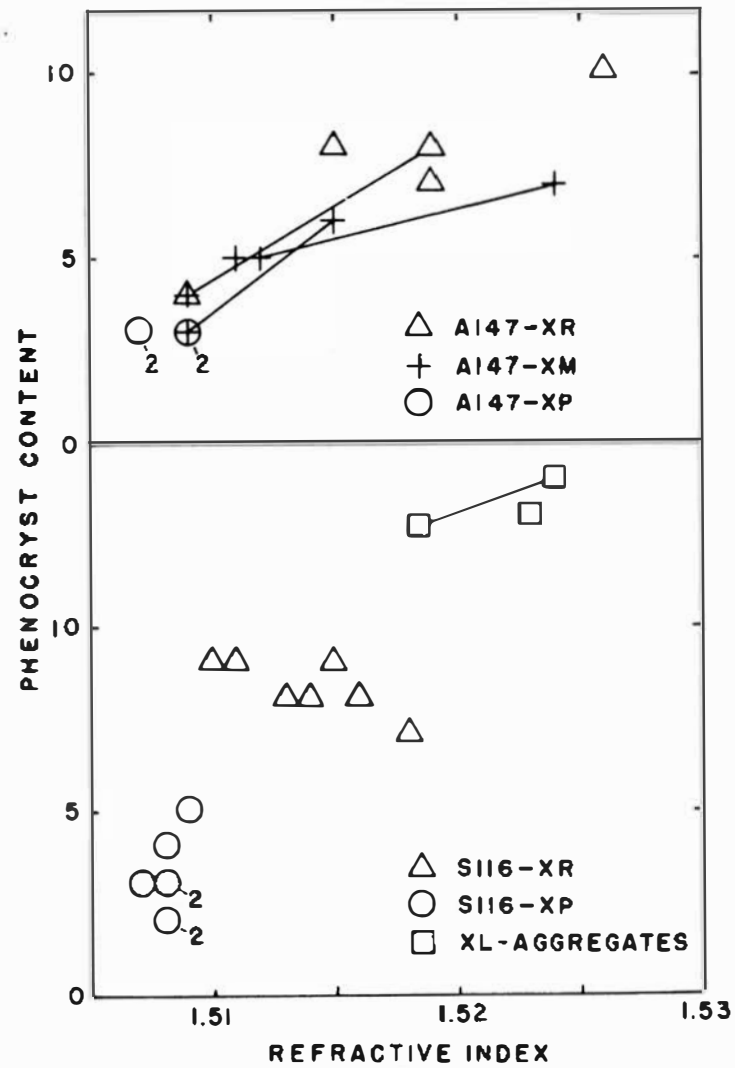

Figure 3. Plots of the refractive index of the gloss phase of individual pumice blocks against the visually estimated phenocryst content (arbitrary approximately geometric scale). Lines connect the two phases of bonded pumices. Crystal aggregates were excluded from the composite samples analyzed chemically. Number 2 indicates that two crystal-poor specimens are plotted at some point. →

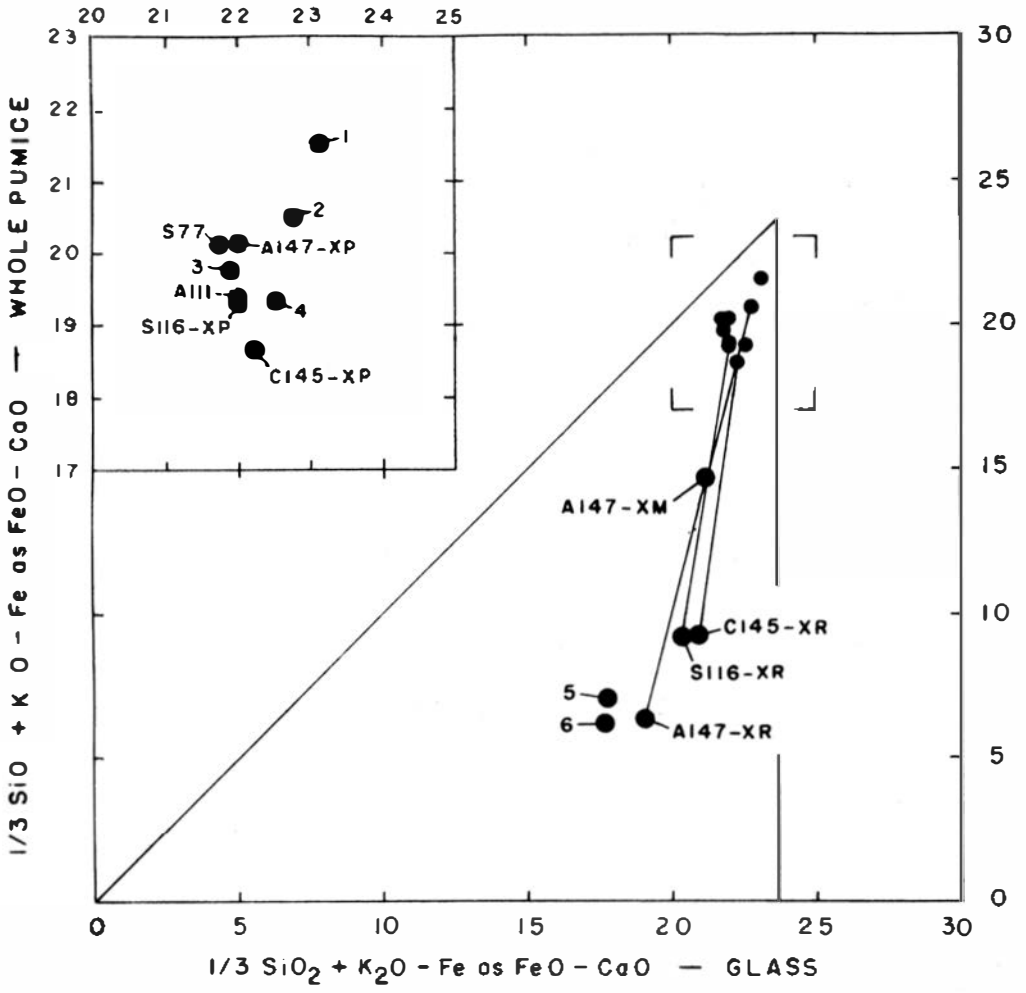

Figure 4. Plot of the parameter ($1/3\ SiO_2 + K_2O$ - Fe as FeO - CoO) for whole-pumice compositions against the same parameter for the associated glass phase of the pumice blocks. The numbers 1 through 6 indicate the bulk pumice-glass pairs (original data, not corrected for water of hydration) of McBirney (1963). Lines connect data for composite samples from the same station.

compositions for their phenocryst content[1/]. Alternatively, refractive index may not provide on accurate measure of gloss composition, possibly because the formation of the minute inclusions, presumably iron-titanium oxides, which crowd many of the glasses tends to lower the refractive index of the gloss. In any case, there seems little question that the variations in whole-pumice composition observed within the pyroclastic deposit mainly reflect variations in the amount and type of phenocryst material.

Williams (1942) suggested that the pumice- and scoria-flow sequence was produced by the eruption of a compositionally zoned magma composed of phenocryst-rich andesitic magma overlain by phenocryst-poor dacite. The present data is consistent with this model, although the continuum of both pumice and gloss compositions suggests that the upward transition from more mafic to more felsic compositions within the magma was more gradational than envisioned by Williams and by McBirney (1968). Moreover, the compositional range is somewhat greater than implied by the terminology of Williams, for the most silicic of the pumices perhaps are better classified as rhyodacite or even rhyolite.

In all probability, several mechanisms combined to produce the mixture of pumice types found throughout the upper part of the deposits. As evinced by the common occurrence of banded pumice, some of the heterogeneity almost certainly resulted from the mixing of magmas during upwelling into the vent or vents immediately prior to eruption. Some may reflect simultaneous eruption of magmas of different composition from separate vents which tapped different levels of the magma chamber. Finally, considerable mixing of successively erupted felsic and mafic pumices could well have taken place within a vertical eruption column and also in the turbulent pyroclastic flows that carried the blocks to their present location. Detailed study of the entire pumice- and scoria-flow deposit will be required before the relative importance of the several mechanisms can be evaluated.

The close physical association of pumice blocks of different composition has been described in the Aso III (ash-flow) sheet in Japan (Lipman, 1967) and in the Rainier Mesa Member of the Timber Mountain Tuff in southern Nevada (Byers and others, 1968) and has been observed by the senior author and others in the Eureka Valley Member of the Stanislaus Formation in eastern California (Slemmons, 1966), and in the Thirsty Canyon Tuff in southern Nevada (Noble and others, 1964). Similar, although perhaps not so pronounced, variations in pumice lithology very likely are present in many other ash-flow sheets. Besides introducing an additional degree of variability which must be taken into account during petrographic and chemical studies, the association of pumices of different mineralogical and chemical composition provides a potentially useful tool with which the mechanisms of pyroclastic eruption and transport may be studied.

Acknowledgments

We are indebted to A. R. McBirney for providing samples of his analyzed pumices and the unrecalculated chemical data for the pumice-gloss pairs. D. W. Chipman assisted the writer in the field and made preliminary chemical determinations on certain of the composite samples.

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1/ McBirney's analyses 5g and 6g probably do not approximate the most mafic gloss compositions present in the scoria-flow deposits, for Williams (1942, p. 146) reports gloss with a refractive index of more than 1.53, and gloss from a pumice from A194 was found to have a refractive index of 1.531.

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ANDESITES OF THE CHILEAN ANDES

Hans Pichler* and Werner Zeil+

Abstract

The High Cordillera of northern Chile between 18° and 27° southern latitude is characterized by imposing chains of about 600 "andesitic" stratovolcanoes. They rest on the Rhyolite Formation which predominantly consists of rhyolitic to rhyodacitic ignimbrites of enormous extent (more than 150,000 square kilometers). A second area of the "Andesite" Formation in the High Cordillera of central and southern Chile lies between 33° and 44° southern latitude.

Twenty-four new chemical analyses of representative volcanics from the "Andesite" Formation of northern Chile were made. The calculation of these and of all available chemical analyses from all over the South American Andes shows that a great portion of the so-called "andesites" of the Andes are not andesites, but latite-andesites (trachy-andesites). No basalts were found.

The bulk of the volcanic rocks of the north Chilean "Andesite" Formation are latite-andesites, whereas those of central and southern Chile are mostly normal andesites. This N-S trend from latite-andesites towards andesites coincides with a more recent and greater activity in the central and southern areas.

Volcanism of the "Andesite" volcanoes in northern Chile is closely connected with that of the Rhyolite Formation. There are evidences that these acidic magmas originated by melting of sialic material in the upper parts of the crust (Zeil and Pichler, 1967). Field relationships, petrographic, and major and minor element behavior are certainly inconsistent with a fractional crystallization origin of the latite-andesites and andesites from a basaltic or high-alumina basaltic magma. The available data are believed to be most consistent with the existence of a primary andesitic magma which originated by partial fusion of material of the lower, degranitized parts of the crust. This possibility is substantiated by comparisons with the andesites and basalts of the Chilean Pacific islands of Juan Fernández. The oceanic andesites of these islands are, in contrast to the continental andesites and latite-andesites of the Andes, products of differentiation of a basaltic parent magma.

In the South American Cordillera there are three extensive areas of young volcanism:

1. In the North, the zone of Colombia/Ecuador between 5° northern latitude and 2° southern latitude. Well-known, currently active volcanoes of this region are the Tolima in Colombia and the Cotopaxi in Ecuador.

2. In the central section, a zone following the bending of the Andes, between 15° and 27° southern latitude in the High Cordillera of Peru, Chile, Bolivia, and Argentine (fig. 1).

3. In the South, a region east of the "Längstalgraben" of Central and Southern Chile with numerous active volcanoes, extending from 33° to beyond 44° southern latitude. Among the "andesitic" stratovolcanoes of this area the currently active volcanoes Llaima, Villarica, and Calbuco shall be mentioned.

