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# High-pressure experimental studies on the origin of anorthosite

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Experimental crystallization of anhydrous synthetic quartz diorite ( $\approx$ andesite), gabbroic anorthosite, and high-alumina basalt has been conducted in their respective partial melting fields at high pressure. The quartz diorite composition shows a large field of crystallization of plagioclase from 0–13.5 kb, together with subordinate amounts of orthopyroxene and clinopyroxene and minor opaque minerals. In the gabbroic anorthosite, plagioclase is the main phase crystallizing from 0–22.5 kb, but at higher pressure it is replaced by aluminous clinopyroxene. Aluminous clinopyroxene is the main phase crystallizing from the high-alumina basalt from 9–18 kb and is joined by plagioclase at lower temperatures. At higher pressure it is joined by garnet. The albite content of the liquidus and near-liquidus plagioclase increases markedly with increasing pressure in each of the three compositions.

The results for the high-alumina basalt and gabbroic anorthosite compositions preclude any major trends towards alumina enrichment and derivation of anorthositic plutons at crustal or upper mantle depths under anhydrous conditions. However, the results for the quartz diorite suggest that anorthositic complexes may form as a crystalline residuum from the partial melting of a lower crust of overall andesitic composition or from fractional crystallization of an andesitic magma. In either case a large separation of plagioclase crystals occurs (andesine – acid labradorite composition at lower crustal pressures), together with subordinate pyroxenes and ore minerals. Under appropriate temperature conditions separation of crystals and liquid by a filter-pressing mechanism during deformation may result in the genesis of igneous complexes containing rock types ranging in composition from gabbro through gabbroic anorthosite to anorthosite, together with associated acid rocks. The acid rocks need not necessarily remain spatially associated with the refractory gabbroic anorthosite and anorthosite. Where these processes have operated in the crust, anorthositic rocks may be left as the main component of the lower crust, while the low melting acidic fraction has intruded to higher levels.

## Introduction

This paper describes an experimental approach to the problem of the origin of the massive type of anorthosites occurring in high-grade Precambrian metamorphic terrains. These anorthosites are characterized by plagioclase of composition  $An_{35}$ – $An_{60}$ ;  $An_{50}$  is the most common composition. Derivation of massive complexes containing plagioclase of this composition cannot readily be explained by fractional crystallization of a basic parent magma in the same way as the stratified anorthositic rocks of layered igneous complexes such as Bushveld or Stillwater. Many different theories of petrogenesis of the massive anorthosites have been proposed, but in recent reviews of the problem (Turner and Verhoogen 1960; Buddington 1961; Kranck 1961) it has generally been concluded that magmatic processes (and possibly closely related anatexis processes) have played the major role in the genesis of these anorthosites. Accordingly, the experimental work described in this paper has been directed towards solving the problem of the origin of the massive anorthosites in terms of magmatic or anatexis processes.

The choice of the complex compositions to be studied has been based on proposed parental

magma compositions for anorthositic complexes. These compositions have variously been considered as basalt (Bowen 1917; Emslie 1965; Morse 1966; Olmsted 1966), diorite (Balk 1931), quartz diorite (Barth 1936), or gabbroic anorthosite (Buddington 1939, 1961; Higgs 1954; Subramaniam 1956; Hargraves 1962). These widely different parental magma compositions are arrived at according to whether the acidic intrusions often reported associated with anorthositic complexes are accepted as being genetically related to the anorthosites, gabbroic anorthosites, and gabbros, or whether they are considered to have an unrelated origin. Field evidence on the interrelationships of the various associated rock types is rarely diagnostic with regard to one origin or another.

On considering the estimated bulk composition of five documented anorthosite complexes plus the associated acid rocks (Adirondacks—Buddington 1939; Egersund—Barth 1936; Nain—Wheeler 1942, 1960; Bergen—Buddington 1939; Belleau-Desaulniers—Philpotts 1966), it is concluded that the overall composition approximates a quartz diorite rather than a basalt or diorite. In each of these cases there are descriptions of very close field relationships between anorthositic and

acidic rocks, frequently with a complete gradation from one type into another. If the acid rocks are excluded, then the bulk composition of these complexes approximates gabbroic anorthosite.

