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HORNBLENDES FROM CALC-ALKALINE VOLCANIC ROCKS OF ISLAND ARCS AND CONTINENTAL MARGINS[1]

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ABSTRACT

Calc-alkaline volcanic rocks occurring in island arcs and continental margins differ in trace element chemistry but overlap in major element composition. When hornblendes from andesites of identical major element composition are compared, those from the island arc environment have higher total alkali, Σ Al content, and lower Fe/Mg ratios. Chemical differences in hornblendes, the position of hornblende in the crystallization sequence, and new experimental data suggest that the liquidus temperatures of chemically identical andesites are higher in island arcs than in continental margin areas as a result of different H_2O contents. This suggests a difference in origin of calc-alkaline rocks in island arcs and continental margins.

INTRODUCTION

There is a graduational sequence from tholeiites to calc-alkaline and to shoshonitic rocks across the island arcs or in the stratigraphical sequence of island arcs (Kuno, 1966; Sugimura, 1968; Dickinson and Hatherton, 1967; Jakeš and White, 1969; and Gill, 1970). Jakeš and White (1971) suggested that two calc-alkaline associations occur in the orogenic regions—an island arc and a continental margin (Andean) calc-alkaline association.

The principal differences of these associations are SiO_2 variation, trace element abundances and phenocryst mineralogy. The differences are summarized in Table 1.

Some medium- and high-K andesites from island arcs have very similar or identical major element composition to rocks occurring in the continental margins (Andean association) or intracontinental chains (Carpathians) (*c.f.*, McBirney, 1969). Those rocks most similar in respect to major element chemical composition and mineral composition are hornblende andesites. In this paper we present new bulk chemical analyses of hornblende-bearing calc-alkaline volcanic rocks and analyses of their phenocrystic minerals in order to establish

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TABLE 1 GENERALIZED DIFFERENCES BETWEEN CALC-ALKALINE VOLCANIC ROCKS OF ISLAND ARCS AND THOSE OF CONTINENTAL MARGINS

	Continental margin (Andean)	Island arc
Range of SiO_2	56.0 - 75.0%	50.0 - 66.0%
$FeO + Fe_2O_3/MgO$	higher than 2.0	lower than 2.0
K_2O/Na_2O	0.60 - 1.1	less than 0.8
Trace elements at same K_2O and SiO_2	higher Rb, Ba, Sr, Th, U, Zr, K/Rb (230), Th/U	lower Rb, Ba, Sr, Th, Zr, K/Rb (400), Th/U
Phenocrysts	biotite, hornblende, clinopyroxene, orthopyroxene, rare quartz, garnet, cordierite	clinopyroxene, orthopyroxene, hornblende (rare biotite) no quartz, garnet, and cordierite
Sequence of phenocryst crystallization (hb —andesites)	hornblende>clinopyroxene>orthopyroxene	clinopyroxene>hornblende>clinopyroxene

possible chemical and petrological differences between both calc-alkaline associations.

ANALYTICAL METHODS

Major elements Si, Ti, Al, total Fe, Mn, Mg, Ca, K, and P were determined in rocks and mineral separates[1] by X-ray spectrographic analyses using the methods of Norrish and Chappell (1967). Na was determined by flame photometry, and ferrous iron by titration and spectrographic methods (Kiss, 1968). Fluorine was determined by using a modification of the colorimetric alizarin blue method (Hall and Walsh, 1969).

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[1] A table listing results of bulk rock chemical analyses and analyses of minerals may be ordered as NAPS Document 01803 from National Auxiliary Publications Service of the A.S.I.S., c/o CCM Information Corporation, 866 Third Avenue, New York, N. Y. 10022; remitting in advance, \$2.00 for microfiche or \$5.00 for photocopies, payable to CCMIC-NAPS.

Some minerals were analyzed using an ARL electron microprobe (Australian National University) with natural and synthetic minerals as standards. The data were corrected for matrix effects. Additional data were obtained using an Hitachi XMA-5 electron microprobe (University of Kanazawa, Japan) with synthetic minerals and oxides as standards: Albee and Ray's (1970) correction factors were applied to these results.

Separation of minerals for analysis was made by electro-magnetic and heavy liquid methods followed by handpicking. The purity of concentrates was higher than 99 percent; impurities were clinopyroxene, magnetite, and apatite intergrown with amphibole. The outer parts of hornblende phenocrysts, usually intergrown with glass or magnetite, were removed during separation and thus analyses of hornblende are more representative of the cores than of the whole crystal.

Composition of Hornblende Andesites

Available chemical data on volcanic rocks from island arcs such as New Guinea, Japan, Kamchatka, and other circum Pacific areas show that there is a relationship between rock composition and the presence or absence of hornblende. In the island arcs hornblende commonly occurs in calc-alkaline or shoshonitic rocks having SiO_2 greater than 55 percent but rarely in rocks with SiO_2 less than this. Hornblende is more common in rocks with higher K_2O content within the calc-alkaline association but the presence of "ghost amphiboles" (pseudomorphs of magnetite + clinopyroxene + plagioclase) in rocks from the Marianas (Schmidt, 1957) suggests that hornblende may have also crystallized in low-K (tholeiitic) rocks. Most hornblende-bearing rocks are high in total alkali content, have high K_2O/Na_2O ratios (0.5–1.0) and are usually highly oxidized (Fe_2O_3/FeO is greater than 0.5). They are from rock associations which show little or no "iron enrichment" in AMF diagrams.