The central section with an extension of about 2000 kilometers by 100 to 200 kilometers which shall be dealt with in this paper, is distinguished from the northern and southern region of volcanic activity by the following characteristics:

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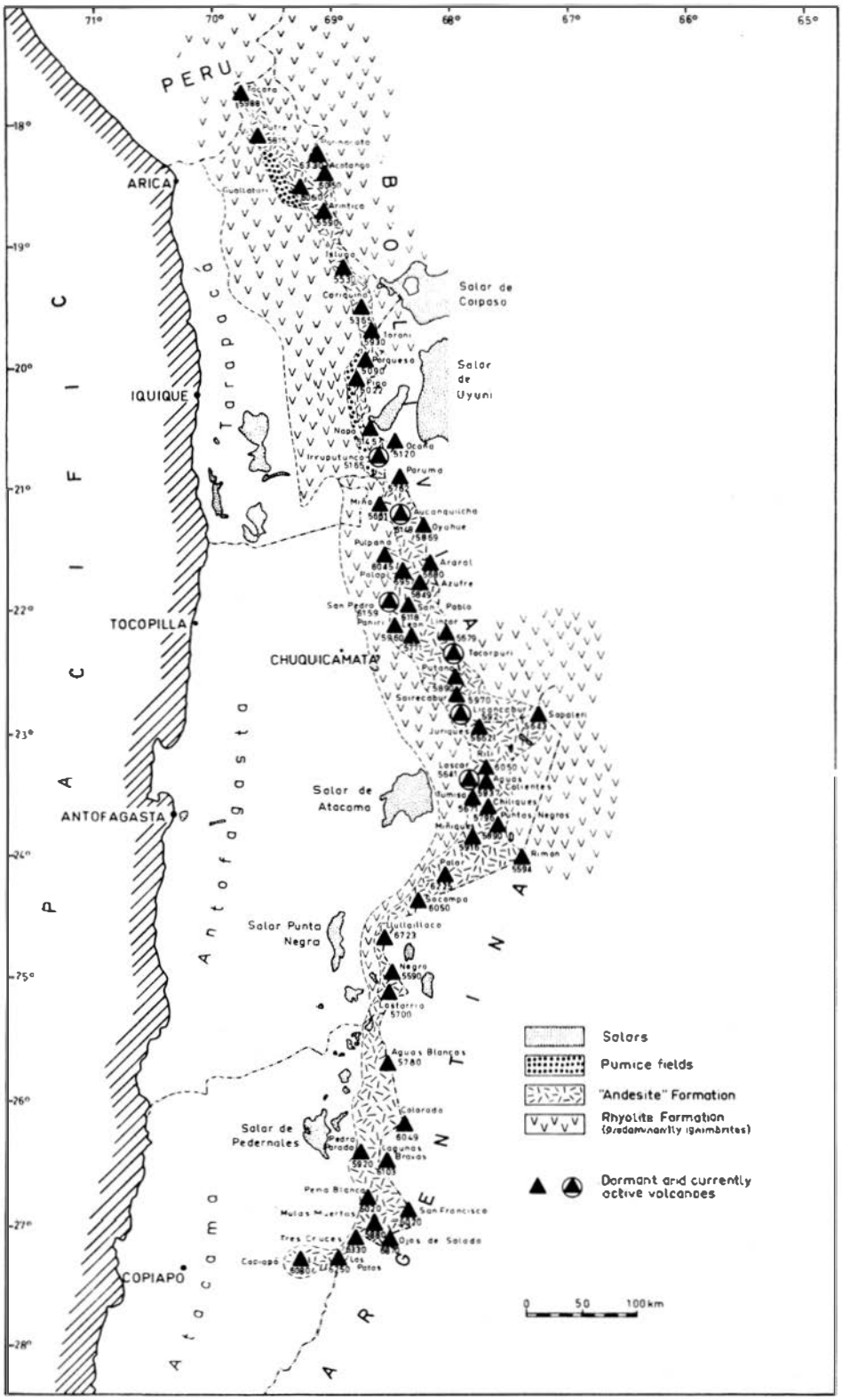

Figure 1. Extent of the young volcanism in the North Chilean Andes. From Zeil (1964 b).

a) The present activity is weak. Though until now no radiometric data were obtained from the "andesites," it may be presumed that the paroxysm of activity was taking place earlier than in the North and in the South of the Andes, at about the boundary of Pleistocene to Holocene time.

b) The morphological feature of the Western Cordillera is entirely characterized by more than 600 stratovolcanoes forming a continuous line of peaks with altitudes between 5000 and 7000 meters perched on on altiplano of on average altitude of 4000 meters (fig. 2). In this port of the High Cordillera, the highest and greatest number of stratovolcanoes on earth are concentrated.

c) The young "ondesitic" stratovolcanoes pierce vast sheets of rhyolitic to rhyodocitic ignimbrites -- their extension of more than 150,000 square kilometers makes it one of the largest Cenozoic Rhyolite Formations on earth (Zeil & Pichler, 1967). According to the results of isotopic age determinations (Clark et ol., 1967; Hollingsorth, 1964; Rutland et al., 1965), these siliceous volcanic rocks were erupted between upper Miocene and lower Pleistocene time.

The stratovolcanoes ore arranged along tectonic lines which on the whole are parallel to the strike of the Western Cordillera; in detail, however, they also follow deviating directions. It is important to note that there is no Cenozoic volcanism in the Coastal Cordillera. The enormous volcanic mobilization since Miocene time is restricted to the High Cordillera; it occurred in connection with heavy tectonic fracturing between the Coastal Cordillera and High Cordillera, as well as with recent uplift of the High Cordillera.

Although the young "andesite" volcanism is of great importance for the character and composition of the central section of the Andes, very little was known until recently concerning the geology and volcanology, and almost nothing concerning the petrologic and geochemical composition of the volcanics. It was only recently that Zeil (1960, 1964 a, b), Zeil & Pichler (1967) and Kotsui & González (1968) communicoted a number of data.

Until now there has been little doubt that the petrologic composition of the young stratovolcanoes corresponds to andesites and basalts (Hausen, 1938; Larsson, 1940; and others). The chemical analyses and petrologic results of our investigations, however, show a picture which differs considerably from the former concept and reveals new aspects of the development of the substructure of the Andes. A comparative sample (No. 24) from the volcano Cotopaxi (Ecuador) and the analyses of Hausen (1938), Katsui & Gonzáles (1968) from the central section of the Andes and those of Kittl (1944), Klerkx (1965), Larsson (1940), and Quensel (1912) from southern Chile show the great uniformity of the products of recent volcanism of the Andes as compared to those of the Chilean Juan Fernández Islands in the Pacific Ocean. The still very schematic concept of the structure of the earth's crust and the upper mantle in the central section of the Andes will have to be revised within the coming years. Unfortunately, detailed studies of geologic and geophysical sections of the fault zone between Coastal Cordillera and High Cordillera as well as investigations of the fractured structures within the High Cordillera ore still missing.

A great number of rock samples of the so-called "Andesite" Formation were collected by W. Zeil in the North Chilean High Cordillera in 1956, 1962, and 1966. Twenty-four representative specimens were selected for chemical analyses. The results will be published in Siegers, Pichler & Zeil (in press). Almost all of the onalyzed rocks are from lava flows erupted during Holocene time. Hence, they ore the youngest emissions of the stratovolcanoes. When selecting samples for analysis, preference was given to olivine-bearing, dark rocks of basaltic appearance, since according to the prevailing opinion they could be expected to be equivalent to basalts.

These new analyses as well os all others available from the South American Andes were converted to their normative mineral composition. This calculation was carried out after a new method recently developed by A. Rittmann (in press). The rocks were classified according to their calculated mineral composition*. It was found that the major port of the so-called "andesites" of the Andes ore not true andesites, but lotite-ondesites (= trachyondesites). This applies, above all, to the central section of the Andes: only two of the 31 analyzed volcanics from this area ore andesites, and these ore quartz-bearing types (table 1).

The most basic rock among our analyzed samples is a lotite-ondesite with a silico content of 52.5 percent and a color index of 31.6. Dark volcanics of pheno-basaltic appearance in the field, described in the post as "basalts" or "olivine-basalts" (Hausen, 1938; Larsson, 1940; etc.), turned out to be

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* Classification according to Streckeisen (1966, 1967; see fig. 3).

Figure 2. "Andesitic" strato-volcano Llulloillaco (6723 m; Northern Chile, Lat. 24°43' S., Long. 68°33'W) from NNW. Young historical summit lavo flow. In the foreground pumice field of the Rhyolite Formation.

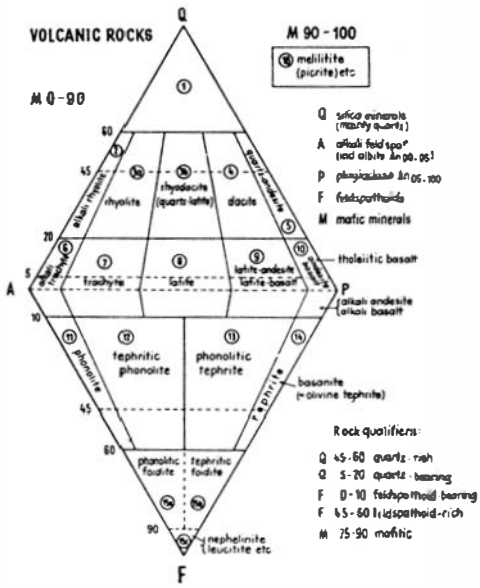

Figure 3. STRECKEISEN classification of volcanic rocks in the double-triangle Q-A-P-F, according to their actual or calculated mineral composition. From STRECKEISEN (1967).

Table 1. Distribution of rock types and range of SiO_2 and colour index of the analyzed volcanics of the "Andesite" Formation in the South American Andes.

	North Chilean Andes and adjacent areas			Central and South Chilean Andes			Colombia and Ecuador		
		Range of SiO_2 (percent)	Range of colour index		Range of SiO_2 (percent)	Range of colour index		Range of SiO_2 (percent)	Range of colour index
Rhyodacites	3	62.7 - 64.4	11.5 - 12.7	-	-	-	-	-	-
Dacites	1	61.5	14.6	-	-	-	3	63.2 - 71.3	5.8 - 13.8
Quartz-bearing latites	3	61.4 - 63.3	12.2 - 13.9	1	62.1	11.6	1	64.1	17.6
Quartz-bearing latite-andesites	19	55.2 - 62.3	11.5 - 25.0[1]	3	53.2 - 65.6	10.7 - 27.6	3	59.0 - 64.6	12.4 - 17.1
Latite-andesites	3	52.5 - 55.0	25.0 - 31.8	3	54.2 - 57.4	18.7 - 27.7	2	56.2 - 58.8	20.2 - 30.7
Quartz-bearing andesites	2	54.7 - 56.0	29.8 - 32.6	5	52.9 - 61.8	12.0 - 33.8	1	59.6	15.1
Andesites	-	-	-	13	49.9 - 56.6	17.8 - 33.0	3	52.9 - 55.3	24.0 - 25.7
Others	-	-	-	-	-	-	4[2]	46.1 - 52.9	14.9 - 31.7
Number of available analyses	31[3]			25[4]			17[5]		

1) 16 lower than CI 20.
2) Phonolitic tephrites of volcano Sumaco/Ecuador.
3) Pichler & Zeil: 24 new analyses; Katsui & Gonzáles (1968): 5; Hausen (1938): 2.
4) Klerkx (1965): 13; Kittl (1944): 2; Larsson (1940): 8; Quensel (1911): 2.
5) Pichler & Zeil: 1 new analysis; Colony & Sinclair (1928): 4; Van Wolf (1929): 12.

andesites or quartz-bearing andesites or latite-andesites.

In the central and south Chilean Andes, however, the major part of the analyzed volcanics are--according to their calculated mineral composition--real andesites. This becomes obvious, if we plot the results of analysis into the Streckeisen double-triangle (fig. 4). But throughout the Andes we could find no true basalts among the rocks of the "Andesite" Formation. The highest color index amounts to only 32.6 in the North Chilean Andes, and to nearly 34 in the Central and Southern Andes. The color index for 10 of a total of 18 andesites of the latter region is lower than 30.

The trend from latite-andesites in Northern Chile towards andesites in Central and Southern Chile coincides with a more recent and greater activity in these central and southern areas.

The common and most abundant latite-andesites and andesites of the Andes are broadly uniform in mineral composition. Phenocrysts are mostly plagioclases (most commonly labradorite) which exhibit reverse and oscillatory zoning, indicating non-equilibrium conditions during crystallization. Glass inclusions in the plagioclases are very abundant. Groundmass laths of plagioclase are andesinic (An_{32-46}). Most of the rocks are characterized by two pyroxenes, hypersthene and augite. A number of samples contain olivine (mostly corroded cores), hornblende and (or) biotite. Thus these rocks belong, in mineralogical respect, to the "hypersthene suite" of Kuno (1950).