Thus the possible parent magma compositions chosen for study are gabbroic anorthosite and quartz diorite. A high-alumina basalt composition has also been studied in order to determine possible conditions under which a gabbroic anorthosite magma may be produced. The quartz diorite composition chosen (Table I) has

TABLE I  
Chosen synthetic compositions

	Quartz diorite	Gabbroic anorthosite	High-alumina basalt
SiO <sub>2</sub>	62.2*	53.5*	50.3*
TiO <sub>2</sub>	1.1*	1.0*	1.7*
Al <sub>2</sub> O <sub>3</sub>	17.3*	22.5*	17.0*
Fe <sub>2</sub> O <sub>3</sub>	0.3†	0.9†	1.5†
FeO	5.9†	4.7†	7.6†
MnO	0.1	0.1	0.16
MgO	2.4*	2.1*	7.8*
CaO	5.2*	9.9*	11.4*
Na <sub>2</sub> O	3.3*	3.7*	2.8*
K <sub>2</sub> O	2.3*	1.1*	0.18*
	100.1	99.5	100.4
	<i>CIPW Norms</i>		
Qz	15.5	2.1	—
Or	13.6	6.5	1.1
Ab	27.9	31.3	23.7
An	25.7	41.5	33.3
Diop	0.2	6.3	18.9
Hyp	14.8	8.5	11.9
Ol	—	—	6.2
Mt	0.4	1.3	2.2
Ilm	2.1	1.9	3.2

\*Denotes content determined by electron-probe analysis of a glass fragment.

†Denotes content determined by chemical analysis (E. Kiss, A. Easton, analysts).

general geological significance, as indicated by comparison with average andesite (Taylor and White 1965), tonalite (Nockolds 1954), quartz diorite (Daly 1933), Archean graywacke (Pettijohn 1949), and Goldschmidt's proposed average composition of Scandinavian Precambrian rocks (Goldschmidt 1954).

The gabbroic anorthosite composition chosen (Table I) is based on an average of seven analyses of gabbroic anorthosite from the Adirondack anorthosite complex (Buddington 1939). The composition is similar to kenningite (von Eckermann 1938), the nearest equivalent to a magma of anorthositic composition so far

recorded. The high-alumina basalt (Table I) prepared is based on an average oceanic tholeiite composition (Engel *et al.* 1965).

The experimental work on the three synthetic compositions has fallen into two parts. The first part has involved the study of the crystallization of quartz diorite at 0–13.5 kb to investigate the feasibility of deriving two complementary fractionates of overall gabbroic anorthosite and acidic compositions from a parent quartz diorite magma. In a previous paper (Green 1969) some results of this study, and the interpretation of these results in terms of a model for anorthosite origin, have been recorded.

The second phase of the investigation has consisted of the study of the crystallization of high-alumina basalt and gabbroic anorthosite at pressures corresponding to those existing in the lower crust and upper mantle, to determine whether there are any fractionation trends towards marked enrichment in plagioclase components at these depths.

The experimental and analytical work has been carried out following procedures outlined in D. H. Green and Ringwood (1967), T. H. Green *et al.* (1966), and T. H. Green and Ringwood (1968). Experiments were conducted on synthetic glasses of quartz diorite and high-alumina basalt composition, and on a finely crystalline synthetic mix (consisting of plagioclase and pyroxene) of gabbroic anorthosite composition.

## Results

Detailed experimental results for each of the three compositions are given in Green (1967b) and are available on request.

### Summary of Results

#### Quartz Diorite

(1) The results for this composition are summarized in Fig. 1. Analyses of phases crystallizing under various conditions are given in Tables II and III.

(2) Plagioclase is the liquidus phase from 0–13.5 kb, and there is a large field of crystallization of plagioclase, together with subordinate crystallization of ortho- and clinopyroxene and opaque minerals over this pressure range. At higher pressures plagioclase is no longer the dominant crystallizing phase (T. H. Green and Ringwood 1968).

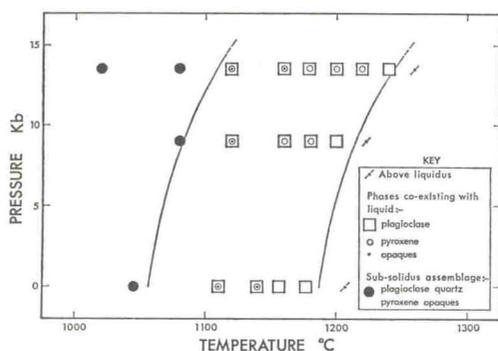


FIG. 1. Results of the experimental runs on the quartz diorite ( $\approx$ andesite) composition in the 0–13.5 kb pressure range.

(3) The albite : anorthite ratio of the feldspar crystallizing is markedly dependent on the pressure of crystallization, with the ratio Ab/An increasing with increasing pressure from 0–13.5 kb for the liquidus and near-liquidus plagioclase (see Fig. 4). No change in Ab/An ratio was detected for the range of temperatures over which the plagioclase crystals were analyzed at any specific pressure.

