GREE-TH 68-0249 49

3 (1965) 155.
11 (1966) 278.
ple, Science 152 (1966)

EARTH AND PLANETARY SCIENCE LETTERS 3 (1967) 481-489. NORTH-HOLLAND PUBLISHING COMP., AMSTERDAM

CRYSTALLIZATION OF BASALT AND ANDESITE UNDER HIGH PRESSURE HYDROUS CONDITIONS

Trevor H. GREEN * and A. E. RINGWOOD
Department of Geophysics and Geochemistry,
Australian National University,
Canberra, Australia

Received 23 January 1968

Experimental crystallization of synthetic high-alumina quartz tholeiite and basaltic andesite glasses at 9–10 kb under conditions of $P_{H_2O} < P_{load}$ demonstrates that sub-silicic clinopyroxene, orthopyroxene and amphibole are the near-liquidus phases above 1000°C. Amphibole is the dominant phase at temperatures of about 960°C and less. Calcic plagioclase occurs nearer the solidus. In an andesite composition plagioclase and clinopyroxene are the near-liquidus phases at 940°C, joined by orthopyroxene, amphibole and garnet at lower temperatures. Electron microprobe analysis of phases crystallizing from the basalt allows calculation of the composition of liquid fractionates obtained under these conditions. The calculated liquid fractionate compositions follow the calc-alkaline trend and demonstrate that the calc-alkaline igneous rock suite may be derived by the fractional crystallization of basalt under hydrous conditions at 30–40 km depth ($P_{H_2O} < P_{load}$) or alternatively by the partial melting of amphibolite under similar conditions. In both cases the crystalline residuum will consist dominantly of amphibole, with subordinate clinopyroxene and orthopyroxene, and possibly minor calcic plagioclase and garnet, depending on the degree of fractionation.

1. INTRODUCTION

In the course of an experimental investigation of the origin of the calc-alkaline series, an exploratory study of fractional crystallization of basalt, basaltic andesite and andesite under hydrous conditions at pressures of 9–10 kb ($P_{H_2O} < P_{load}$) has been carried out. The preliminary results and implications of this study are reported in this communication. Preliminary results of an experimental investigation of an alternative hypothesis of origin of the calc-alkaline series viz. partial melting of quartz eclogite at depths of 100–150 km have already been reported [1]. The detailed experimental results and conclusions from both investigations will be given in a subsequent longer paper.

The hypothesis that the calc-alkaline series may be derived by hydrous fractional crystallization or partial melting of mafic material near the base of the crust or in the upper mantle (e.g. at 30–40 km depth) has frequently been referred to in the literature [2-6], but so far there have been no experimental data directly applicable to the testing of this hypothesis. Yoder and Tilley [7] conducted pioneering work on the crystallization of a number of natural basalt compositions under controlled water vapour pressure conditions from 0–10 kb ($P_{H_2O} = P_{load}$) using a gas apparatus. They demonstrated lowering of the liquidi of the compositions with increasing P_{H_2O}, together with a marked increase in the size of the field of crystallization of amphibole, but the composition of the amphibole was not known. The presence of such a large field of crystallization of amphibole from basalt under these conditions suggests that the composition of the amphibole may be a key factor in testing the hypothesis for the derivation of calc-alkaline rocks from a basic parent under hydrous conditions. Accordingly, in the present investigation the sequence of crystallization and the composition of the

---

* Present address: Hoffman Laboratory, Harvard University, Cambridge, Mass. 02138, USA.

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

	1. High-alumina quartz tholeiite	2. Basaltic andesite	3. Andesite
SiO_2	52.9	56.4	62.2 **
TiO_2	1.5	1.4	1.1 **
Al_2O_3	16.9	16.6	17.3 **
Fe_2O_3	0.3 *	3.0 *	0.3 *
FeO	7.9 *	5.7 *	5.9 *
MnO	0.2	0.1	0.1
MgO	7.0	4.3	2.4 **
CaO	10.0	8.5	5.2 **
Na_2O	2.7	3.0	3.3 **
K_2O	0.6	1.0	2.3 **
	100.0	100.0	100.1
Mol. Prop. $\frac{100\ \mathrm{MgO}}{\mathrm{MgO}+(\mathrm{FeO}+0.9\mathrm{Fe_2O_3})}$	60.4	47.7	41.0

* Denotes chemically determined content (E. Kiss, A.N.U., analyst).
** Denotes content determined by electron microprobe analysis.

crystallizing phases (obtained using the electron microprobe) in quartz tholeiite, basaltic andesite and andesite compositions have been determined for conditions of $P_{H_2O} < P_{load}$ (such conditions are considered geologically more probable than $P_{H_2O} = P_{load}$ at depths of 30–40 km in the lower crust or upper mantle). These results have then been used to determine quantitatively the composition of liquid fractionates obtained from a parent basic composition.