Trace element determinations of the analyzed volcanic rocks of the North Chilean "Andesite" Formation yielded the following results (Siegers, Pichler & Zeil, in press): Barium abundances are closer to the average Ba content of the crust than to that of oceanic basalts. The same is generally found with regard to Rb contents. Sr values are mostly higher than Sr abundances in Japanese and New Zealand andesites (Taylor & White, 1966). The content of Ni is, in general, conspicuously lower and does not agree with an origin of the North Chilean "Andesites" by fractionation of a basaltic magma.

Field criteria show that the "Andesite" Formation is closely associated with the Rhyolite Formation in time and space. This is also shown by the rock-type distribution in the Streckeisen double-triangle (fig. 4). The siliceous rocks of the Rhyolite Formation are alkali-rhyolites, rhyolites and rhyodacites (= quartz-latites). We see that there is no gap in the distribution of the rocks of both formations, but a gradual transition. This close connection is also obvious, if we consider the serial index (ϑ-method of Rittmann, 1957; fig. 5). Both formations show the same serial index: on the average, they belong to the calc-alkaline assemblage (distinctly calcalkalic). For comparison, we have also plotted all available analyses of the samples from the Juan Fernández Islands in the diagram. This volcanic archipelago is situated in the eastern Pacific (Lat. 33° 39.5' South, Long. 78° 51' West). Among the volcanic rocks of these islands, there are basalts and andesites, but andesites of quite another type than those in the Andes. Their serial index is sadic.

From the Juan Fernández group, 8 analyses are published (Quensel, 1912, 1953). Among these are 4 olivine-basalts (SiO_2 ranging from 43.4 to 46.5%, CI 36.1-66.1) and 3 andesites (SiO_2 ranging from 46.1 to 47.6, CI between 34 and 35). One analysis is of no use (altered material).

These oceanic andesites, which according to MacDonald (1960) are hawaiites and mugearites, belong to the alkaline suite. In mineralogical respect, they are very different from the two-pyroxene andesites and hornblende-bearing andesites of the Andes. Thus the plagioclase phenocrysts in the andesites of the Andes are labradorite, those in the rocks of the Juan Fernández Islands are andesine and oligoclase. Hypersthene is absent in the Juan Fernández lavas and their color index is much higher than that of the continental andesites. The dissimilarity is evident from chemical analyses as well. Thus both the total silica content and the ratio of silica to alkalis is much lower in the Juan Fernández andesites than in those of the High Cordillera.

In view of this obvious dissimilarity, the origin of the High Cordillera andesites and of those of the Juan Fernández Islands must be quite different. The latter are considered to be products of fractionated crystallization of a basaltic parent magma, as are similar rocks of other islands of the mid-Pacific Ocean.

The dissimilarity between these oceanic andesites and the continental andesites and latite-andesites of the High Cordillera becomes even more evident, if we consider the relation between the ϑ-values and the silica content in both cases. Gottini Grosso (1968) has found that the ϑ-value which is taken as the relation Al_2O_3-Na_2O/TiO_2 (in weight per cent of the analysis), is very low for oceanic basalts and andesites, but relatively high for continental ones. The oceanic volcanic rocks of the Hawaiian and other mid-Pacific islands have ϑ-values lower than 6, continental andesites are characterized by higher ones (generally above 9). If we compare the ϑ-values of the Juan Fernández volcanic rocks and the High Cordillera andesites and latite-andesites, we get a conspicuous gap between both rock types (fig. 6). The same is the case in the Alk-Fe-Mg variation diagram (fig. 7).

Field criteria as well as petrologic and geochemical data for the rocks of the "Andesite" Formation

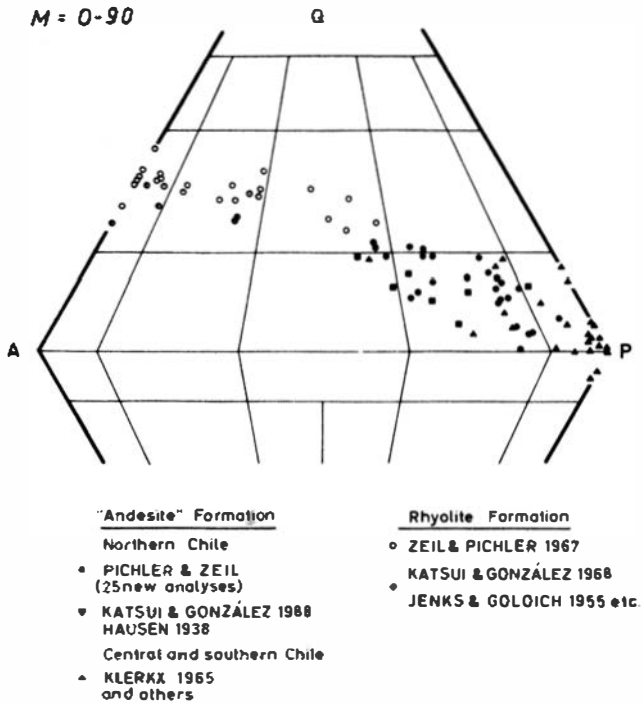

Figure 4. Distribution of all analyzed volcanics of the "Andesite" and Rhyolite Formations in Chile and Peru in the STRECKEISEN double-triangle.

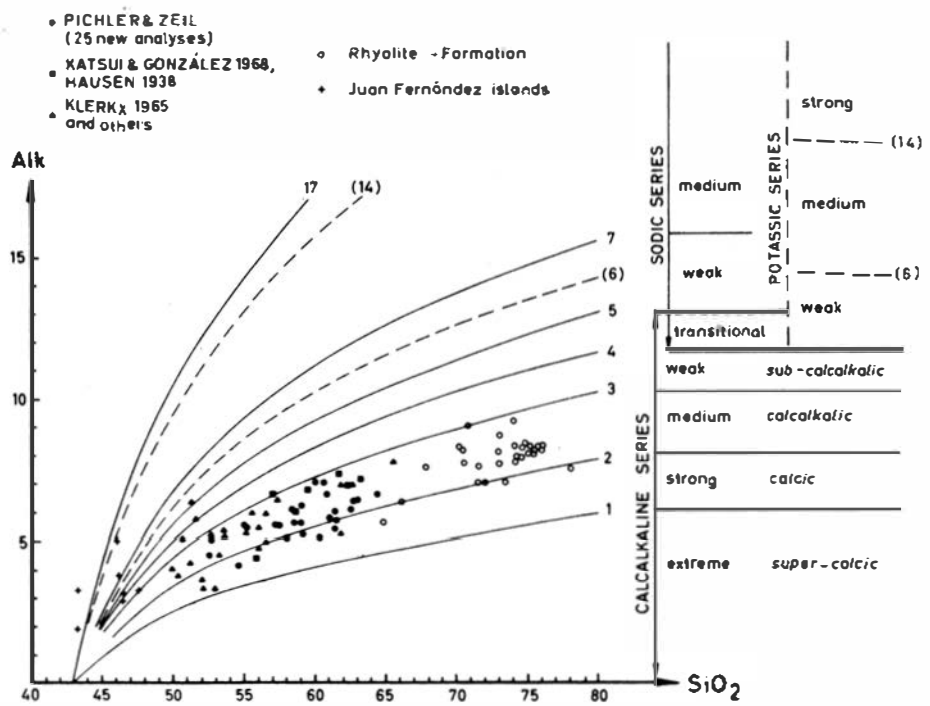

Figure 5. The serial index of all analyzed volcanic rocks of the "Andesite" and Rhyolite Formations in Chile and Peru in comparison to the Juan Fernández Islands.

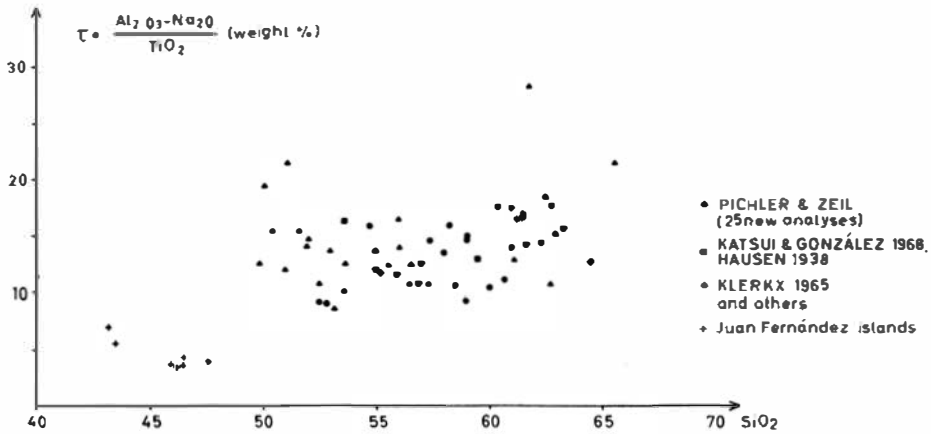

Figure 6. Distribution of ϑ-values vs. SiO_2 of all analyzed volcanics of the Chilean "Andesite" Formation and the Juan Fernández Islands.

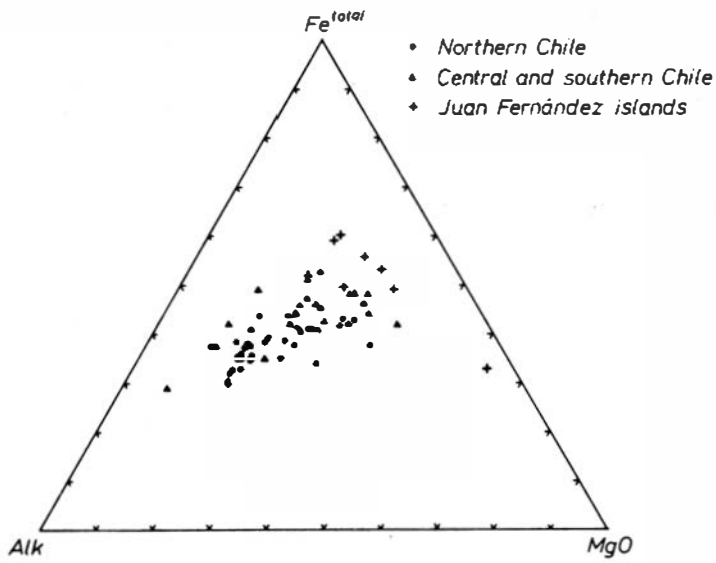

Figure 7. Alk-Mg-Fe diagram showing the relationship between all analyzed volcanics of the "Andesite" Formation of the Chilean Andes and those of the Juan Fernández Islands.

are inconsistent with their derivation by fractional crystallization from a basaltic parent magma, or by direct mantle derivation involving a single stage process. It is suggested that these High Cordillera rocks are products of a primary andesitic magma which is due to partial fusion of material of the lower crust. Evidence for this suggestion is:

1. The total absence of true basalts.

2. The lack of differentiation processes, e.g. the lack of evidence of a complementary basic accumulative fraction, even as xenoliths.

3. The trace element behaviour, e.g. the low nickel content.

4. The close connection between the "Andesite" and Rhyolite Formation, both in space and time, and in their geochemical and petrologic aspects. It was shown that these very voluminous acidic magmas must be derived by a widespread fusion of upper crustal rocks of granitic composition (Zeil & Pichler, 1967). Reasons for preferring this origin are: the enormous volumes of the siliceous volcanic rocks, the Al surplus in the analyzed rocks (manifested by normative cordierite), the existence of aggregates of quartz-xenocrysts, and the trace element behavior (extremely high contents in Cu -- up to 1800 ppm -- and Zr -- up to 12000 ppm --; El Hinnawi, Pichler and Zeil, in press). With the exception of the Cu and Zr contents, there is a continuity in trace element abundances from the Rhyolite to the "Andesite" Formation, according to the increase of the basic character.

5. The high ϑ-values. Taking into consideration the possible origin of the High Cordillera "Andesites" by contamination of basaltic magma by assimilation of siliceous crustal material, we should expect ϑ-values filling the gap between the orogenetic "andesites" of the Andes and those of the Juan Fernández Islands (fig. 6). We can fill this gap by plotting the ϑ-values of Columbia River Basalts (calculated from analyses given by Waters, 1961) in the same diagram (fig. 8). According to these criteria, the Columbia River Basalts contain, besides andesites and latite-andesites, a great portion of true basalts. Some of these Columbia River Basalts may result from contamination of basalts by sialic crustal material.