Hatherton (1968) related hornblende andesites to the "miogeosynclinal" environment, and Japanese authors have noted the absence of hornblende-bearing volcanic rocks near the recent volcanic front: both features may be attributed to their distinct rock chemistry. Factors controlling the presence or absence of hornblende such as the retention of volatile content until late stages of crystallization make amphibole andesites unreliable indicators of magma variation across the island arcs. Examples of hornblende-bearing and hornblende-free andesites from island arcs show that the major element and trace element chemical composition may be very similar although phenocryst mineralogy differs. Some authors consider hornblende andesites in island arcs to result from crustal contamination (Kuno, 1950). The major and trace element chemistry suggests that if the contamination hypothesis is applied, it must be applied equally to hornblende-free andesites.

MINERALOGY

Hornblendes

In most calc-alkaline volcanic rocks of both island arcs and continental regions phenocrysts of hornblende from 0.5 to 5.0 mm in length have a euhedral acicular or bladed form. Polycrystalline aggregates are rare and the amount of hornblende varies in different rock types, but in rocks with a glassy matrix the amphibole forms about 50 percent of phenocrysts (the other phenocrysts are mostly plagioclases, and to lesser extent clinopyroxene). Simple twins parallel to (100) are commonly observed.

There is some degree of disequilibrium between hornblendes and the host rocks, the phenocrysts showing different degrees of resportion or recrystallization. "Opacite rims" consisting of a reaction corona of plagioclase, orthopyroxene and an abundance of fine-grained opaque phase are common. In some hornblendes there are two, three or even more "buried" opacite rims observable in sections oriented perpendicular to "*z*" axis. Zoning is characterized by a deepening in color and a small change in extinction angle in some samples. Microprobe data show that for iron and magnesium oxides the variation does not exceed 2.wt percent and usually is less than 1.5 percent. The cores have higher Mg, Ti, and sometimes Al, whereas rims have higher Fe and Si contents.

New chemical analyses of hornblendes show relatively narrow compositional range. In all analyses, except three from silica-rich volcanic rocks of continental areas, the content of aluminum was sufficient to fill the Z group: in exceptional cases Fe^{3+} has been added to the Z group. In most of the analyses the total number of cations in Y exceeds 5.00 and Leake (1968) claims a value of 5.25 as a limit for superior analysis. Because of the positive correlation of OH + F and total cations in the Y group (*e.g.*, Leake 1968) and significantly low content of OH + F in the hornblendes from volcanic rocks, a value of 5.35 was accepted as satisfactory. The X group is completely filled with Ca and Na, and excess Na + K is attribued to occupancy of the A site.

Geological and petrological features mentioned in Table 1 were used to subdivide the studied hornblende andesites into two groups:

a) island arc occurrences
b) continental margin (intracontinental chain) occurrences.

The Fijian, Solomon Island, East Papuan, New Zealand (Mt. Egmont and Solander Island), and Western United States (Mt. Shasta and Mt. Mazama) are of island arc type calc-alkaline rocks, whereas those from Mt. Tateyama and Mt. Hakusan in Japan, Neogene andesites from Carpathians, and Carboniferous andesites and dacites from New South Wales are of continental type. Only two samples can not be clearly classified into mentioned groups. These are Japanese samples 21 and 22 (603) which come from new still poorly studied localities (Yamasaki, 1970, pers. comm.) and sample 20 (1) from Mt. Elden, Arizona, which shows alkaline rather than calc-alkaline characteristics.

The relationship between Al^{iv}-Si^{iv} in hornblende and the SiO_2 content of the host rocks is shown in Figure 1. There is some overlap of both SiO_2 and Al_2O_3 values in most rocks of both associations, but hornblendes from island arc volcanic rocks are appreciably more aluminous ($Al^{iv} = 1.5$–1.6) than those of continental areas ($Al^{iv} = 1.0$–1.5). Hornblendes from continental (Andean) calc-alkaline rocks are similar to those from diorites and some granitic rocks. Kostyuk and Sobolev (1969) suggest an average of 1.3 Al^{iv} in hornblendes from diorites and this is a typical value for Al^{iv} in hornblendes from Andean calc-alkaline rocks. This means that dioritic and tonalitic masses (with SiO_2 around 62 percent) in continental areas, are comparable with Andean andesites and dacites not only in rock composition (*e.g.*, Hamilton, 1969, 1970) but also in chemical composition of hornblendes (*c.f.*, Dodge *et al.* 1968 data on Sierra Nevada Batholith). This may suggest that diorites and tonalites are genetically more closely related to Andean type calc-alkaline magmas than to island arc types.

The total aluminum content (Al^{iv} and Al^{vi}) is also higher in hornblendes from island arc rocks than in those from continental areas although the aluminum content in the whole rocks is equal. Generally higher Al^{vi} content in island arc hornblendes suggests by analogy with experiments by Green and Ringwood (1968), and Holloway and Burnham (1972) higher pressure of their crystallization. Total aluminum in hornblendes from island arc occurrences is only slightly lower than that in amphiboles from lherzolite, websterite, and clinopyroxenite inclusions (Kuno and Aoki, 1970; Aoki and Kushiro, 1968) in alkali basalts and from clinopyroxene-hornblende inclusions in calc-alkaline rocks (Yamazaki *et al.*, 1966). The differences if any are in octahedral aluminum rather than tetrahedral. Hornblendes from calc-alkaline rocks and their inclusions have relatively low contents of Ti, Na, and K compared with those occurring as phenocrysts or xenocrysts in alkali basalts (*c.f.*, Le Maitre, 1969; McBirney and Aoki, 1969; Best, 1970).