2. EXPERIMENTAL

The experimental work has involved use of the same series of synthetic glass compositions described previously [1]. The compositions are given in table 1. Oxidation states and iron contents have been checked by chemical analysis (E. Kiss, A.N.U., analyst). The glasses have been subjected to pressures of 9–10 kb at temperatures of 800–1000°C in a piston-cylinder high pressure apparatus similar in design to the one described by Boyd and England [8, 9]. The high pressure experimental techniques involved have been described fully elsewhere [10], with the exception that in these hydrous runs undried pressure cell components without boron nitride sleeves have been used, and the sample is packed into a thin walled platinum tube (0.004 in. wall thickness) with about 1 mgm of water. The tube is then crimped but not sealed. The runs have been conducted for 1–8 hr. At the conclusion of a run the sample has been examined by optical, X-ray and, in selected cases, electron microprobe techniques. The procedure results in uncontrolled hydrous conditions during the experiment, with P_{H_2O} undoubtedly less than P_{load}. The water present caused a lowering of the liquidus by about 200°C and the probable P_{H_2O} causing this effect would be from 2–5 kb. The exact value is not known. A pressure correction of −10% has been applied to the nominal load pressure, to allow for friction and imperfect pressure transmission in the furnace assemblies [11]. The experimental method is not ideal because of some iron-loss to the platinum sample capsules during the long experiments, and also because of the uncertainty of P_{H_2O} on the sample, but it is adequate for this exploratory investigation. An empirical correction for the iron-loss effects based upon a comparison of measured Fe/(Fe+Mg) crystal-liquid partition coefficients in an additional series of runs carried out in graphite capsules, in which no iron was lost, has been applied. It can be demonstrated that this correction adequately compensates for the iron loss.

3. Andesite
62.2 **
1.1 **
17.3 **
0.3 *
5.9 *
0.1
2.4 **
5.2 **
3.3 **
2.3 **
100.1
41.0

ı thin walled platinum
with about 1 mgm of
d but not sealed. The
l–8 hr. At the conclu-
en examined by opti-
ȷ, electron microprobe
ılts in uncontrolled
experiment, with
load. The water present
us by about 200°C and
ȷ effect would be from
known. A pressure
ıplied to the nominal
ion and imperfect
ınace assemblies [11].
ıt ideal because of
sample capsules during
because of the uncer-
but it is adequate for
An empirical correc-
sed upon a comparison
al-liquid partition co-
s of runs carried out in
iron was lost, has been
d that this correction
e iron loss.

---

3. ANALYTICAL PROCEDURE

Direct quantitative analysis of amphibole, pyroxene and plagioclase crystals has been carried out using an electron microprobe. Prepared synthetic glasses of approximate amphibole, pyroxene and plagioclase compositions have been used as standards. Because of similarity in composition between standards and unknowns no correction procedures have been followed. The accuracy of analysis obtainable is sufficient for the purpose of indicating fractionation trends of major elements under certain *P–T* conditions, which is the main aim of this experimental project.

4. RESULTS

In the high-alumina quartz tholeiite composition clinopyroxene is the liquidus phase at about 1100°C and it is joined by orthopyroxene and amphibole at lower temperatures. Amphibole is the dominant phase at temperatures of about 960°C and less. Orthopyroxene is only present in minor quantities. Plagioclase joins the ferromagnesian phases at about 920°C. Accessory pseudo-brookite (?) needles are also present. A similar sequence of crystallization is observed in the basaltic andesite, and again amphibole is the dominant phase below 960°C. Plagioclase is present at 900°C. In contrast to these two compositions where plagioclase does not appear until temperatures are well below the liquidus, in the andesite composition under hydrous conditions at 10 kb, plagioclase and clinopyroxene are the near-liquidus phases at 940°C. These phases are joined by garnet, amphibole, orthopyroxene and accessory pseudo-brookite (?) by 900°C. A few runs conducted on the high-alumina quartz tholeiite using graphite capsules showed a similar sequence of crystallization to the runs in platinum capsules, but due to the difficulty in achieving equivalent P_{H_2O}, there are different degrees of crystallization in graphite and platinum capsule runs at corresponding temperatures.