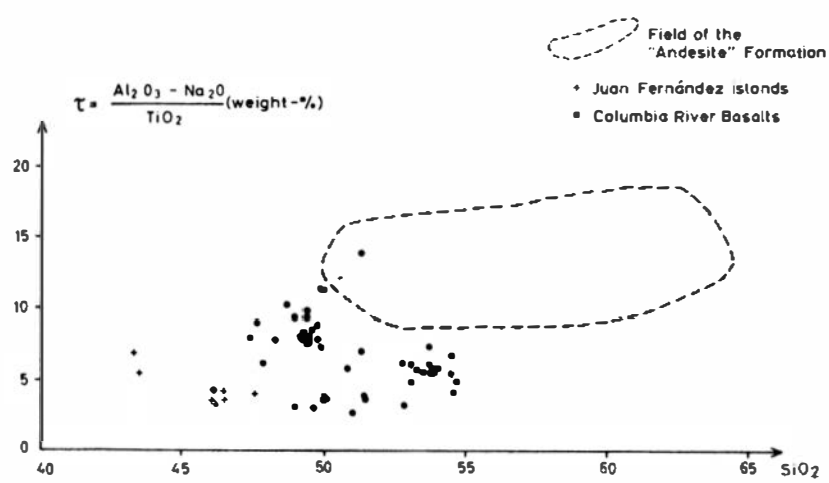

Figure 8. ϑ-values vs. SiO_2 of the Columbia River Basalts in comparison to the volcanics of the Chilean "Andesite" Formation and the Juan Fernández Islands.

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THE VOLCANIC CENTRAL ANDES--A MODERN MODEL FOR THE CRETACEOUS BATHOLITHS AND TECTONICS OF WESTERN NORTH AMERICA*

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Abstract

Modern analogues for the great Late Cretaceous batholiths of western North America appear to be present only in the volcanic fields of the continental margins about the Pacific basin, and particularly in the central Andes. This paper proposes an analogy between volcanic Andes and Mesozoic batholiths, and then infers the paleotectonic setting of the batholiths from the modern setting of the Andes.

Andean volcanism occurs in a belt 200 to 400 km inland from the axis of the Peru-Chile trench, above the Benioff seismic zone dipping under the continent from the trench. The central Andean volcanic field, 100-200 km wide and 2000 km long, faces and is approximately coextensive with the deepest part of the trench, the region of greatest seismicity, and the fastest-spreading sector of the East Pacific Rise. This volcanic field consists of a broad ignimbrite plateau of upper Miocene and younger rhyodacite and rhyolite, from the central part of which rise high stratovolcanoes of andesite and dacite. A huge late Cenozoic batholith has presumably formed beneath the volcanic field.

The major late Mesozoic batholiths of western North America are dimensionally similar to the Andean volcanic field. Andean and batholithic rocks are compositionally similar calc-alkaline assemblages. The Andean rocks are in bulk more silicic than the Mesozoic batholiths, in accord with the demonstration elsewhere that ignimbrites are frequently more silicic than the magmas that remained lower in the chambers from which they come.

The original positions of the North American Mesozoic batholiths have been much altered by Cenozoic rifting, strike-slip faulting, and the volcanic growth of new crust. Reversal of the deformation leads to the interpretation that the batholiths formed at a uniform 150-200 km from the continental margin, and hence in the same position as the modern volcanic Andes.

Late Cretaceous North America was analogous tectonically to modern South America. Following a latest Jurassic and Early Cretaceous period of relative stability and the continental-rise, abyssal-plain, and abyssal-hill sedimentation of the Franciscan Formation, there was a period of rapid mantle motion in Late Cretaceous time. Pacific mantle moved eastward at a velocity of perhaps 100 km per million years, turned downward at a trench at the continental margin, and flowed along an inclined Benioff seismic zone. Melting in the Benioff zone yielded voluminous magma in a belt centered 250-300 km inland from the trench axis. The magmas produced great elongate fields of ignimbrites, beneath which crystallized shallow batholiths. The Franciscan Formation was scraped off the moving mantle against the continental margin.

Introduction

Deductions in the literature regarding the origin and tectonic setting of ancient batholiths have been made primarily from the geologic relationships of the granitic complexes. A batholith represents one vertical zone of exposures in a feature which obviously must give way both upward and downward to quite different complexes, so broad interpretations based on the exposed geology of these zones alone are necessarily incomplete. (The parable of the blind men and the elephant comes to mind.) Further, interpretations become so interwoven with assumptions regarding such problems as the nature of eugeosynclines and the origin of magmas that the conclusions are often mere restatements of the assumptions. An understanding of batholiths has been further retarded by the assumption that there are no modern analogues for them--that batholiths represent mysterious processes active at past times deep in the earth, unrelated to volcanism or other activity of sorts now visible at the surface. This paper pursues the opposite course by assuming that there are indeed batholiths now forming.

Hamilton and Myers (1967) considered various Paleozoic, Mesozoic, and Cenozoic assemblages

* Publication authorized by the Director, U.S. Geological Survey.

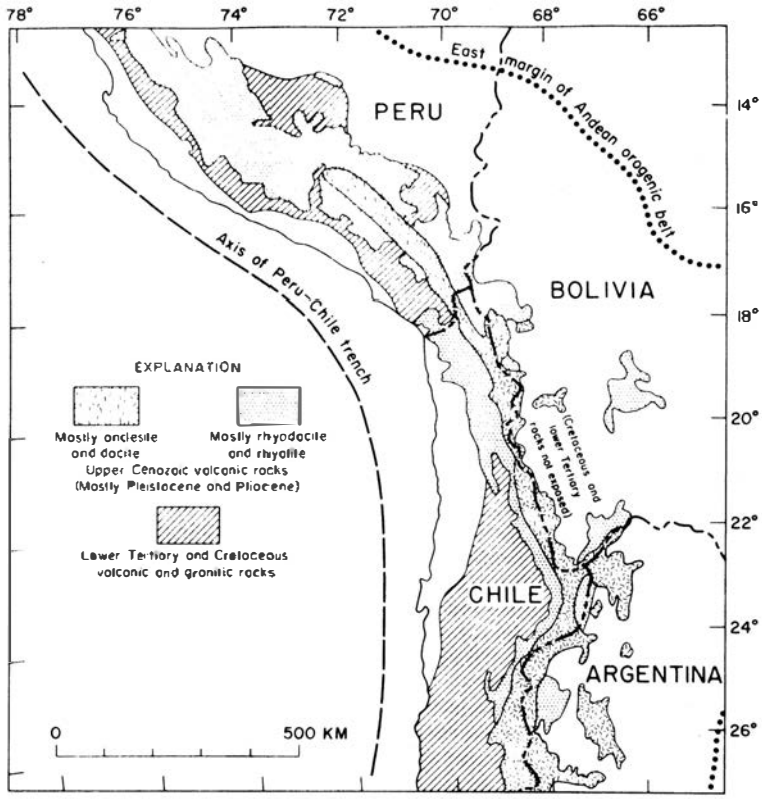

Figure 1. Some volcanic and tectonic elements of the central Andes. Adopted from Zeil and Pichler (1967, fig. 1) and Lomego (1964).

of metamorphic, granitic, and volcanic rocks in the United States to represent different erosion levels in similar complexes. The exposed features of the various assemblages when thus ordered led us to conclude that batholiths are thin, and form from magmas which typically rise completely through the crust and spread out laterally beneath a cover a few kilometers thick of their own volcanic ejecta. The reader is referred to our paper for documentation for these concepts, from which the present paper proceeds.

A corollary is that any very young batholith will be roofed by a broad field of intermediate and silicic calc-alkaline rocks. The problem of finding an active analogue for an ancient batholith then begins with the search for a volcanic field of appropriate composition and dimensions, and proceeds with an analysis of other features of the volcanic and granitic complexes considered to see if they are indeed analogous in other ways. This procedure is followed here to show that an analogy between the late Mesozoic batholiths of western North America and the modern volcanic terrane of the central Andes of South America is reasonable, and that much can be learned regarding the Mesozoic tectonics of North America from the modern tectonics of South America.

Calc-alkaline volcanic rocks are erupted above all of the inclined Benioff seismic zones of intermediate and deep earthquakes of the island arcs and continental margins about the Pacific Ocean. The magmas are erupted mostly about 150 to 400 km from the axes of the submarine trenches. Island-arc volcanism produces predominantly andesite, dacite, and high-alumina basalt, whereas continental-margin volcanism also produces a greater abundance of more silicic rocks.

The only modern volcanic fields comparable in dimensions and compositions to major ancient batholiths are those associated with Benioff zones of the continental margins. If batholiths are now forming anywhere, they should be mostly beneath these zones, as in Sumatra, New Zealand, and South America. The largest of these fields of late Cenozoic volcanic rocks, that of the central Andes, provides the best analogue for a modern batholith comparable in dimensions and other parameters to the great late Mesozoic batholiths of western North America.

The Volcanic Andes

The Andes face the Peru-Chile trench and lie above the Benioff zone dipping under South America from that trench. Calc-alkaline late Cenozoic volcanic rocks have been erupted along most of the Andes in a belt 200 to 400 km inland from the trench axis. The most extensive late Cenozoic Andean volcanic field, that of the central part of the chain, maintains a width of 100 to 200 km for a length of 2000 km, and is mostly included within the area of figure 1. The volcanic terranes north and south of this field are discontinuous and narrower.

The Peru-Chile volcanic field consists of late Miocene to Holocene andesite, dacite, rhyodacite, and rhyolite. The silicic rocks form a broad ignimbrite plateau, from the central part of which rise high stratovolcanoes of andesite and dacite (fig. 1; Bearth, 1938; Hausen, 1938; Jenks and Goldich, 1956; Katsui and Gonzalez-F., 1968; Petersen-B., 1958; Zeil, 1964; Zeil and Pichler, 1967). The axis of the volcanic belt is 150 to 200 km inland from the upper edge of the continental slope. Historic eruptions in Peru and northern Chile have been only of intermediate magmas; rhyolite and rhyodacite have been erupted in addition to more basic rocks in historic time in southern Chile (Casertano, 1963; Parodi-I., 1966). As eruptions of rhyolite are in general far less frequent and far more voluminous than are eruptions of intermediate magma, the central Andean silicic terrane may be active but have a historic record too short for its activity to have been yet observed.

During parts of late Mesozoic and Cenozoic time, the Andean region has been the site of intermittent magmatism of the same type as that now active. Calc-alkaline volcanic and granitic rocks, mostly of Cretaceous(?) and Tertiary ages but including pre-Cretaceous complexes (Levi and others, 1963), are exposed at the sides of the Andean volcanic belt (fig. 1). Late Tertiary granitic rocks, 7 to 20 million years old, also are exposed (Giletti and Day, 1968), but are not separated from the older igneous complexes on the figure.

The pre-Cretaceous rocks oceanward of the igneous terrane are mostly eugeosynclinal materials that may represent ensimatic ocean-floor and island-arc rocks (as Bürgl, 1967, argued for Colombian examples), added tectonically to the continent during Mesozoic and Cenozoic time.

Plate Tectonics and the Benioff Zone

An explosion in tectonic concepts has occurred in the past several years, sparked by interpretation of geophysical data from the ocean basins. Particularly important papers developing the new tectonics include those by Heirtzler and others (1968), Isacks and others (1968), Le Pichon (1968), and Morgan (1968). They and others have demonstrated that the earth's crust and upper mantle consist, in a broad way, of a number of large plates, of which the continents are parts, moving irregularly toward, past, and away from one another. So many features (including paleomagnetism and the classical geologic evidence for continental drift, as well as the oceanic geophysical information) are accounted for by these concepts that they already appear established as an explanation for the broader motions of the earth's outer shell.

A requirement of the data and concepts of plate tectonics is that eastern Pacific crust and upper mantle, spreading relatively eastward from the East Pacific Rise, turns down beneath the west edge of South America, as that continent in turn moves relatively westward as part of the plate moving away from the Mid-Atlantic Ridge. The Benioff seismic zone of intermediate and deep earthquakes, dipping eastward beneath South America, represents the contact between South America and eastern Pacific plates. The central Andean volcanic terrane is opposite that part of the East Pacific Rise which has the most rapid present spreading rate (12 cm/yr across the rise, or 6 cm/yr for each limb) yet determined by the Vine and Matthews magnetic method for any part of the midocean ridge system (Heirtzler and others, 1968, fig. 10).