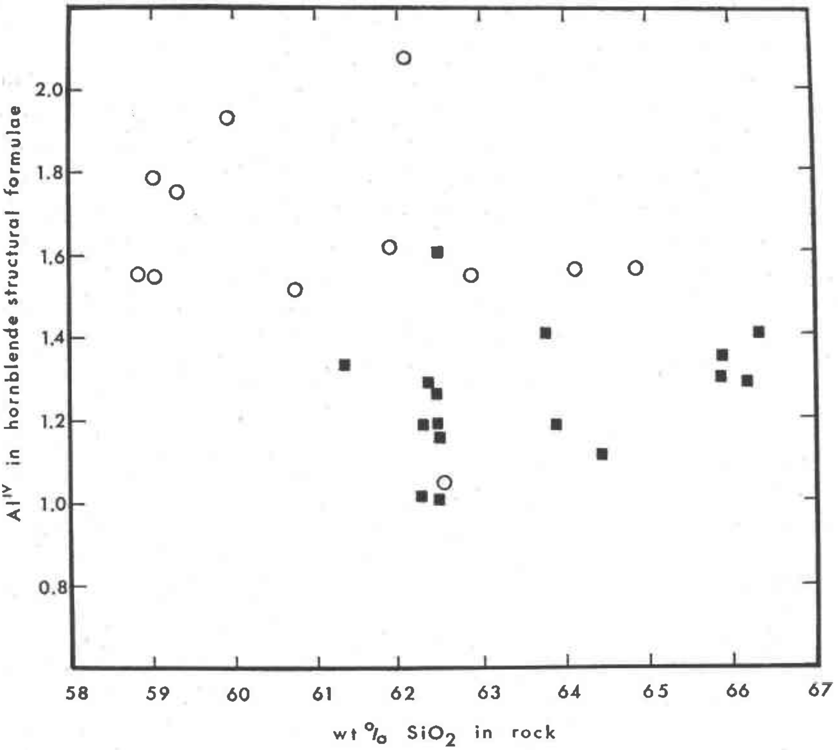

FIG. 1. Relationship between tetrahedral aluminum (Al^{IV}) in hornblende and SiO$_2$ content of the host rock. Amphiboles from Continental calc-alkaline rocks (squares) generally have a lower Al^{IV} content than those from island arc calc-alkaline rocks (circles) even for rocks of the same SiO$_2$ content.

There is positive correlation between Na + K and Al^{iv} (Fig. 2) among hornblendes from continental calc-alkaline andesites. The range of Na + K values is very similar in both groups but slightly higher in island arc rocks. The positive correlation between Al^{iv} and Fe^{3+} + Al^{vi} + Ti results from charge balance and valency requirements (Dodge *et al.*, 1968).

The relationship between total iron and magnesium in hornblendes and their host rocks is shown in Figure 3. There is an increase of Fe/Mg ratio in hornblende with increasing Fe/Mg of the host rock although the range of Fe/Mg in hornblende is fairly constant despite large variations in the host. The Fe/Mg ratio tends to be higher in Andean rocks than in island arc rocks and hence hornblendes from

Andean rocks have higher Fe/Mg ratios but where the two rock series overlap in chemical composition and have the same Fe/Mg ratios (1.6–2.2) hornblendes of continental type andesites have higher Fe/Mg ratios. Clinopyroxene crystallizes before hornblende in island arc rocks whereas in Andean rocks hornblende (as well as plagioclase) appear first. Clinopyroxenes generally have lower Fe/Mg ratios than coexisting hornblendes so that when they crystallize first there is marked increase of Fe/Mg in the amphibole.

All of the hornblendes have higher Na/K ratios than their host rocks although the K_2O content of the hornblende is dependent on the total K_2O content of the rock (Fig. 4). This plot is similar to plot used by Best, 1970 (p. 40). Hornblende phenocrysts and hornblendes from inclusions in the same rocks show that K_2O is higher in early crystals (assuming that the inclusions are cumulates), and therefore the view of Best (1970) that higher K results from crystallization at higher pressure can be supported but only in systems having the same major element chemistry.