5. ANALYTICAL DATA

Analyses of clinopyroxene, orthopyroxene, amphibole and plagioclase from runs on the high-alumina quartz tholeiite are given in tables 2–4. The pyroxenes show high alumina content in tetrahedral co-ordination and correspondingly low silica contents. The amphiboles correspond to aluminous edenitic hornblendes with a significant alumina content in tetrahedral co-ordination and a low silica content. Since H_2O could not be analyzed using the electron microprobe, the structural formula has been calculated on an anhydrous basis. The Mg/(Mg + Fe) ratio is significantly lower in the amphibole than in the co-existing pyroxenes. The plagioclase crystallizing well below the liquidus is noteworthy for its high anorthite content, when compared with plagioclases crystallizing from a similar basalt under dry conditions [12].

In summary the important features of these experimental results are the large field of crystallization of sub-silicic amphibole, subordinate crystallization of aluminous sub-silicic pyroxenes and, nearer the solidus, crystallization of calcic plagioclase from the basaltic composition. Similar crystallization occurs in the basaltic andesite.

6. CALCULATION OF FRACTIONATION TRENDS

Knowing the compositions of the crystallizing phases, and estimating their proportions, the composition of the residual liquid fractionates can be calculated, and the fractionation trends determined. There is a significant amount of iron loss to the platinum capsules in the 4–8 hour wet runs (e.g. an average loss of about 2.3% FeO, iron calculated as FeO). This results in crystallization of phases possessing higher 100 Mg/(Mg + Fe) ratios than would have occurred in runs without iron loss, and in turn affects the calculated fractionation trends. Appropriate corrections have been applied for this loss as discussed previously (section 2) thus yielding the true fractionation trend. The corrections have been verified by analyses of pyroxenes and amphiboles from runs in graphite capsules where no iron loss occurred.

The calculated residual liquid compositions are given in table 5. These liquids show marked silica and alkali enrichment, and also some alumina enrichment in the early stages. The 100 Mg/(Mg + Fe) ratio obtained for varying degrees of crystallization follows that of the calc-alkaline trend, showing only minor iron enrichment relative to magnesium. The slight

Table 2

Electron microprobe analyses of clinopyroxenes and orthopyroxenes from selected wet runs.

Composition	High alumina quartz tholeiite										
Conditions of run	10 kb 920°C $7\frac{1}{2}$ hr WET	10 kb 960°C 4 hr WET	9 kb 1040°C 4 hr WET	9 kb 1040°C 4 hr WET	10 kb 920°C $7\frac{1}{2}$ hr WET	10 kb 960°C 4 hr WET	9 kb 1040°C 4 hr WET	9 kb 1040°C 4 hr WET	10 kb 960°C 4 hr WET	10 kb 940°C 6 hr WET	10 kb 960°C 4 hr WET
	Runs conducted in platinum capsules				Analyses adjusted for iron loss				Runs conducted in graphite capsules		
Co-existing phases	amph *, opx, plag *	amph *, opx	amph *, opx *	amph *, cpx *	amph *, opx, plag *	amph *, opx	amph *, opx *	amph *, cpx *	opx *, ilm	amph *, opx, ilm	cpx *, ilm
SiO_2	47.2	48.0	47.3	47.5	46.7	47.5	46.8	46.3	51.7	52.0	49.4
TiO_2	1.6	1.6	1.7	0.8	1.6	1.6	1.7	0.8	1.2	0.9	0.6
Al_2O_3	10.0	10.6	8.6	7.5	9.9	10.5	8.5	7.3	9.2	11.3	8.4
FeO	7.0	6.1	5.8	11.8	9.0	7.9	7.6	15.4	6.4	8.3	11.1
MgO	11.6	11.9	14.9	26.6	10.5	10.9	13.9	24.5	13.6	13.8	27.9
CaO	21.6	18.7	20.1	1.7	21.4	18.5	19.9	1.7	19.7	19.8	1.4
Na_2O	0.7	0.7	0.6	–	0.7	0.7	0.6	–	0.1	0.2	–
	99.7	97.6	99.0	95.9	99.8	97.6	99.0	96.0	101.9	106.3	98.8
$\frac{100\ Mg}{Mg + Fe}$	74.7	77.7	82.1	80.1	67.5	71.1	76.5	73.9	79.1	74.8	81.7
Formula 6 [0]											
Si	1.7543	1.7922	1.7567	1.7722	1.7500	1.7888	1.7532	1.7588	1.8430	1.7904	1.7754
Al z	0.2457	0.2078	0.2433	0.2278	0.2500	0.2112	0.2468	0.2412	0.1570	0.2096	0.2246
Al	0.1921	0.2585	0.1330	0.1018	0.1874	0.2586	0.1283	0.0857	0.2295	0.2490	0.1313
Ti	0.0447	0.0448	0.0475	0.0224	0.0450	0.0453	0.0480	0.0228	0.0321	0.0234	0.0162
Fe	0.2176	0.1905	0.1801	0.3682	0.2822	0.2490	0.2382	0.4892	0.1909	0.2386	0.3337
Mg $x + y$	0.6428	0.6626	0.8252	1.4800	0.5867	0.6122	0.7765	1.3878	0.7231	0.7086	1.4952
Ca	0.8600	0.7479	0.7998	0.0679	0.8593	0.7465	0.7985	0.0692	0.7525	0.7303	0.0540
Na	0.0505	0.0507	0.0433	–	0.0509	0.0512	0.0437	–	0.0068	0.0132	–
x	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
$x + y$	2.01	1.96	2.03	2.04	2.01	1.96	2.03	2.05	1.94	1.96	2.03
At. Prop.											
Mg	37.4	41.4	45.7	77.3	34.0	38.1	42.8	71.3	43.4	42.2	79.4
Fe	12.6	11.9	10.0	19.2	16.3	15.5	13.1	25.1	11.5	14.2	17.7
Ca	50.0	46.7	44.3	3.5	49.7	46.4	44.1	3.6	45.1	43.6	2.9