#### Gabbroic Anorthosite

(1) The results for this composition are summarized in Fig. 2. Analyses are given in Tables IV and V.

(2) The crystallization is dominated by plagioclase up to pressures of 22.5 kb. The corresponding low melting fraction is basic in composition, approximating to an alkali gabbro.

(3) The Ab/An ratio of the liquidus and near-liquidus plagioclase is dependent on the pressure of crystallization, with an increasing Ab/An ratio with increasing pressure, similar to that observed in the quartz diorite composition (Fig. 4). The plagioclase crystallizing from the gabbroic anorthosite composition at a specific pressure shows an increase in Ab/An ratio with decreasing temperature.

(4) There is a large field of crystallization of aluminous clinopyroxene at pressures of 27–36 kb.

#### High-alumina Basalt

(1) The complete results for this composition are summarized in Fig. 3. Analyses of phases crystallizing at 13.5–18 kb are given in Tables VI, VII and VIII. Other results are related to different problems and are discussed elsewhere (Green *et al.* 1967; Green 1967a; Green and Ringwood 1968).

(2) There is a large field of crystallization of aluminous clinopyroxene, especially at 18 kb where pyroxene is the only phase crystallizing for 60 °C below the liquidus.

(3) Clinopyroxene is joined by plagioclase and garnet at 18 kb and plagioclase at 13.5 kb at lower temperatures.

(4) Minor suppression of crystallization of plagioclase occurs in the presence of water.

#### Interpretation of Experimental Results

##### Quartz Diorite

From careful optical examination of the experimental runs, both as powders mounted in

TABLE II

Partial analyses of feldspars from selected runs on the quartz diorite composition (iron content recalculated to zero; soda content calculated)

Conditions of run	13.5 kb 1 hr 1240 °C	13.5 kb 1 hr 1220 °C	13.5 kb 1 hr 1200 °C	13.5 kb 1 hr 1180 °C	9 kb 1 hr 1200 °C	9 kb 1 hr 1180 °C	9 kb 1 hr 1160 °C	0 kb* 1½ hrs 1177 °C	Av. 13.5 kb Compo- sition	Av. 9 kb Compo- sition
SiO <sub>2</sub>	57.9	57.3	57.0	58.0	56.4	56.4	56.6	53.6	57.6	56.5
Al <sub>2</sub> O <sub>3</sub>	26.2	26.0	26.4	26.4	27.5	27.5	27.5	29.6	26.3	27.5
CaO	8.1	8.1	8.5	8.2	9.7	9.5	9.5	11.9	8.2	9.6
Na <sub>2</sub> O	6.5	6.4	6.1	6.4	5.6	5.7	5.7	4.6	6.4	5.7
K <sub>2</sub> O	0.7	0.7	0.9	0.8	0.8	0.8	0.8	0.3	0.8	0.8
TOTAL	99.4	98.5	98.9	99.8	100.3	99.9	100.1	100.0	99.3	100.2
Mol. Prop.										
Or	4.1	4.1	5.2	4.6	4.6	4.6	4.6	1.6	4.6	4.6
Ab	56.7	53.6	53.4	55.6	48.6	49.4	49.4	40.7	55.6	49.2
An	39.2	42.3	41.4	39.8	46.8	46.0	46.0	57.7	39.8	46.2

\*Calculated from measured CaO and K<sub>2</sub>O contents.

TABLE III  
Electron microprobe analyses of pyroxenes from selected runs on the quartz diorite composition

Conditions of run	13.5 kb 2 hrs 'Wet' 1180 °C cpx	13.5 kb 2 hrs 'Wet' 1180 °C opx	9 kb 2 hrs 'Wet' 1160 °C opx	9 kb Estimated Composition cpx
SiO <sub>2</sub>	51.1	53.0	53.0*	51.3
TiO <sub>2</sub>	1.2	0.8	0.9	1.2
Al <sub>2</sub> O <sub>3</sub>	8.6	6.1	4.7	5.2
FeO	10.8	11.2	14.8	14.4
MgO	17.2	27.0	23.2	14.9
CaO	10.7	2.6	3.3	12.3
Na <sub>2</sub> O	0.8	—	—	0.7
TOTAL	100.4	100.7	99.9	100.0
100 Mg				
Mg+Fe	73.9	81.1	73.7	65.0
<i>Numbers of ions on the basis of 6 oxygens</i>				
Si	1.8456	1.8662	1.9135	1.8975
Al	0.1544	0.1338	0.0865	0.1025
Al	0.2116	0.1193	0.1136	0.1256
Ti	0.0326	0.0212	0.0245	0.0335
Fe	0.3263	0.3299	0.4470	0.4481
Mg	0.9265	1.4178	1.2492	0.8322
Ca	0.4140	0.0980	0.1276	0.4904
Na	0.0560			0.0253
Mg	55.6	76.8	68.5	47.0
Fe	19.6	17.9	24.5	25.3
Ca	24.8	5.3	7.0	27.7

\*Denotes calculated composition.