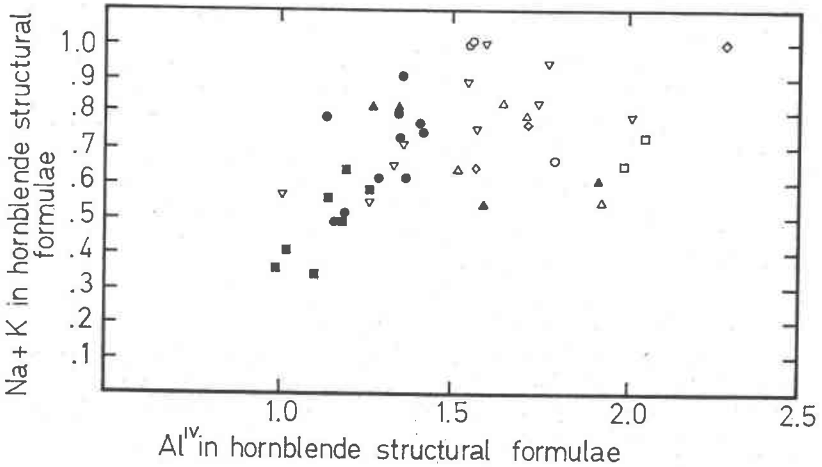

FIG. 2. Relationship of total alkali content and tetrahedral aluminum in hornblende structural formulae in island arc volcanic rocks and continental calc-alkaline volcanic rocks. Island arc occurrences: ○—Fiji; △—New Zealand (Mt. Egmont and Solander Island); ▽—Eastern Papua and Solomon Islands, □—Japan (603); ◇—Western United States (Mt. Mazama and Mt. Shasta); Continental (Andean) occurrences: ▲—Carpathians (Czechoslovakia), ■—Hunter river area, N. S. W., Australia; ●—Japan (Mt. Hakusan and Mt. Tateyama); criteria for island arc and continental type andesites division are given in Table 1.

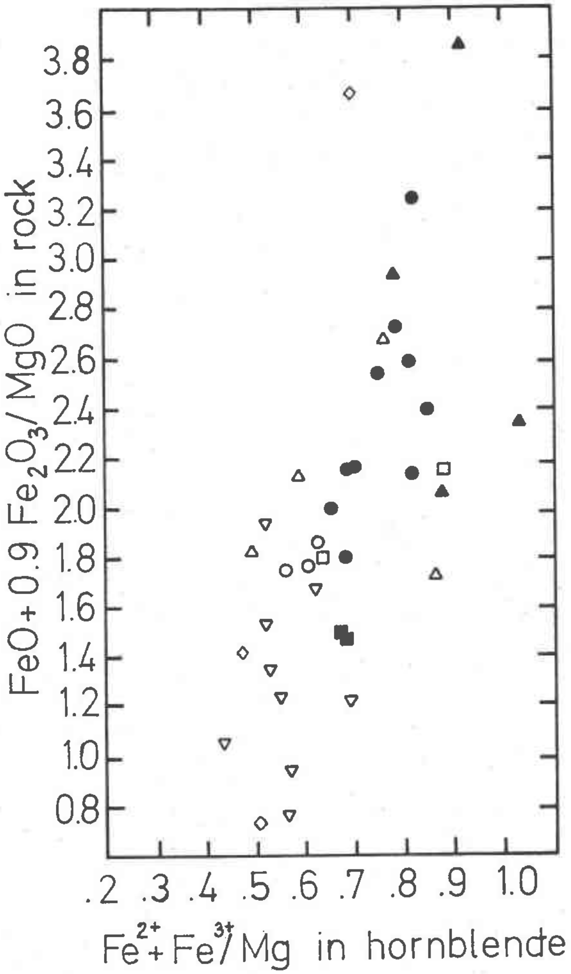

FIG. 3. The relationship of iron-magnesium ratios in hornblendes and their host rocks. Note that at same Fe/Mg ratio in rocks hornblendes from island arcs rocks (circles) have lower Fe/Mg ratios than hornblendes of calc-alkaline rocks from continental areas. Symbols as in Fig. 2.

Clinopyroxenes

Hornblende-bearing calc-alkaline rocks from island arcs usually contain euhedral only exceptionally partly resorbed crystals of clinopyroxene. Aggregates of clinopyroxene crystals, associated with minor opaque phases, and surrounded by a rim of plagioclase, amphibole and opaque minerals are common. The volume of clinopyroxene phenocrysts usually does not exceed 25 percent and clinopyroxene is far more frequent as a phenocrystic phase in island arc rocks than in Andean types.

Clinopyroxenes show a narrow range of composition. All are highly calcic and substantially different from those of the pigeonitic series of island arcs (Aoki, 1967; Kushiro, 1960). Both Al^{iv} and Al^{vi} are low as in SiO_2-saturated magmas (Kushiro, 1960) but their total Al content is slightly lower than in the clinopyroxenes from hornblende pyroxenite inclusions in calc-alkaline rocks (Yamazaki *et al.,* 1966). Alkali contents are comparable in both hornblende-bearing and hornblende free inclusions.

Orthopyroxene

Orthopyroxene occurs as colorless, weakly pleochroic phenocrysts in hornblende-bearing calc-alkaline rocks. It is rare in rocks from