* Denotes co-existing phase analyzed.

Table 3

Electron microprobe analyses of amphiboles from selected wet runs on the high-alumina quartz tholeiite composition.

Conditions of run	10 kb 920°C $7\frac{1}{2}$ hr WET	10 kb 960°C 4 hr WET	9 kb 1040°C 4 hr WET	9 kb 1040°C 4 hr WET	10 kb 960°C 4 hr WET	10 kb 920°C $7\frac{1}{2}$ hr WET	10 kb 940°C 6 hr WET	10 kb 920°C $5\frac{1}{2}$ hr WET
	Runs conducted in platinum capsules			Analyses adjusted for iron loss			Runs conducted in graphite capsules	
Co-existing phases	cpx *, opx, plag *	cpx *, opx	cpx *, opx *	cpx *, opx *	cpx *, opx	cpx *, opx, plag *	cpx *, opx, mt	cpx, opx, mt
SiO_2	40.5	40.8	39.8	39.3	40.2	39.9	40.0	40.2
TiO_2	2.9	2.8	3.9	3.8	2.8	2.9	3.0	3.1
Al_2O_3	15.8	14.4	15.8	15.6	14.2	15.6	14.8	15.4
FeO	10.0	8.2	7.6	9.8	10.6	12.6	9.4	9.8
MgO	13.1	14.9	14.9	13.7	13.6	11.6	12.9	12.1
CaO	12.4	11.7	12.0	11.8	11.5	12.2	11.6	11.8
Na_2O	2.5	2.7	2.9	2.9	2.7	2.5	2.0	1.8
K_2O	0.4	0.4	0.2	0.2	0.4	0.4	0.3	0.3
	97.6	95.9	97.1	91.7	96.0	97.7	94.0	94.5
$\frac{100\ Mg}{Mg + Fe}$	70.3	76.4	77.8	71.4	69.6	62.1	71.0	68.8
Structural formulae – calculated on 'dry' basis of 23 [0] since H_2O content could not be determined								
z Si	5.932	6.025	5.802	5.790	6.002	5.909	6.288	6.039
z Al	2.068	1.975	2.198	2.210	1.998	2.091	1.712	1.961
y Al	0.659	0.531	0.516	0.498	0.500	0.631	1.029	0.766
y Ti	0.320	0.311	0.427	0.422	0.314	0.323	0.354	0.350
y Fe	1.209	1.013	0.927	1.208	1.324	1.561	1.236	1.231
y Mg	2.862	3.281	3.239	3.011	3.029	2.561	3.024	2.710
z Ca	1.945	1.851	1.874	1.862	1.840	1.936	1.954	1.899
z Na	0.709	0.861	0.820	0.829	0.781	0.717	0.610	0.524
z K	0.074	0.075	0.037	0.037	0.075	0.075	0.060	0.058
z	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
y	5.05	5.14	5.11	5.14	5.17	5.08	5.64	5.06
z	2.73	2.79	2.73	2.73	2.70	2.79	2.62	2.48