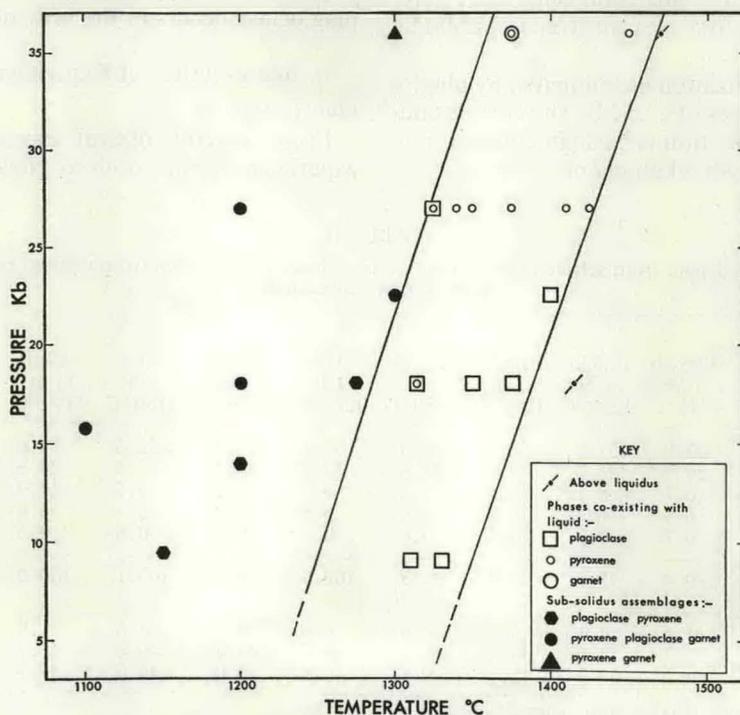


FIG. 2. Results of the experimental runs on the gabbroic anorthosite composition.

TABLE IV

Partial analyses of feldspars from selected runs on the gabbroic anorthosite composition (iron content recalculated to zero)

Conditions of run	18 kb	18 kb	18 kb	9 kb	9 kb
	1 hr 1375 °C	1 hr 1350 °C	1 hr 1315 °C	1 hr 1330 °C	1 hr 1300 °C
SiO <sub>2</sub>	54.8	54.7	55.7	52.6*	52.5*
Al <sub>2</sub> O <sub>3</sub>	28.5*	28.8	27.6*	30.1	29.8
CaO	11.2	10.7	10.1	12.6	12.3
Na <sub>2</sub> O	4.6	5.2	5.1	4.2	4.3
K <sub>2</sub> O	0.5	0.4	0.8	0.3	0.3
	99.6	99.8	99.3	99.8	99.2
<i>Mol. Prop.</i>					
Or	3.0	2.3	4.6	1.7	1.7
Ab	41.4	45.7	45.5	37.0	38.1
An	55.6	52.0	49.9	61.3	60.2

\*Denotes calculated content.

liquids of suitable refractive index, and as polished discs, and also from examination of X-ray powder photographs, estimates of the amounts of crystalline phases present have been made. In Table IX compositions are given of possible liquids fractionating from the quartz diorite when it is partly crystallized. These are residual compositions calculated by extracting the estimated amounts of crystals of measured composition

from the initial quartz diorite composition. The liquid fractionates are broadly granodiorite to adamellite in composition, while the crystalline residuum approximates a gabbroic anorthosite composition. Calculated compositions of crystal separates of gabbroic anorthosite and anorthosite modes are given as well.

The effect of pressure on the compositions of possible liquids fractionating from the quartz

TABLE V

Analyses of pyroxenes from selected runs on the gabbroic anorthosite composition

Conditions of run	27 kb	27 kb	36 kb
	1 hr 1340 °C	1 hr 1350 °C (Wet run)	1 hr 1450 °C
SiO <sub>2</sub>	46.7	45.4	46.0
TiO <sub>2</sub>	1.3	1.4	0.8
Al <sub>2</sub> O <sub>3</sub>	24.5	23.9	27.2
FeO	4.8	1.4	2.8
MgO	4.8	6.2	4.8
CaO	17.0	19.5	16.5
Na <sub>2</sub> O	2.6	2.4	3.4
TOTAL	101.7	100.2	101.5
100 Mg	64.0	88.9	75.4
Mg+Fe			
	<i>Numbers of ions on the basis of 6 oxygens</i>		
Si	1.6433	1.6049	1.6069
Al	0.3567	0.3951	0.3931
Al	0.6593	0.6005	0.7267
Ti	0.0345	0.0372	0.0210
Fe	0.1413	0.0414	0.0819
Mg	0.2519	0.3268	0.2500
Ca	0.6408	0.7366	0.6174
Na	0.1772	0.1644	0.2301
Mg	24.4	29.6	26.3
Fe	13.7	3.7	8.6
Ca	61.9	66.7	65.1