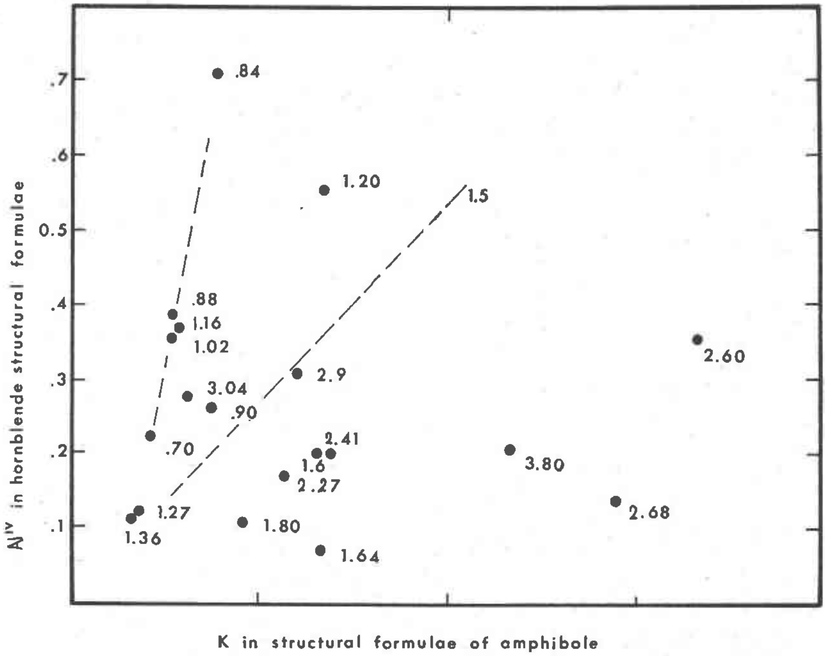

FIG. 4. The relationship of tetrahedral aluminum and potassium in hornblende structural formula. Only calc-alkaline rocks from island arcs are plotted. Number near each dot indicates K_2O content in parent rock. Right from 1.5 dashed line all parent rocks have higher content of K_2O than 1.5 percent. Tie line connects hornblende phenocryst and hornblende in accumulative "inclusion" of the same lava.

island arcs but it is more common in the continental association although this may result from the more siliceous mode of the continental types. Orthopyroxene is common in the groundmass in rocks from both associations.

New analyses show that the hypersthenes have a narrow composition range ($Fs_{24} - Fs_{45}$): this is also a feature of orthopyroxenes from the hypersthenic series of Japan (Kuno, 1968). Calcium is low even compared with other igneous orthopyroxenes and aluminum is also low. The distribution coefficients of Fe and Mg between "coexisting" ortho- and clinopyroxenes in hornblende-free lavas associated with hornblende-bearing rocks in island arcs (East Papua) indicate temperatures of around 1050° if the curves of Bunch *et al.* (1970) are used (Jakeš, 1970). However for hornblende-bearing rocks the same method gives erratic results.

Opaque Minerals

There is rarely any textural evidence that magnetite is an early crystallizing phase in the hornblende-bearing rocks of continental areas (*c.f.*, Smith and Carmichael, 1968) but titaniferous magnetite occurs in the groundmass. It occurs sometimes associated with early clinopyroxenes in island arc rocks. Phenocrystic Ti-magnetites are richer in Mg, Al, and Si than groundmass magnetites (Carmichael and Nicholls, 1967; Smith and Carmichael, 1968). Temperatures derived using Buddington and Lindsley's (1964) method modified for microprobe data by Carmichael (1967) range around 900°C, but these probably represent the final stages of crystallization.

Biotite

Biotite is rare in the calc-alkaline volcanic rocks of island arcs where it is limited to high-K types. It is more frequent in continental type andesites. Biotite from hornblende-bearing rocks are characteristically low in aluminum and have higher Fe/Mg ratios than those of hornblendes and clinopyroxenes.

DISCUSSION

Experimental Evidence

The liquidus and near liquidus phase relations of dry calc-alkaline andesite were studied in detail by Green and Ringwood (1968) over a wide range of pressures, and by Brown and Schairer (1968) at 1 atm pressure. Their data indicates that near liquidus crystallization is dominated at low and moderate pressures (0–10 kb) by plagioclase, at high pressures (10–18 kb) by plagioclase and clinopyroxene, and at extremely high pressures (20 kb) by garnet. Yoder (1969) suggested by analogy with basalts that olivine is a liquidus phase. There is little petrographic evidence of olivine precipitation in andesites, however (58 percent SiO_2).

Wet liquidus mineralogy of andesites were studied by Green and Ringwood (1968) and of related composition by Merill *et al.* (1970), at high pressure and at low pressures by Piwinski (1968), Lambert and Wyllie (1970), and Jakeš (1970). Near liquidus mineralogy in "wet" andesite experiments is dominated by the presence of hornblende at lower and moderate pressures (5–12 kbar) and by clinopyroxene and garnet at higher pressures. Magnetite is an omnipresent opaque phase. The presence of amphibole at 900°C and not at 940°C at the same pressure reported by Green and Ringwood (1968) is probably due to either smaller content of H_2O or escape of water during their experiments. In the experiments with andesite $+H_2O$, (5 percent H_2O, Jakeš, 1970) hornblende crystallizes near the liquidus over a wide range of pressures 2.5–12 kbar and is accompanied at lower temperatures or higher pressures by clinopyroxene.

The interpolation of data on dry (Green and Ringwood, 1968), 5 percent H_2O (Jakeš, 1970), water saturated (Merill *et al.*, 1970) andesites, and natural basalt composition (Holloway and Burnham, 1972) provides a model of crystallization for natural rocks and an explanation of their different mineralogies. The relevant data are generalized in Figure 5.