The Peru-Chile trench is a topographic expression of the Benioff-zone contact between Pacific and South American plates. The modern central Andean volcanic field faces and is broadly coextensive with that part of the trench which is deeper than 6 km, and is coextensive with that part of the Andean Benioff seismic zone in which intermediate and deep earthquakes are most pronounced (compare geologic map of Lomega, 1964, bathymetric map of Udintsev, 1964, and seismic map of Gutenberg and Richter, 1954, fig. 11).

Direct evidence that Pacific crust is indeed moving rapidly toward South America and disappearing beneath the continental margin is provided by the continuous seismic profiles across the trench by Scholl, von Huene, and Ridlon (1968). They found that the thin pelagic carbonatic oozes of the open ocean turn downward with the oceanic crust at the west side of the trench, and lie beneath the terrigenous muds and turbidites across the floor of the trench. The terrigenous trench clastics are so thin--and

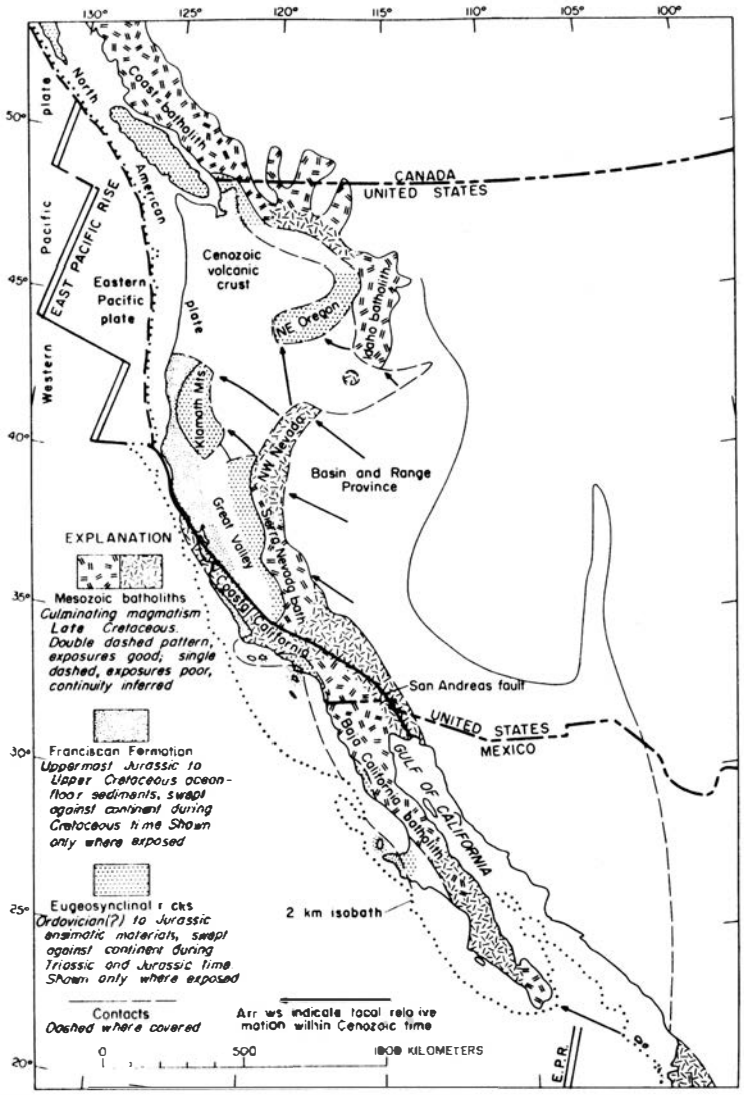

Figure 2. Late Mesozoic complexes of west-central North America, showing inferred motion relative to the continental interior during Cenozoic time.

are locking entirely in some sectors--that they are likely to be wholly of Quaternary age, and certainly cannot antedate the very late Tertiary. The oceanic crust upon which these thin sediments are ridinghas been adjacent to South America for only a short time: the oceanic conveyor belt carries the pelagic sediments to the continental margin, where they are covered by terrigenous clastic sediments before the entire complex disappears beneath the continent. The profiles of Scholl and others show no compressive deformation of the trench-floor sediments, so the actual zone of motion between oceanic and continental plates must be either at the juncture between trench floor and continental slope (where the seismic records are ambiguous), or on the landward wall of the trench.

The Benioff seismic zone of intermediate and deep earthquakes dipping eastward from the Peru-Chile trench is poorly defined by published data, being known primarily from the approximate locations tabulated by Gutenberg and Richter (1954). The Gutenberg and Richter data for earthquakes assigned depths of 300 km or less suggest that the Benioff zone may dip only 20 or 25 degrees eastward to this depth (see plots byHorrington, 1963, figs. 3 and 4).

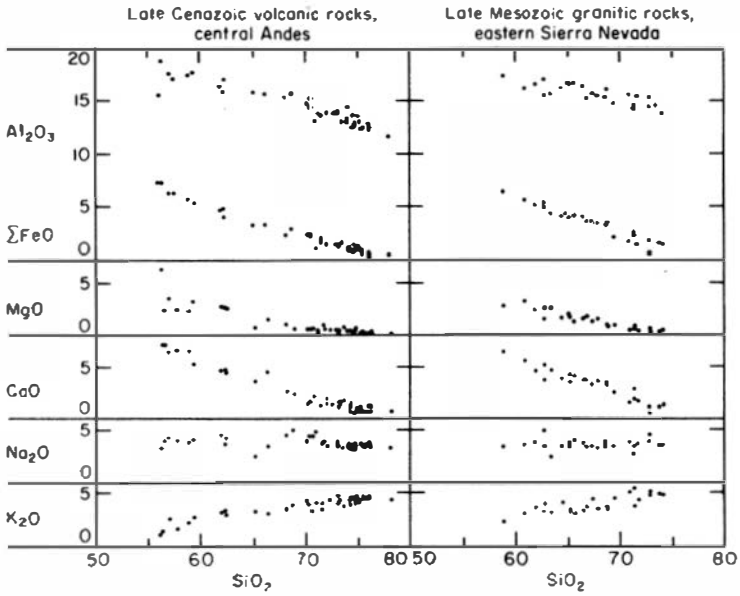

Figure 3. Silica-variation diagrams of chemical analyses of late Cenozoic volcanic rocks of the central Andes of South America, and of late Mesozoic granitic rocks of the east-central Sierra Nevada batholith of California. Analyses from Bateman and others (1963, table 3), Beorth (1938, tables 16 and 17), Jenks and Goldich (1956, table 3), Kotsui and Golzolez-F. (1968, table 4), and Zeil and Pichler (1967, fig. 8).

Comparisons of Volcanic Andes and Mesozoic Batholiths

The major late Mesozoic botholiths of western North America ore comparable in dimensions to the Andean volcanic fields. The Coast batholith is 100-200 km wide and about 1000 km long. The Baja California, Sierra Nevada, and Idoho batholiths ore each 100-150 km wide and hundreds of km long (fig. 2), and these botholiths probably were connected before Cenozoic rifting and strike-slip faulting in o much longer batholith. The late Cenozoic ignimbrite field of the central Andes is mostly wider than the Mesozoic North American batholiths because the volcanic rocks lop across older complexes and extend beyond the underlying batholith.

The volcanic Andes represent only 10 or 15 million years of magmatism, whereas the North American batholiths ore composites of plutons formed over a much longer period but, ot least in the case of the Sierra Nevada, mostly in ports of Late Jurassic and Late Cretaceous time (Bateman and Wohrhoftig, 1966, p. 117). Andean Cretaceous, early Cenozoic, and late Cenozoic granitic complexes together provide a more complete analogue for the total North American batholiths. So many North American oge determinotions indicate Lake Cretaceous plutonism, however, that this culminoting episode con be compared directly with the late Cenozoic Andes.

The silicic volcanic rocks of the central Andean late Cenozoic field ore quite similar in composition to the late Mesozoic granitic rocks of the eastern Sierra Nevada. Silico-voriotion diagrams (fig. 3) define almost identical curves for both provinces, although the Andean rocks ore in general more silicic.

Probably most ignimbrites ore more silicic than the granitic magmas which remained below in the magma chambers. Cenozoic ignimbrites of southern Nevada (Lipman and others, 1966), southwestern Colorado (Ratté and Steven, 1967, p. 54), northwestern New Mexico (Smith and Bailey, 1966), and Japan (Lipman, 1968) were erupted from chambers which were graded downward from highly silicic to less silicic magmas. The experimental doto of Currie (1968) accord with these observations. Thus we con expect the Andean ignimbrites to be more silicic than the granitic batholiths beneath them.

It is suggested that o great late Cenozoic batholith, comparable in size and composition to the late Mesozoic batholiths of western North America, has formed beneath the young volcanic pile of the central Andes. If the concepts of Hamilton and Myers (1967) ore basically correct, this batholith lies beneath only a few kilometers of cover of the volcanic rocks, which were erupted mostly from plutons that rose completely through the earth's crust and spread out between basement and volcanic scum.

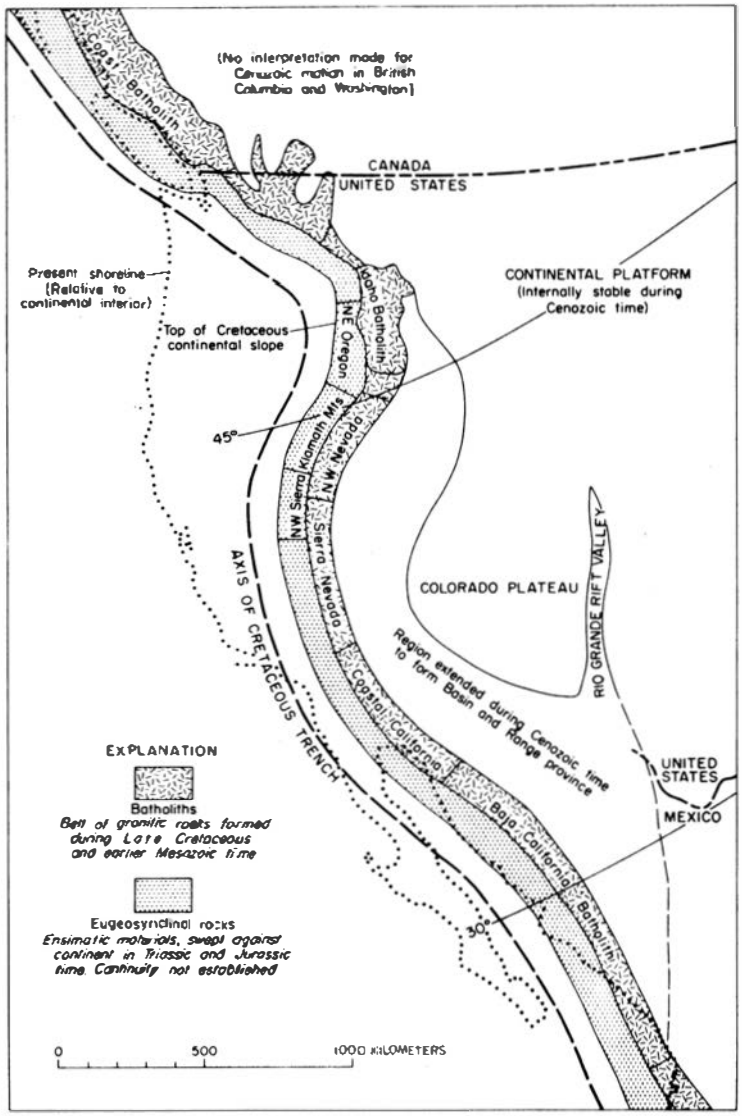

Figure 4. Paleogeographic map of the continental-margin complexes of west-central North America in Late Cretaceous time. Inferred Cenozoic extension has been reversed to derive this map from that (fig. 2) of present geography. The paleolotitudes correspond to a pole at 70° N., 175° E., as suggested by paleomagnetic orientations (Hanna, 1967; Helsley, 1967).

Original Position of Mesozoic Batholiths

Mony Mesozoic tectonic elements of western North America match Cenozoic ones of western South America: but the present geometry of the North American elements is quite different from that of their South American analogues. For example, the midlines of the late Mesozoic batholiths of western North America now lie 250 to 750 km inland from the Pacific coast (fig. 2). A detailed analogy between the two continents cannot be made in terms of the present tectonic geometry.

It is however probable that the Cretaceous geometry of western North America was for more like the present geometry of South America, for North America has been affected by much internal deformation during middle and late Cenozoic time. The concept that the Cenozoic has been a period of tensional fragmentation and sundering of the continental crust of the western United States has been developed by various people, and presented in the most detail by Hamilton and Myers (1966); the reader is referred to our paper for documentation. The effect of the motion we inferred on the late Mesozoic complexes of

western North America is summarized by figure 2.