* Denotes co-existing phase analyzed.

enrichment of iron relative to magnesium would have been decreased if the experiments had not been carried out under such reducing conditions, since under more oxidising conditions a significant amount of iron in the trivalent state may be taken into the amphibole and pyroxene structures. For example amphiboles and pyroxenes from plutonic and effusive members of the calc-alkaline series contain a significant amount of ferric iron ([$(100\ Fe_2O_3)/(FeO + Fe_2O_3)$] ranges from 15.7–48.6 for amphiboles and from 19.1–32.8 for clinopyroxenes [13-16]).

The most significant feature of this experimental investigation at 9–10 kb under hydrous conditions where $P_{H_2O} < P_{load}$, is that the amphiboles and pyroxenes are subsilic, so that extraction of these phases provides a very efficient means of enriching liquid fractionates in silica. Thus the residuum in equilibrium with a liquid of basaltic andesite composition will consist of approximately equal proportions of pyroxene and amphibole. However, amphibole and subordinate pyroxene will form the residuum in equilibrium with a liquid of andesite composition (the

Table 4
Electron microprobe analysis of plagioclase from a wet run on the high-alumina quartz tholeiite composition.

Conditions of run	10 kb 920°C $7\frac{1}{2}$ hr
Co-existing phases	cpx *, opx, amph *
SiO_2	52.9 **
Al_2O_3	30.0
CaO	13.9
Na_2O	3.9
K_2O	0.1
	100.8
Mol. Prop.	
Or	0.6
Ab	33.4
An	66.0

* Denotes co-existing phase analyzed.
** Denotes calculated content.

residuum will be approximately 45% by weight of the initial basalt). Finally amphibole, pyroxene, plagioclase and possibly minor garnet will constitute the residuum when dacitic and rhyodacitic liquids are extracted.

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 basaltic composition. If a basalt with an alumina content of about 14% had been used then the alumina 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.

7. APPLICATION OF RESULTS TO THE ORIGIN OF THE CALC-ALKALINE IGNEOUS ROCK SUITE

These experimental results and calculated fractionation trends suggest that the calc-alkaline igneous rock suite may be derived by the fractional crystallization of a hydrous basalt at 30–40 km depth under conditions of $P_{H_2O} < P_{load}$, or alternatively by the partial melting of an amphibolitic lower crust at similar depths and water pressure conditions. In both cases the crystalline residuum will consist dominantly of amphibole, with subordinate clinopyroxene and orthopyroxene, and possibly calcic plagioclase and garnet, depending on the extent of fractional crystallization or partial melting.

In the first case the required P_{H_2O} conditions may be obtained in a basalt magma at 30–40 km depth in such areas as continental margins and island arcs. It might be postulated that the ultimate source of the water was the hydrosphere, and that it was introduced into the mantle by a sinking limb of a convection cell containing some hydrated rocks, as in the hypothesis of 'sea-floor spreading' [17]. This, in turn, might explain the association of calc-alkaline rocks with a particular tectonic environment. The basalt magma may be derived by direct partial melting of the mantle at 30–40 km depth (in which case a high-alumina basalt would be expected [18]), or it may have been derived at greater depth and subsequently rose to a depth of 30–40 km before being contaminated with water and undergoing fractional crystallization under hydrous conditions (in this case the parent basalt may be an olivine tholeiite or an alkali basalt type [19]). The overall composition of the calc-alkaline suite resulting from such fractional crystallization will vary to some extent, depending on the parent basaltic composition and on the depth at which the process takes place.

The crystalline residuum will be comparatively poor in alkalies and similar to an alkali-poor olivine tholeiite. Under appropriate $P–T$ conditions subsequent to the fractional crystallization, the residuum may lose its water content and over a long period of time transform to eclogite [20, 10]. The work of Ringwood and D. H. Green demonstrated that such a composition transformed to eclogite more readily than other basalts. If the transformation takes place then the residuum may subsequently sink into the mantle because of its high density (~ 3.6 g/cm^3). In this way no volume problem arises regarding the crystalline residuum resulting from the derivation of the calc-alkaline series from the fractional crystallization of a parent basalt.