In natural hornblende andesites from island arcs clinopyroxene is first phase to precipitate on liquidus. Brown and Schairer (1968) ascribed hornblende precipitation in such rocks to a "build up of H_2O pressure." Such mechanism may be effective in the low pressure region (<10 kbar) where the curve for hornblende stability is subparallel to liquidus curve for a given H_2O content; however, at higher pressures, the divergence of the hornblende stability curve and the liquidus curve necessitates extensive clinopyroxene crystallization to significantly increase the H_2O content. There is no evidence (*i.e.*, chemical composition) that clinopyroxene of island arc hornblende bearing rocks crystallized above 10 kbar pressure—*i.e.*, in a region where the field of amphibole stability can be entered by a pressure drop. A decrease of temperature at low or moderate pressures (<10 kbar) is, therefore, the most likely explanation for the appearance of hornblende. This suggests that the initial water content in these rocks was low, and consequently liquidus temperatures were above the field of hornblende stability. The possibility that water was introduced from an external source is unlikely, because this would

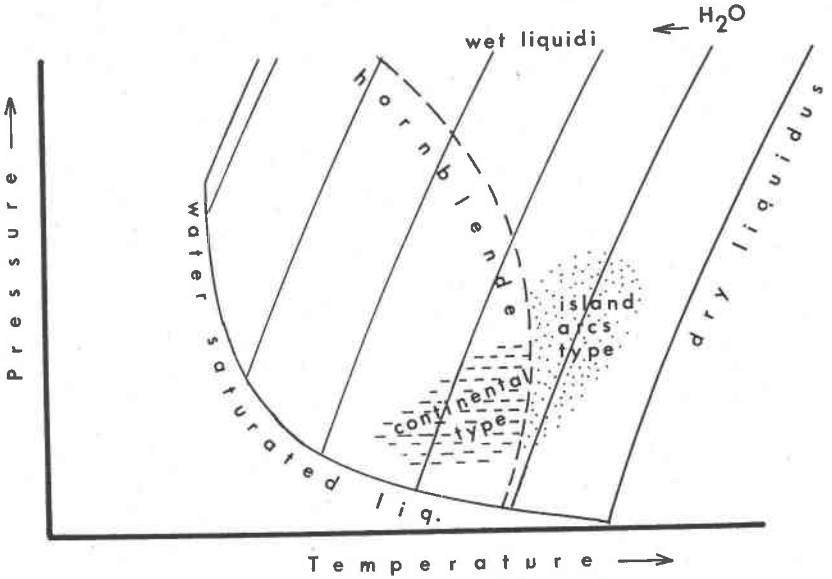

FIG. 5. Generalized relationships of initial crystallization of hornblende andesites from island arcs and continental areas.

cause a general decrease of liquidus temperature resulting in resorption or corrosion of clinopyroxenes for which there is no textural evidence.

In the continental type of andesites and some high-K rocks from island arcs (Eastern Papua) the crystallization of hornblende as the first phase on liquidus suggests that the liquidus temperatures lay within hornblende field of stability. Hornblende is joined later by clinopyroxene and plagioclase.

Compiling older and new experimental data the approximate fields of crystallization are drawn in Figure 5 and we suggest that most of the continental type of calc-alkaline rocks have contained more than 2.5 percent H_2O, whereas island arc hornblende-bearing andesites H_2O contents were probably lower than 3 percent.

If the water content is the primary feature of calc-alkaline magmas of both types and does not result from a contamination of "island arc andesites" by uppermost part of continental crust to produce continental type andesites, then the differences in a liquidus temperature allows some speculation on their origin.

Comparison of experimental and natural data shows that hornblende is unlikely to be a residual phase of partial melting or an early fractionate in the island arc andesites, but could be in continental andesites. Using trace element evidence Jakeš and White (1970) suggested that in island arcs a down-going slab of oceanic crust is melted by the decomposition of H_2O bearing phases (amphibole and mica). The low melting point fraction in this case contains most of the water available and inherits some of the geochemical character of minerals from which it has been formed.

The geochemical character of island arc lavas—*i.e.*, relatively high K/Rb ratios, low Ba and Sr, contrasts with relatively low K/Rb high Ba, Sr, etc., in continental suite of calc-alkaline rocks. We believe that the differences, although they may result from primary character of source material, could also result from hornblende fractionation in source area. Hornblende precipitation can explain such features of continental calc-alkaline rocks as the change of K_2O/Na_2O ratios with increasing SiO_2 content as well as relatively low Mg contents of continental type rocks, because hornblende fractionates K/Na and Fe/Mg.

Source Material

Jakeš and White (1971) pointed out that in older, highly evolved island arcs and in the continental margins both types of calc-alkaline volcanic are probably present. The source material for island arc rocks has been widely discussed (*i.e.*, Ringwood and Green, 1968; Ringwood, 1969; Tatsumoto, 1969) and was considered to be a mixture of oceanic crust of tholeiitic (abyssal tholeiite) composition and some associated sedimentary rocks or other (alkaline) volcanic rocks (Armstrong, 1971). In order to produce rare earth element patterns and other trace element characteristics of calc-alkaline rocks from relatively primitive tholeiitic rocks, the residuum after partial melting should have a clinopyroxene—garnet mineralogy. These residual phases also result from the fraction necessary to produce the chemical characteristics of continental andesites from a more primitive rock with hornblende crystallization accounting for Rb, K/Na, and Mg abundances. The question of source material for continental andesites is related to the composition of the lower crust, which we believe is the area where the largest volume of these rocks forms. It has been suggested that early stages of island arcs are characterized by tholeiitic activity (Baker, 1968; Jakeš and White, 1969; Gill 1970) and that basement of island arc is formed by the island arc tholeiites (Jakeš and Gill, 1970) in agreement with the fact that tholeiites are the most voluminous portion of island arcs (Sugimura, 1968). It is apparent that the primitive lower part of the island arc crust is tholeiitic and the crust, as a whole, primarily stratified with calc-alkaline rocks in its upper part. Such lower crust has lower contents of large cations, *e.g.*, K, Rb, Ba, Sr, very primitive Sr isotope ratios (0.702 ± 0.001) and does not differ substantially from oceanic basalts (*c.f.*, Jakeš and Gill, 1970) in major element chemistry except that it probably has larger proportions of Si-rich rocks. We believe that this type of lower crust, together with associated sediments, is a source material of the "continental type calc-alkaline suite" and has garnet-clinopyroxene amphibolite mineralogy.