Distances of the midlines of the western batholiths from the continental slope in Cretaceous time probably were much more uniform than their present erratic distances, the scatter having been produced by Cenozoic disruption. The Idaho batholith is far inland owing to the Cenozoic volcanic growth of northwestern Oregon and southwestern Washington upon crust that was oceanic in Mesozoic time. The northern part of the Baja California batholith is farther inland than the southern part owing to the tensional fragmentation and extension of the submerged continental borderland in the north. The Sierra Nevada batholith owes its inland position to the northward drift of coastal California in front of it, along the San Andreas fault system. The eugeosynclinal belts which comprise the Klamath Mountains are offset from the correlative belts of the northwestern Sierra Nevada, and have pulled far away from the batholith of northwestern Nevada and from the eugeosynclinal terrane of northeastern Oregon, which has itself swung away from the Idaho batholith.

Figure 4 illustrates the Late Cretaceous paleogeography of west-central North America, as determined by reversal of the inferred Cenozoic deformation summarized by the preceding paragraph. The distance from the edge of the continent to the midlines of the batholiths is seen to be a uniform 150-200 km in this reconstruction. It should be emphasized that this reconstruction is based primarily on an analysis of Cenozoic deformation, and not on assumptions regarding past simplicity of the continental margin. The fact that the analysis leads to a tectonic paleageometry which has a modern analogue in South America adds confidence to the interpretations.

The major Mesozoic batholiths of the western United States lie approximately along the boundary between crust which was continental before Mesozoic time and that which was oceanic. Rocks west of the main batholiths are eugeosynclinal, and in a paper being submitted elsewhere for publication are interpreted to belong to four major types of assemblages: (1), nearly unfossiliferous slate-graywacke-chert associations, which represent continental rise, abyssal plain, and abyssal hill sedimentation, and their abyssal-tholeiite oceanic crust; (2), belts dominated by andesite and keratophyre, formed in ensimatic island arcs; (3), ultramafic rocks, from the lower oceanic crust or upper mantle, kneaded tectonically into the upper crust and injected along underthrust faults as ocean-floor and island-arc suites were swept and thickened against the edge of the ancient continent; and (4), intermediate and silicic volcanic rocks, erupted across these amalgamated assemblages from the surfacing batholithic magmas.

After Jurassic time, only the uppermost Jurassic and Cretaceous Franciscan terrane was added to the continental margin of California and southwestern Oregon. This terrane is not incorporated in the Cretaceous reconstruction of figure 4 because it was only being welded to the continent during Late Cretaceous time. The Franciscan consists of ocean-floor slate, siltstone, graywacke, chert, and abyssal tholeiite, overridden by correlative continental-shelf and continental-slope strata and by continental crystalline rocks along a system of great overthrust faults followed discontinuously by serpentine sheets (Bailey and others, 1964; Brown, 1964; Hamilton and Myers, 1966; Irwin, 1964, 1966; Page, 1966). Rocks of Franciscan type and age occur also in northwestern Washington, where they have been similarly overthrust by continental crystalline rocks, but tectonic patterns there are poorly understood; and rocks of Franciscan type but unknown age and structural relations occur also along the Pacific margin of central Baja California.

It therefore appears that the great Mesozoic batholiths of western North America formed at the same distance inland from the margin of the continent as have the late Cenozoic volcanic rocks of the Andes. This reinforces the conclusion that the modern volcanic Andes and the Mesozoic batholiths represent the same phenomenon.

Cretaceous Tectonic Setting of North America

If the analogy drawn between the modern volcanic Andes and the Cretaceous batholiths of western North America is valid, and if the Cenozoic deformation of North America has been interpreted correctly in figures 2 and 4, then the Cretaceous tectonic setting of North America can be deduced.

During the Late Cretaceous episode of intensive granitic magmatism recorded by the great batholiths of western North America, the continent was bounded on the west by a deep trench (figs. 4, 5). A Benioff zone of intermediate and deep earthquakes dipped eastward under the continent from the trench, and marked the discontinuity along which Pacific crust and mantle slid beneath the continental mantle. Dehydration reactions in the Benioff zone perhaps weakened the downflowing crustal rocks to permit earthquakes (Raleigh, 1967). Magmas were generated in or directly above the Benioff zone (Coats, 1962; Dickinson and Hatherton, 1967) because the liberated water caused melting of intermediate magmas (Green and Ringwood, 1966). The magmas underwent profound modification by reactions with the mantle and crust through which they rose (Hamilton and Myers, 1967, p. 21). Such a model fits strontium and lead isotopic data (Armstrong, 1968). The melting occurred mostly in a belt 100 to 250 km inland from

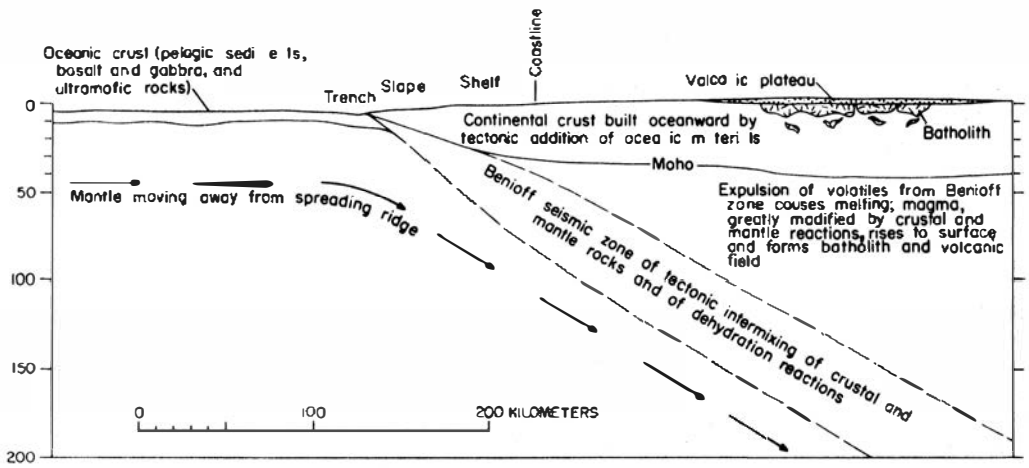

Figure 5. Cross section illustrating possible relationships between moving oceanic mantle, Benioff seismic zone, and the formation of a batholith and its copping volcanic field. This interpretation is made for the modern Andes, and for the Late Cretaceous batholiths of western North America.

the top of the continentol slope.

The general eastward increase of the ratio of potassium to silicon in the granitic rocks of the batholithic belt of California (Bateman and others, 1963, fig. 20; Dickinson, this symposium; More, 1959) accords with the concept that the belt formed above on east-dipping Benioff zone. The potassium-silicon ratio of volcanic rocks now forming about the Pacific basin increases systematically with the depth to the Benioff zones beneath them (Dickinson, 1968; Dickinson and Hotherton, 1967; Kuno, 1966; Sugimuro, 1967).

The batholiths formed during Late Cretaceous time, as Pacific crust and mantle spread continentword from a mid-ocean ridge at a velocity of perhaps 100 or more km per million years. The rapid-motion episode followed a latest Jurassic and Early Cretaceous period of relative stability, during which the Franciscan sediments accumulated to form a continental rise and abyssal plain. During the episode of motion, the oceanic sediments were carried eastward, depressed into the newly formed continent-margin trench, and covered by trench sediments before being incorporated in the chaos at the edge of the continent.

The analogy between Cretaceous North America and modern South America apparently extends to structures far inland. The broad Cretaceous basin that in North America separates the Cordilleran foldbelt from the Paleozoic platform and Precambrian shield of the eastern half of the continent has about the some dimensions and relative position as the modern lowlands, with their late Cenozoic fill, between the Andes and the Brazilian and Guiana Shields. The east-directed Laramide folding and imbricate thrusting in the western part of the North American Cretaceous basin has as its analogue the continuing late Cenozoic east-directed and eastward-plunging folding and imbrication of the western margin of the modern South American basin.

Older Mesozoic episodes of rapid eastward motion of Pacific crust and mantle beneath the margin of North America con be inferred, on the basis of less complete evidence, to hove occurred in Early or Middle Triassic time and in the Middle and Late Jurassic. Plutonism (less widespread than that of the Late Cretaceous) and continental accretion of eugeosynclinol assemblages apparently occurred at these times, and in terms of the model developed here should record ocean-floor spreading episodes of lower velocities than the Cretaceous event.

Overview

Andesites and batholiths ore mostly products of the some motion systems, and form where one great plate of crustal and mantle materials turns downward beneath the margin of another. The some motion systems corry oceanic crust and sediments and island orcs to the turndowns, where they ore scraped off against the margin of the upper plate. By studying ancient andesites and batholiths, we should be able to learn much about post motions of tectonic plates, both around the margins of continents and in orogenic belts where continental plates have collided.

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COMPOSITIONAL VARIATIONS IN CENOZOIC CALC-ALKALINE SUITES OF CENTRAL AMERICA

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Some of the most instructive insights into the origin of andesites are those found in the compositional variations of calc-alkaline rocks series from different geologic environments. This is especially true of andesites that rise through crustal rocks of differing thickness and composition. Gorshkov, elsewhere in this volume, has discussed the variations of andesitic suites along and across volcanic belts where differences in the nature of the underlying crust are believed to be important. He observes that the trends of differentiation in volcanoes of a single linear belt are essentially uniform regardless of the thickness or composition of the crust through which the magmas rise, and he concludes that these relations strongly support an origin below the crust with little if any contamination or assimilation.

Important as differentiation trends may be, the proportion of different rock-types and their order of appearance in the volcanic sequence may be equally significant. Too often the rocks selected for analysis and definition of differentiation trends are chosen more for their place in the petrochemical series than for their volumetric importance in specific igneous centers or segments of the province. For example, if one examines the calc-alkaline rocks of the Cascade Range (p. 101-107 of the Andesite Conference Guidebook) it is apparent that, although the composition of Recent andesites appears to be uniform from one end of the chain to the other, the degree of differentiation and proportion of different rock types varies widely.

A similar, though somewhat simpler situation prevails in Central America. The Cenozoic volcanic rocks of Guatemala, El Salvador, Honduras, Nicaragua, and Costa Rica (figure 1) have been erupted from a chain of volcanoes that extends 1200 kilometers along the Pacific Coast of Central America. The province crosses two strongly contrasting basement series. The volcanoes of Guatemala, Honduras, and part of El Salvador stand upon a thick sequence of Paleozoic or older metamorphic and plutonic rocks and a Mesozoic and Tertiary sedimentary series that includes shale, limestone, and a wide range of continental and shallow marine clastic rocks. To the southeast, this thick sialic series is not found. Instead, the underlying rocks are mainly Mesozoic and Tertiary volcanic rocks and volcanic sediments that rest on ultramafic rocks of unknown age. The rocks in southern Central America have been interpreted as oceanic crust that was added to the continent in relatively recent geologic time (Weyl, 1966).

There are also structural differences from one end of the chain to the other. At the northwestern end, the Guatemalan volcanoes rise from an elevated plateau high above sea level. The volcanoes are not related to obvious faulting or folding. To the southeast, the base elevation of the chain becomes lower; most of the volcanoes of El Salvador and Nicaragua are within a structural depression that follows the crest of a broad anticlinal warp. Many are situated on faults or tensional features. At the extreme southeastern end of the chain in Costa Rica, the volcanoes resemble those of the opposite end in that they rise from a high upland and show little relation to deformation. The Middle American Trench that parallels the chain just off the continental shelf becomes progressively shallower from northwest to southeast.

It would seem inevitable that if crustal rocks play any significant role at all in the genesis of calc-alkaline magmas this contrast in the composition and structure of the basement series would be reflected in the character of the andesites from one end of the chain to the other. But if one considers the province as a whole, all of the rocks fit into a remarkably regular differentiation series, and trends of variation from one end of the chain are indistinguishable from those in any other part. Nor is there any perceptible difference in the isotopic composition of the andesites. All have Sr^{87}/Sr^{86} ratios very close to 0.704 (Pushkar, 1968).

There is a complete range of rocks from basalt to rhyolite, which plot on smooth curves on almost any variation diagram. In figure 2, for example, all analyzed Quaternary volcanic rocks of the main andesitic belt are plotted on a Harker diagram for total alkalis vs. silica. Despite the wide geographic and geologic range represented by the rocks, they show a remarkably narrow deviation from a single trend that lies precisely within the field of high-alumina rock series defined by Kuno (1965).