In the second case it is envisaged that the calc-

–40 km depth under
alternatively by the
ic lower crust at simi-
nditions. In both
ill consist dominantly
clinopyroxene and
cic plagioclase and
of fractional crystalli-

P_{H_2O} conditions may
t 30–40 km depth in
s and island arcs. It
imate source of the
that it was introduced
b of a convection cell
, as in the hypothesis
is, in turn, might ex-
line rocks with a
The basalt magma
melting of the mantle
se a high-alumina
or it may have been
sequently rose to a
g contaminated with
crystallization under
the parent basalt may
li basalt type [19]).
alc-alkaline suite re-
tallization will vary
e parent basaltic com-
ich the process takes

be comparatively
alkali-poor olivine
T conditions subse-
ation, the residuum
ver a long period of
10]. The work of
onstrated that such
logite more readily
rmation takes place
ntly sink into the
y (~ 3.6 g/cm^3). In
es regarding the crys-
he derivation of the
tional crystallization

ged that the calc-

Table 5

Calculated compositions of liquid fractionates and crystalline residua derived from the high-alumina quartz tholeiite at 9–10 kb under wet conditions *.

Pressure		9 kb	10 kb	10 kb
Temperature		1040°C	960°C	920°C
Nature and estimated % of crystals extracted	Initial liquid	18% cpx 5% amph 2% opx 1% ilm	18% cpx 25% amph 2% opx 1% ilm	18% cpx 32% amph 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
CaO	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. $\frac{100\ MgO}{MgO + FeO_{tot}}$	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
CaO		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

* The orthopyroxene analysis obtained at 1040°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 part of the crystalline residua. This is because an accessory iron-titanium rich opaque mineral phase occurred in the experimental runs in graphite capsules where no iron loss took place. This phase could not be analyzed quantitatively and as a first approximation for these calculations was taken as ilmenite.

alkaline series is derived from the mantle as the result of a two-stage process. In the first stage large piles of basalt of overall saturated composition develop in the earth's crust in such areas as island arcs and continental margins. Limited access of water to the basalt pile results in formation of amphibolite in the lower regions. The water content of the amphibolite may be of the order of 1%. Subsequent heating of this amphibolite, due to renewed or continued volcanic activity from the mantle may result in partial melting taking place. The pressures at which such partial melting takes place may be as high as 10 kb, corresponding to the base of the crust and water vapour pressure is likely to be less than the load pressure. The experimental work described in this paper indicates that the residual phases from such melting will consist mainly of amphibole with subordinate clinopyroxene and possibly calcic plagioclase and garnet, depending on the degree of partial melting. As in the first case the initial overall composition of the parent basic material and the temperature and depth at which partial melting occurs will be important factors in determining the composition of the derived calc-alkaline magmas. Similarly the residuum may transform to eclogite and sink into the mantle.

This second case is essentially a complementary two-stage model to that proposed in a previous paper (viz. the partial melting of a sinking quartz eclogite at 100–150 km depth [1]). Both models involve derivation of the calc-alkaline suite by a two-stage magmatic process, incorporating in the first stage large scale extrusion of saturated basaltic magma in the earth's crust. The subsequent history of this basalt pile, whether it remains dry and transforms to eclogite, or whether water has access changing it to amphibolite, determines whether the calc-alkaline suite is produced according to the eclogite melting model [1] or by melting of amphibolite as outlined in this paper. Both models explain the derivation of the calc-alkaline suite in areas where no sialic material occurs and so provide a mechanism for continental evolution from an undersaturated upper mantle.

Because of the sub-silicic nature of the residual phases (aluminous amphiboles, pyroxenes and possibly minor garnet and calcic plagioclase) hydrous fractional crystallization of a basaltic magma or partial melting of amphibolite at about 30–40 km depth provides a highly efficient way of deriving intermediate to acidic compositions from a basic parent. Thus in the derivation of andesite magma the mass ratio of residual phases to andesite magma produced is approximately unity. In contrast in models involving fractional crystallization of low pressure phases (e.g. from crystallization of dry basalt) the mass ratio of crystalline material to magma would be two or more, even under idealized conditions.

REFERENCES

[1] T. H. Green and A. E. Ringwood, Origin of the calc-alkaline igneous rock suite, Earth Planet. Sci. Letters 1 (1966) 307.