Recent growth of island arcs (*e.g.*, Sugimura, 1968) suggests that within a period of 80–100 million years the crust of island arcs reaches a thickness between 20–30 km. The load pressure on the base of such crust will be of the order of 5–7.5 kbar, and temperatures may locally rise to 750°–800°C if most of the heat is produced along the Benioff zone (*e.g.*, Minear and Töksoz,1970). Such pressure and thermal conditions at the base of island arc or continental margin crust permit "wet" partial melting.

The differences in thermal regimes of the upper part of down-going slab with relatively low water contents and consequently higher melting temperatures (1050–1100°) and relatively high contents of water and lower liquidus temperatures for "Andean-continental type of calc-alkaline rocks" also explain the lack of basaltic members in a continental suite. The assumption of tholeiitic parent for both calc-alkaline types explains low Sr isotope ratios. Intensive piling of volcanic material together with the gradual change of thermal regime in the upper mantle and the crust above the descending slab can account for the presence of continental type (high-K) calc-alkaline rocks in late stages of island arc evolution or its presence in the continental margins.

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References

Albee, A. L., and L. Ray (1972) Correction factors for electron probe microanalysis of silicates, oxides, carbonates, phosphates and sulphates. *J. Geol.* (in press).

Aoki, K. (1967) Petrology and petrochemistry of latest Pliocene olivine tholeiites of Taos Area, northern New Mexico, U.S.A. *Contrib. Mineral. Petrology,* **14,** 190–203.

———, and I. Kushiro (1968) Some clinopyroxenes from ultramafic inclusions in Dreiser Weiher, Eife. *Contrib. Mineral. Petrology,* **18,** 326–337.

Armstrong, R. L. (1971) Isotopic and chemical constrains on models of magma genesis in volcanic arcs. *Earth Planetary Sci. Lett.* **12**, 137–142.

Baker, P. E. (1968) Comparative volcanology and petrology of the Atlantic island-arcs. *Bull. Volcan.* **32**, 189–206.

Best, M. G. (1970) Kaersutite-peridotite inclusions and kindred megacrysts in basanitic lavas, Grand Canyon, Arizona. *Contrib. Mineral. Petrology,* **27**, 25–44.

Brown, G. H., and J. F. Schairer (1968) Melting relation of some calc-alkaline volcanic rocks. *Carnegie Inst. Wash. Year Book,* **1966–1967**, 460–467.

Buddington, A. F., and D. F. Lindsley (1964) Iron-titanium oxide minerals and synthetic equivalents. *J. Petrology,* **5**, 310–357.

Bunch, T. E., K. Keil, and E. Olsen (1970) Mineralogoy and petrology of silicate inclusions in iron meteorites. *Contrib. Mineral. Petrology,* **25**, 297–370.

Carmichael, I. S. E. (1967) The iron-titanium oxides of salic volcanic rocks and their associated ferromagnesian silicates. *Contrib. Mineral. Petrology,* **14**, 36–64.

———, and J. Nicholls (1967) Iron-titanium oxides and oxygen fugacities in volcanic rocks. *J. Geophys. Res.* **72**, 4665–4687.

Dickinson, W. R., and T. Hatherton (1967) Andesitic volcanism and seismicity around the Pacific. *Science,* **157**, 801–803.

Dodge, F. C. W., J. J. Papike, and R. E. Mays (1968) Hornblendes from granitic rocks of the central Sierra Nevada Batholith, California. *J. Petrology,* **9**, 378–410.

Gill, J. B. (1970) Geochemistry of Viti Levu, Fiji, and its evolution as an island arc. *Contrib. Mineral. Petrology,* **27**, 179–203.

Green, T. H., and A. E. Ringwood (1968) Genesis of the calcalkaline igneous rock suite. *Contrib. Mineral. Petrology,* **18**, 105–162.

Hall, A., and J. N. Walsh (1969) A rapid method for the determination of fluorine in silicate rocks and minerals. *Anal. Chim. Acta,* **45**, 341–342.

Hamilton, W. (1969) The volcanic central Andes, a modern model for Cretaceous batholiths and tectonics of western North America. *Ore. Dep. Geol. Mineral. Ind., Bull.* **65**, 175–184.

——— (1970) Mesozoic California and the underflow of Pacific Mantle. *Bull. Geol. Soc. Amer.* **80**, 2709–2430.

Hatherton, T. (1968) "Miogeosynclinal" andesites. *Earth Planetary Sci. Lett.* **4**, 441–447.