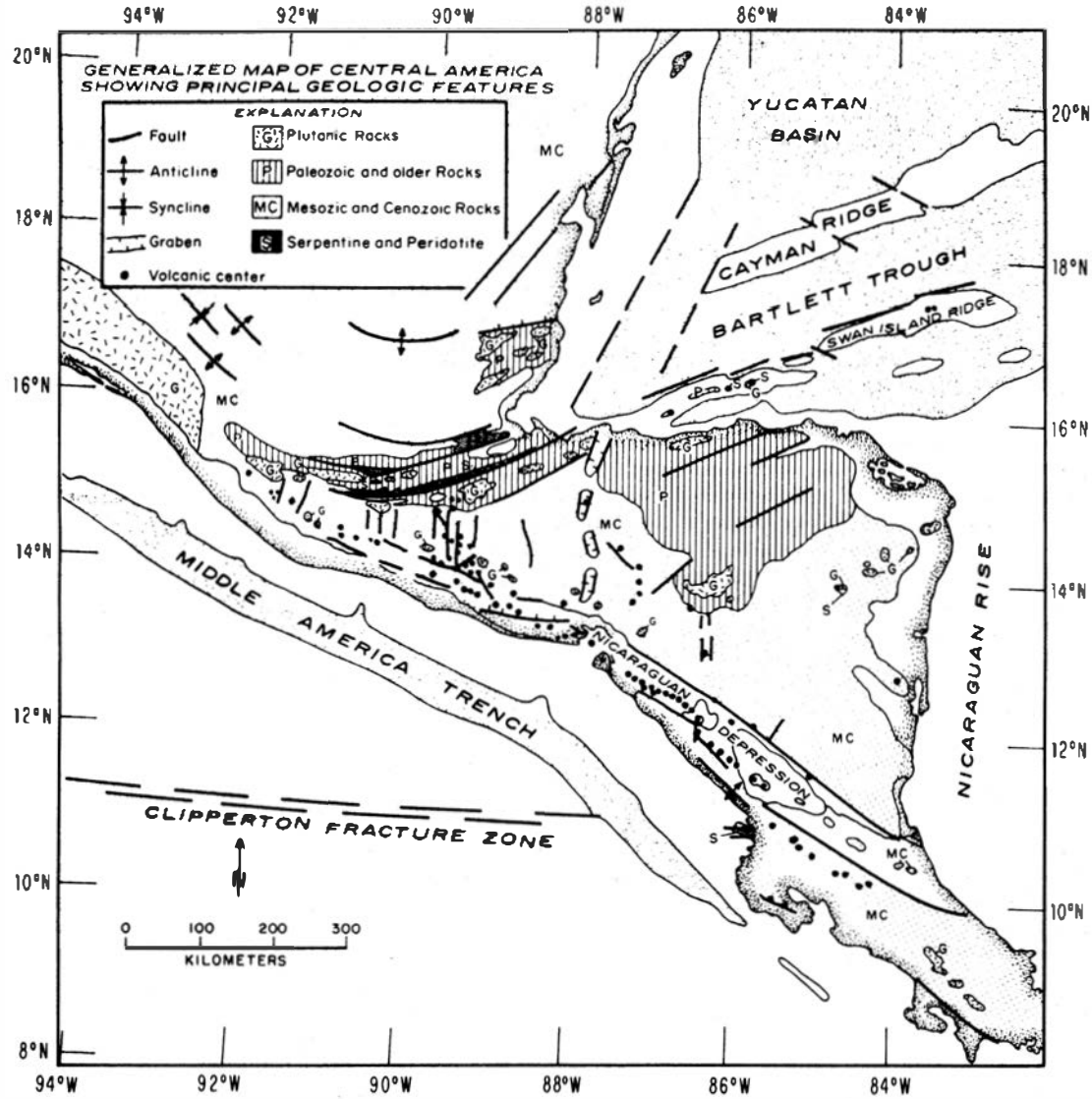

Figure 1. Generalized map of Central America showing principal geologic features.

Similarly, the some rocks fall on a continuous smooth curve on on AMF diagram ($No_2O + K_2O$: MgO: total Fe as FeO), as shown in figure 3. There seems to be no apparent reflection of the different environments of rocks from northern or southern parts of the chain.

This continuity disappears, however, if one considers individual parts of the chain and examines separate groups of volcanoes within a restricted volcanic field. It then becomes apparent that the continuity of the province as a whole is the result of grouping excessively large segments of the chain. The dominant feature of the variations found in individual subprovinces is a strong discontinuity of the rock series. The associations are of the 'divergent' type described for the Cascade system. The main volume of the large mature volcanoes is composed of andesite of rather uniform composition. Later rocks associated with these volcanoes tend to fall into two divergent compositions, one of siliceous pumice and viscous extrusions and the other of basalts with somewhat more erratic compositions. (Of all the volcanic rocks of the province, basalts have the greatest chemical irregularity, even though they are seldom as porphyritic as the andesites.) The rocks of a single volcanic center form three distinct populations on variation diagrams, such as those of figure 4, but when the composition of the main andesite is very mafic the gap between basalts and andesites disappears and only two groups are distinguishable, one mafic and

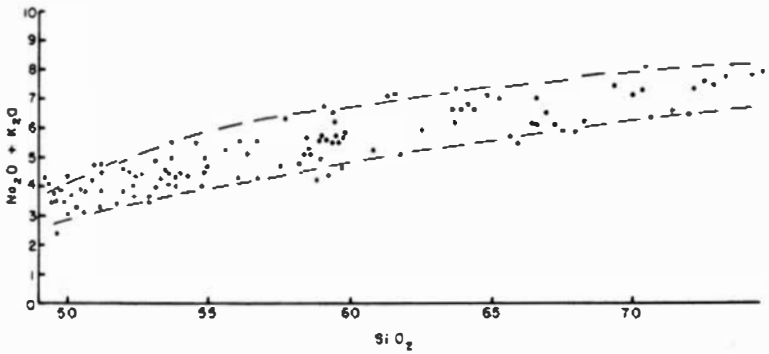

Figure 2. Alkali - silica variation diagram for Quaternary volcanic rocks of Central America.

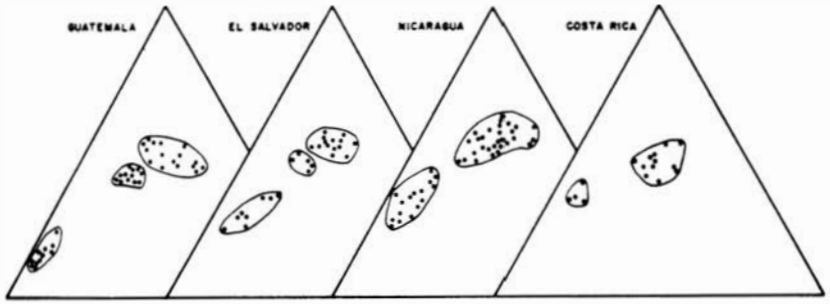

Figure 4. AMF diagram for the rocks shown in figure 3 separated on a geographic basis.

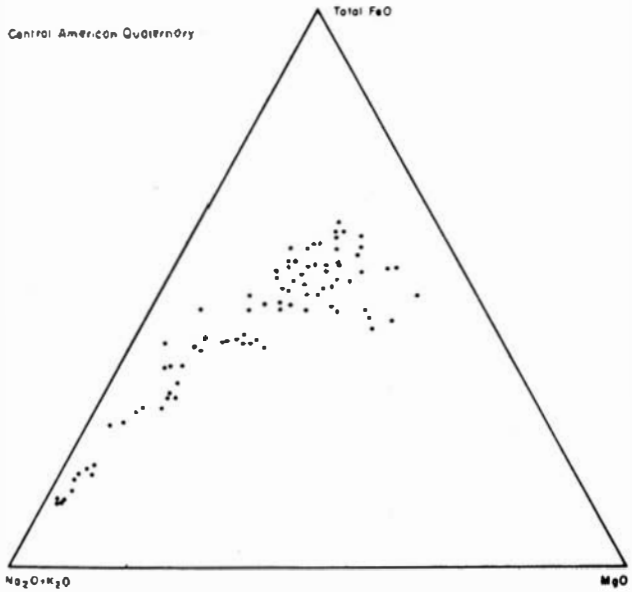

Figure 3. AMF diagram ($Na_2O + K_2O$: MgO : total iron as FeO) for the Quaternary volcanic rocks of Central America.

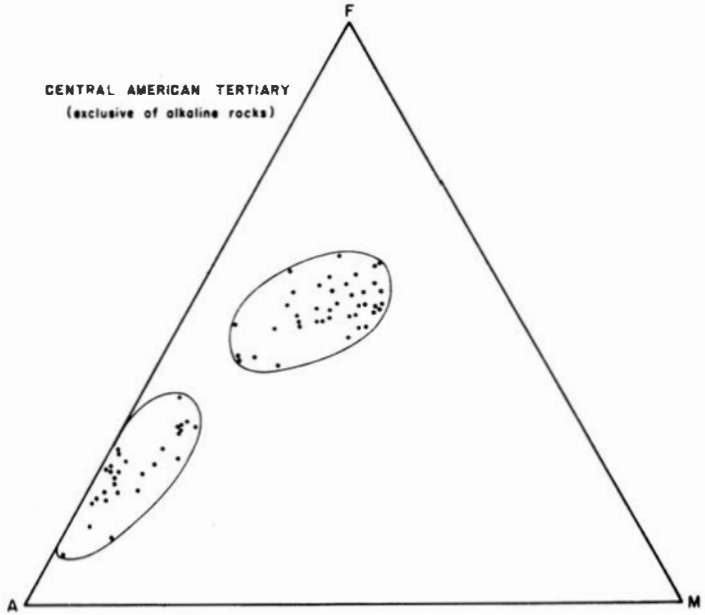

Figure 5. AMF diagram for Tertiary volcanic rocks of Central America.

the other felsic.

Following the chain from the Guatemalan Highlands toward the southeast, a progressive change can be seen. The composition of the andesites becomes steadily more basic until, in Nicaragua, it is impossible to make a clear separation of the andesites and basalts, which merge into a single group with a wide overlapping scatter. At the same time, the felsic rocks become progressively less siliceous with rhyolites of Guatemala giving way to rhyodacite in El Salvador, dacite in Nicaragua and ferrodacite in Costa Rica. There have been few if any Quaternary rhyolites erupted from andesitic cones south of Guatemala, and there are no rocks in Guatemala similar to the iron-rich dacites of Costa Rica. The changes along the length of the system are gradual ones that show no recognizable break near the boundary of the two contrasting basement series or from one geologic setting to another. The only structural feature that shows a similar progressive change from northwest to southeast is The Middle American Trench, which becomes shallower and narrower in that direction (Fisher, 1961).

Turning to the Tertiary rocks (figure 5), two features are immediately apparent. There is a marked bimodal distribution of compositions, and there is no obvious variation along the length of the chain. These features are especially remarkable when it is recognized that the analyzed Tertiary rocks come from a wide geographic distribution covering the entire length and breadth of Central America, and the rocks were erupted over a period of time that includes most of the Tertiary Period. Alteration is more common than it is in the Quaternary rocks. If it were possible to obtain analyses of perfectly fresh specimens erupted from restricted regions during short periods of Tertiary time, the grouping of compositions into two distinct populations would certainly be even more pronounced.

During Tertiary time, the compositional contrasts of the basement series of northern and southern Central America were at least equal to those observed today, and yet the regional trend of the Quaternary andesites and related rocks had not yet developed; whatever the cause of the Quaternary variations, it must be a structural feature that became effective after volcanism was already long established. It is evident, therefore, that the character of the andesites must be largely independent of the crustal rocks and more a function of differences at some level below the crust.

The divergence of composition from voluminous uniform andesites to later siliceous rocks erupted in close association with basalts and basaltic andesites is the salient feature of igneous differentiation in the province as a whole.

Results of recent experimental studies at elevated water pressures offer a possible explanation for the observed relations. Elsewhere in this volume, Yoder has pointed out the important role of water in calc-alkaline magmas. Increasing water pressure decreases the stability fields of crystalline feldspar and quartz relative to pyroxene and olivine, so that liquids produced by crystal fractionation or partial melting are markedly richer in SiO_2, Al_2O_3, Na_2O and K_2O than they would be under dry conditions. Yoder offers a possible explanation for the discontinuity of divergent calc-alkaline suites by relating the andesites and their associated differentiates to the compositions of two invariant points in the system diopside - forsterite - silica. The mechanism requires separation of an andesitic liquid and remelting it after it has crystalized in an olivine-free environment. The same result could be produced by single-stage melting in two different horizons, one with olivine and the other without it.