[2] R. A. Daly, Igneous rocks and the depths of the earth (McGraw-Hill, New York, 1933).

[3] R. R. Coats, Magma type and crustal structure in the Aleutian Arc, in Crust of the Pacific Basin, Geophys. Mon. 6 (1962) 92.

[4] W. Hamilton, Origin of high-alumina basalt, andesite and dacite magmas, Science 146 (1964) 635.

[5] E. G. Lidiak, Petrology of andesitic, spilitic and keratophyric flow rock, north-central Puerto Rico, Geol. Soc. Am. Bull. 76 (1965) 57.

[6] C. D. Branch, Genesis of magma for acid calc-alkaline volcano-plutonic formations, Tectonophys. 4 (1967) 83.

[7] H. S. Yoder Jr. and C. E. Tilley, Origin of basalt magmas: an experimental study of natural and synthetic rock systems, J. Petrol. 3 (1962) 342.

[8] F. R. Boyd and J. L. England, Apparatus for phase-equilibrium measurements at pressures up to 50 kb and temperatures up to 1750°C, J. Geophys. Res. 65 (1960) 741.

[9] F. R. Boyd and J. L. England, Effect of pressure on the melting point of diopside, $CaMgSi_2O_6$ and albite $NaAlSi_3O_8$ in the range up to 50 kb, J. Geophys. Res. 68 (1963) 311.

[10] D. H. Green and A. E. Ringwood, An experimental investigation of the gabbro to eclogite transformation and its petrological applications, Geochim. Cosmochim. Acta 31 (1967) 767.

[11] T. H. Green, A. E. Ringwood and A. Major, Friction effects and pressure calibration in a piston-cylinder apparatus at high pressure and temperature, J. Geophys. Res. 71 (1966) 3589.

[12] T. H. Green, unpublished results.

[13] E. S. Larsen, J. Irving, F. A. Gonyer and E. S. Larsen, Petrologic results of a study of the minerals from the Tertiary volcanic rocks of the San Juan region, Colorado, Am. Min. 21 (1936) 679.

[14] K. Aoki, On hornblende from Ammadaki, Iki Islands, Northern Kyushu, Japan, J. Jap. Assoc. Min. Pet. Econ. Geol. 45 (1961) 115.

a basic parent. Thus
ma the mass ratio of
a produced is ap-
models involving
pressure phases (e.g.
) the mass ratio of
uld be two or more,

d, Origin of the calc-
h Planet. Sci. Letters 1

he depths of the earth
).
ustal structure in the
cific Basin, Geophys.

mina basalt, andesite
(1964) 635.
sitic, spilitic and kerato-
Puerto Rico, Geol. Soc.

for acid calc-alkaline
ctonophys. 4 (1967) 83.
, Origin of basalt mag-
atural and synthetic
) 342.
pparatus for phase-
essures up to 50 kb and
Geophys. Res. 65 (1960)

ffect of pressure on the
Si$_2$O$_6$ and albite
0 kb, J. Geophys. Res.

d, An experimental in-
ogite transformation and
ochim. Cosmochim. Acta

d A. Major, Friction ef-
a piston-cylinder appa-
erature, J. Geophys. Res.

s.
nyer and E. S. Larsen,
the minerals from the
an Juan region, Colorado,

mmadaki, Iki Islands,
. Assoc. Min. Pet. Econ.

[15] P. W. Lipman, Mineralogy and paragenesis of amphibole from Gibson Peak pluton, Northern California, Am. Min. 49 (1964) 1321.

[16] W. A. Deer, The composition and paragenesis of the hornblendes of the Glen Tilt Complex, Perthshire, Min. Mag. 25 (1938) 56.

[17] H. H. Hess, History of ocean basins, in: A. E. J. Engel, H. L. James and B. F. Leonard (eds.), Petrologic Studies – Buddington Vol. Geol. Soc. Am., N.Y., 599.

[18] T. H. Green, D. H. Green and A. E. Ringwood, The origin of high-alumina basalts and their relationships to quartz tholeiites and alkali basalts, Earth Planet. Sci. Letters 2 (1967) 41.

[19] D. H. Green and A. E. Ringwood, Genesis of basaltic magmas, Contr. Mineral. Petrol. 15 (1967) 103.

[20] A. E. Ringwood and D. H. Green, An experimental investigation of the gabbro-eclogite transformation and some geophysical implications, Tectonophys. 3 (1966) 383.