Holloway, J. R., and C. W. Burnham (1972) Melting relations of basalt with equilibrium water pressure less than total pressure. *J. Petrology* (in press).

Jakeš, P. (1970) *Analytical and Experimental Geochemistry of Volcanic Rocks From Island Arcs.* Ph.D. Thesis, Australian National University.

———, and J. B. Gill (1970) Rare earth elements and the island arc tholeiitic series. *Earth Planetary Sci. Lett.* **9**, 17–28.

———, and A. J. R. White (1969) Structure of the Melanesian arcs and correlation with distribution of magma types. *Tectonophysics,* **8**, 223–236.

———, and ——— (1970) K/Rb ratios of rocks from island arcs. *Geochim. Cosmochim. Acta,* **34**, 849–856.

———, and ——— (1972) Major and trace element abundances in volcanic rocks of orogenic areas. *Geol. Soc. Amer. Bull.* **83**, 29–40.

Kiss, E. (1968) Chemical determination of some major constituents in rocks and minerals. *Anal. Chim. Acta,* **39**, 223–234.

KOSTYUK, A. E., AND V. S. SOBOLEV (1969) Paragenetic types of calciferous amphiboles of metamorphic rocks. *Lithos,* **2**, 67–81.

KUNO, H. (1950) Petrology of Hakone volcano and the adjacent areas, Japan. *Geol. Soc. Amer. Bull.* **61**, 957–1020.

——— (1966) Lateral variation of basalt magma type across continental margins and island arcs. *Bull. Volcan.* **29**, 195–222.

——— (1968) Differentiation of basalt magmas. *In* H. Hess and A. Poldervaart, eds. *Basalts,* John Wiley and Sons, 623–688.

———, AND K. AOKI (1970) Chemistry of ultramafic nodules and their bearing on the origin of basaltic magmas. *Phys. Earth Planet. Int.* **3**, 273–301.

KUSHIRO, I. (1960) Si-Al relation in clinopyroxenes from igneous rocks. *Amer. J. Sci.* **258**, 548–554.

LAMBERT, I. B., AND P. J. WYLLIE (1972) An experimental investigation of tonalite in the presence of excess water to 25 kilobars. *J. Geol.* (in press).

LEAKE, B. E. (1968) A catalog of analyzed calciferous and subcalciferous amphiboles together with their nomenclature and associated minerals. *Geol. Soc. Amer. Spec. Pap.* **98**, 210.

LEMAITRE, R. W. (1969) Kaersutite-bearing plutonic xenoliths from Tristan da Cunha, South Atlantic. *Mineral. Mag.* **37**, 185–197.

MCBIRNEY, A. R. (1969) Andesitic and rhyolitic volcanism of orogenic belts. *Amer. Geophys. Union, Mongr.* **13**, 501–507.

———, AND K. AOKI (1969) Petrology of the island of Tahiti. *Geol. Soc. Amer. Mem.* **116**, 523–556.

MERILL, R. B., J. K. ROBERTSON, AND P. J. WYLLIE (1970) Melting reactions in the systems $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O to 20 kilobars compared with results for other feldspar-quartz-H_2O and rock-H_2O systems. *J. Geol.* **78**, 558–569.

MINEAR, J. W., AND M. N. TÖKSOZ (1970) Thermal regime of a downgoing slab and new global tectonics. *J. Geophys. Res.* **75**, 1397–1419.

NORRISH, K., AND B. W. CHAPPELL (1967) X-ray fluorescence spectrography. *In* J. Zussman, (ed.), *Physical Methods in Determinative Mineralogy,* 161–214.

ONUKI, H. (1967) Significance of molecular formulas in metamorphic hornblendes with relation to P-T conditions. *Sci. Rep. Tohoku Univ.* **10**, 77–97.

PIWINSKI, A. J. (1968) Experimental studies of igneous rock series: centra Sierra Nevada Batholith, California. *J. Geol.,* **76**, 548–570.

RINGWOOD, A. E. (1969) Composition and evolution of the upper mantle. *Amer. Geophys. Union Monogr.* **13**, 1–17.

SCHMIDT, R. G. (1957) Petrology of the volcanic rocks, Saipan, Mariana Islands. *U. S. Geol. Surv. Prof. Pap.* **280**, 127–176.

SMITH, A. L., AND I. S. E. CARMICHAEL (1968) Quaternary lavas from the Southern Cascades, Western U.S.A. *Contrib. Mineral. Petrology,* **19**, 212–238.

SUGIMURA, A. (1968) Spatial relations of basaltic magmas in island arcs. In H. Hess and A. Poldervaart (eds) *Basalts,* John Wiley and Son, 573–557.

TATSUMOTO, M. (1969) Lead isotopes in volcanic rocks and possible ocean-floor thrusting beneath island arcs. *Earth Planet. Sci. Lett.* **6**, 369–376.

YAMASAKI, M., N. NAKANISHI, AND Y. KASENO (1964) Nueé ardente deposit of Hakusan volcano. *Sci. Rep. Kanazawa Univ.* **9**, 189–201.

YODER, H. S. (1969) Calcalkalic andesites: Experimental data bearing on the origin of their assumed characteristics. *Ore. Dep. Geol. Mineral. Ind. Bull.* **65**, 77–89.

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