The sympathetic compositional variations of Central American suites are consistent with such a system operating at different water pressures. The progressive decrease of silica from one end of the chain to the other may reflect decreasing depths of origin for the calc-alkaline rocks between Guatemala and Costa Rica. This explanation agrees with certain geological features, such as the decreasing heights of volcanoes and the shallower depths of the Middle America Trench from north to south. If the height to which a volcano grows is a function of the hydrostatic balance of the magma column and the solid rocks through which it rises, the high volcanoes of Guatemala tap a deeper source than the relatively low volcanoes at the opposite end of the chain. The fact that the trench becomes shallower toward the south and finally disappears off Costa Rica suggests that an underthrust oceanic plate would be somewhat deeper below the Guatemalan volcanoes than below those of Costa Rica. Unfortunately, seismic data are inadequate to evaluate this difference.

Any mechanism for generation of large volumes of uniform magma by melting at elevated water pressures requires a means of retaining the water during the process of heating and melting. Rates of diffusion of water exceed those of heat, especially in tectonically active areas, and water will normally be driven out in advance of melting. Even though the pressure of water may be high, the amount of water will be low, and much higher temperatures are required as melting proceeds beyond the initial water-saturated stage and the liquid becomes progressively drier (Tuttle and Bowen, 1958, p. 122-125).

This problem is overcome if an underthrust oceanic plate sharply depresses the isotherms and causes an inversion of the thermal gradient under the volcanic axis. Water driven out of the plate and

rising into the overlying horizons will enter rocks of higher temperatures and will lower their melting temperature so that it could intersect the geothermal gradient. Substantial melting can thus be achieved with little if any addition of heat, and the rate of magma generation will be largely controlled by dehydration of the underthrust plate (figure 6).

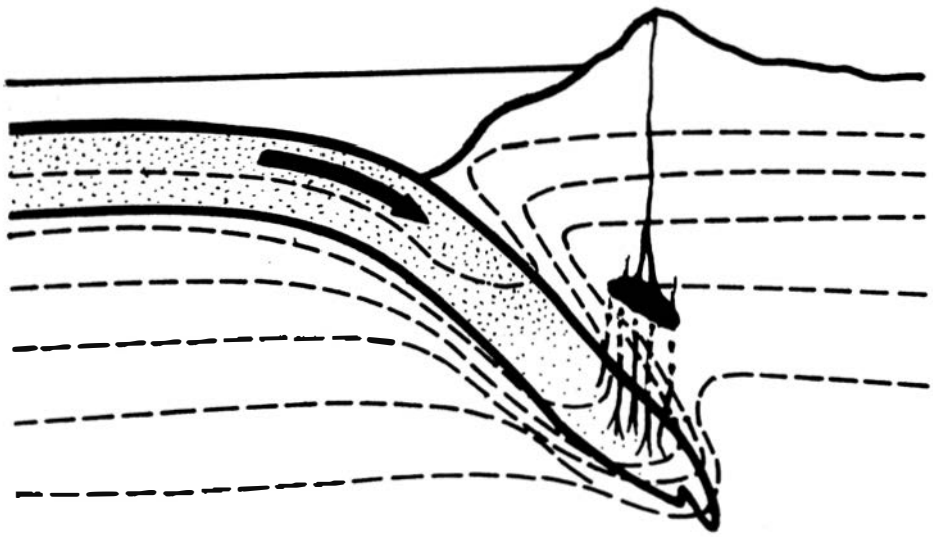

Figure 6. Underthrusting of an oceanic plate beneath the continental margin causes a sharp depression of the isotherms and an inversion of the temperature gradient in rocks immediately above the plate. Water driven from wet oceanic crustal rocks streams up into a hotter horizon and lowers its melting temperature. Magma will be produced where the melting temperature is depressed below the prevailing temperature.

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ABSTRACTS

LEAD IN THOLEIITIC AND HIGH-ALUMINA BASALTS FROM CENTRAL JAPAN

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The isotopic composition of lead and concentration of lead, uranium, and thorium have been determined in tholeiitic volcanic rocks from Ō-shima and Hakone volcanoes and in high-alumina volcanic rocks from Fuji, Ō-mura-yama, and Amagi volcanoes, including calc-alkaline rocks. All lead in these volcanic rocks plots between $\mu = 8.7$ and 8.8 growth curve and clusters near the primary zero isochron (between +100 m.y. to -100 m.y. model age). Lead in Ō-shima tholeiite shows a slight radiogenic excess in Pb^{206}/Pb^{204} (18.5 ~ 18.7) and those of the tholeiite series from Hakone and the high-alumina series from Fuji, Ō-muro-yama, and Amagi are slightly deficient in Pb^{206}/Pb^{204} (18.3 ~ 18.4) compared to modern lead in a closed system. All ratios of the observed U^{238}/Pb^{204} (μ), except some calc-alkaline rocks, and observed Th^{232}/U^{238} (k) are lower than those estimated from the isotopic composition of lead. Measurable difference of Ō-shima lead from those of Izu Peninsula might be related to the fact that Ō-shima is located outside the andesite line. However, the relative decrease of radiogenic character in lead from basalt to andesite and dacite of each of the volcanoes compared to the relative increase of radiogenic character in lead from basalts to differentiates from Hawaiian volcanoes rather suggests that Ō-shima is inside the andesite line.

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THE SOURCES OF CALC-ALKALINE MAGMAS AS INDICATED BY SR ISOTOPES

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There are probably only two really positive statements that can be made about the sources of calc-alkaline magmas on the basis of Sr isotope studies to date. These are: 1) There is nothing unique, in terms of Sr isotopes, about the calc-alkaline magmas as compared to other types, and 2) calc-alkaline magmas are not formed by simple refusion of old sial. The strontium isotopic composition of calc-alkaline magmas is like or only slightly more radiogenic than that of oceanic basalts. Those which have come up through an old continental crust tend to carry somewhat more radiogenic Sr, but so do all magma types. The amount of sial which is apparently incorporated into calc-alkalic magmas depends upon certain assumptions, but it would appear most reasonable that these amounts are small. The present Sr isotopic data apparently indicate that calc-alkaline magmas do not owe their distinction from other magmas types either to a markedly different source or to a significantly greater amount of crustal assimilation.

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LIQUID STRUCTURE AND ELEMENT FRACTIONATION

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One of the ultimate problems of igneous petrology is to understand the melting and crystallization behaviour of a very large range of compositional types. It is now apparent that to advance this knowledge and allow reasonable thermodynamic extension from known simple systems, we require knowledge of silicate liquid structures with similar detail to that available for many silicates in the solid state. Some methods are available for examining site geometry and site populations in liquids. Absorption spectra measurements may provide information for transition metals and Mössbauer spectra may be used for a wider range of types of element.

Some results from the study of transition metal site distribution in glasses will be discussed with particular reference to element fractionation. It is emphasized that distribution coefficients between liquid and crystals may change drastically with the bulk composition of the liquid and for transition metals, some of these trends may be related to liquid structure and crystal-field parameters. There is also the distinct possibility, that fractionation trends in plutonic cumulates may provide a useful guide to the bulk chemistry of the liquid present at the time of crystallization.

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PETROGENETIC SIGNIFICANCE OF ANDESITIC VOLCANISM IN THE SAN JUAN MOUNTAINS, COLORADO

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In the Oligocene San Juan volcanic field of southwestern Colorado, lava flows and hypabyssal stocks of intermediate composition are closely associated in time and space with widespread silicic ash-flow tuffs. Much of the lava (>30 m.y.), mainly alkalic andesite and rhyodacite, preceded the ash-flow tuffs (30-27 m.y.), but lava was also erupted intermittently with the ash flows and afterwards. Ages of the hypabyssal stocks have not everywhere been determined, but most stocks were emplaced relatively late in the volcanic sequence (29-27 m.y.). The lavas and ash-flow tuffs are about equally voluminous, each representing several thousand cubic miles of magma; this contrasts with many other Tertiary ash-flow fields in the western United States, in which andesitic lavas are minor.

More than 200 published and unpublished chemical analyses of volcanic rocks in the San Juan field indicate only minor differences among the early lavas, late lavas, and intrusive rocks, all having mean SiO_2 contents of about 60 percent. The ash-flow sheets, however, are distinctly more silicic, with SiO_2 contents of 66-74 percent. Compositional zonations in some individual sheets, from basal rhyolite upward into quartz latite, represent, in inverse order, vertical differentiation of the source magma. This suggests that the ash-flow sheets represent the differentiated tops of magma bodies that are approximately similar in bulk composition to the lava flows and exposed stocks.

If the lava flows and hypabyssal stocks of the San Juan volcanic field adequately represent the shallow batholith inferred to underlie the cauldron-complex source area of the ash-flow tuffs, the batholith consists mainly of diorite and monzonite. Similar chemical contrasts between Tertiary ash-flow sheets and intrusive rocks in the Basin and Range province suggest that many other rhyolitic ash-flow sheets represent differentiated tops of less silicic magma bodies. Such contrasts indicate the need for caution in making chemical comparisons between volcanic fields and plutonic terranes.

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SPECULATIONS ON THE ORIGIN OF MEDICINE LAKE CALDERA

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Recent work by the present writer and by other workers has shown that a number of collapse calderas which formed as the result of the eruption of large volumes of silicic pyroclastic material later were filled, in some cases to overflowing, by lavas, in large part of intermediate composition, erupted from vents located within the collapse depression. Indeed, with the recognition by R. E. Wilcox (oral communication, 1967) and Higgins and Waters (1967) of significant amounts of silicic welded tuff at the Newberry volcano, it now appears possible that explosive pyroclastic eruption contributed to the formation of the classic Newberry caldera.

Could the Medicine Lake volcanic center (Anderson, 1941) have a similar history? Perhaps the Medicine Lake caldera formed concurrently with, or immediately after, the eruption of the "andesite tuff," a unit of ash-flow tuff of dacitic, or perhaps rhyodacitic, composition which crops out northwest and locally north and southwest of the caldera and which likely is present at depth east and south of Medicine Lake. The several degree northwesterly dip of the contact between the main body of andesite tuff and the overlying "older platy olivine andesite" is consistent with a source to the southeast in the direction of the caldera. The non-welded top of the andesite tuff is exceptionally well preserved southeast of Dock Wells where it is overlain by the older platy olivine andesite. The preservation of this very incoherent material suggests that the ash-flow unit was erupted not long before the older platy olivine andesite, which in the present working hypothesis would post-date caldera collapse. A preliminary attempt to date the andesite tuff isotopically was unsuccessful.

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ANDESITES FROM THE ANDES AND ANTARCTICA

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Late Cenozoic andesitic rocks that constitute an important part of the orogenic belt from the Andes, the Scotia arc, and Antarctic Andes have been examined on the basis of 145 chemical major elements analyses.

The South Sandwich Islands of the Scotia arc are composed of tholeiite, mafic andesite and a few dacites, all of which are characterized by low alkalies, especially potash. At the extremities of the Andes and the Antarctic chain such low-potash rocks are unknown. High-alumino basalt, mafic andesite and a few sodic rhyolites occur in the South Shetland Islands. In the South Andes basalt and mafic andesite predominate, while no basalt has been found in the northern extension of the chain where extensive pyroclastic plateaus of rhyolite and stratovolcanoes of andesite predominate. The volcanic rocks of the Andes together with those of the Antarctic Andes, however, are similar in their over-all petrographic character. They are composed of high-alumina basalt, andesite and rhyolite, all of which are rich in both soda and potash. On the continental side of these volcanic regions there are alkalic rocks rich in potash.

These modes of occurrence suggest that most of the andesite in this belt has been derived from basaltic magma, but in the Central and Northern Andes andesite magma may have originated through partial melting of the mantle. Lateral variations of rock types across the orogenic belt could be partly explained by a hypothesis of generation of different magmas at different depths along an inclined seismic zone dipping toward the continent. Attention should be also given to longitudinal variations of rock types along the orogenic belt. The South Sandwich Islands consist of only low-potash rocks, whereas the Andes and Antarctic Andes lack this suite and are accompanied by alkalic rocks on the continental side. The Scotia chain represents an intra-oceanic island arc of recent origin. Eight of the nine volcanoes of the arc are still active. It seems that under such active regions tholeiitic magma is generated at a shallow depth in the upper mantle.

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