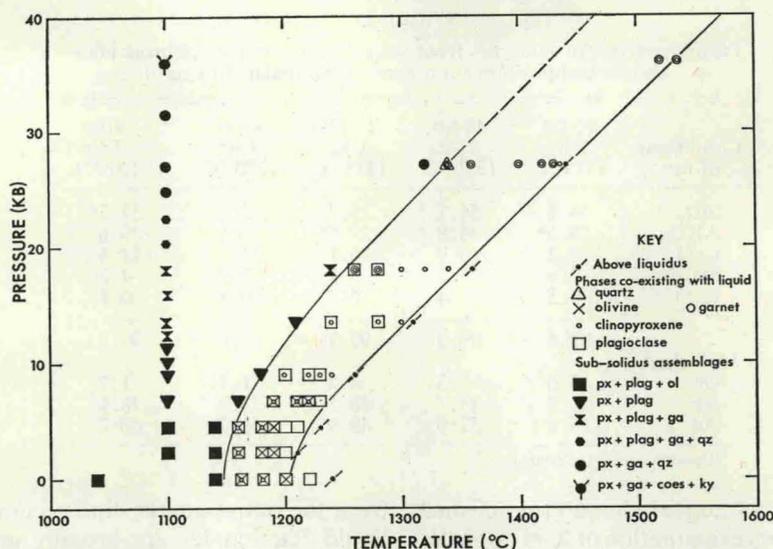


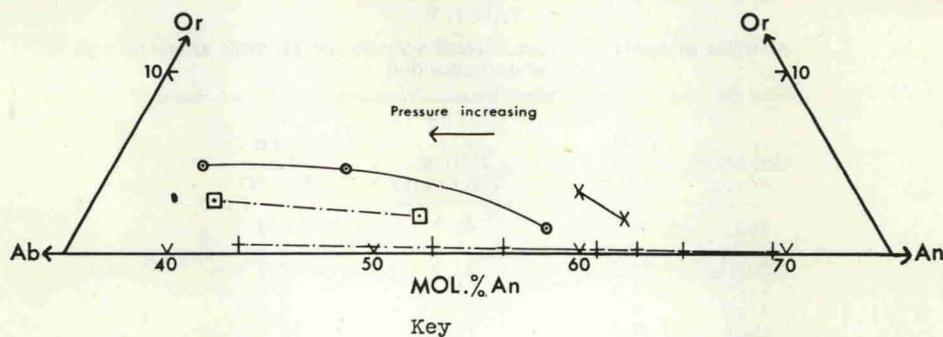
FIG. 3. Results of the experimental runs on the high-alumina basalt composition.

diorite and on the compositions of crystalline residua of gabbroic anorthosite modes is emphasized by considering the  $K_2O/Na_2O$  and  $CaO/Na_2O$  ratios. Both ratios increase with increasing pressure for the liquid fractionates, and corre-

spondingly decrease with increasing pressure for the crystalline residua.

#### Gabbroic Anorthosite

At pressures of 22.5 kb and less, large crystal



Plagioclase from:	Pressure range (kb)
† high-alumina basalt	0 - 18
□ basaltic andesite	9 - 18
⊙ quartz diorite (≈ andesite)	0 - 13.5
× gabbroic anorthosite	9 - 18
— denotes plagioclase liquidus phase	
- - - denotes plagioclase co-existing with pyroxene or garnet	

FIG. 4. Variation in composition of plagioclase with pressure.

TABLE VI

Electron microprobe analyses of clinopyroxenes from selected runs on the high-alumina basalt composition in the pressure range 13.5–18 kb

Conditions of run	13.5 kb 1300 °C 1 hr dry	13.5 kb 1280 °C 1 hr dry	13.5 kb 1240 °C 2 hrs wet	18 kb 1340 °C 1 hr dry	18 kb 1320 °C 1 hr dry	18 kb 1300 °C 1 hr dry	18 kb 1260 °C 2½ hrs wet	18 kb 1230 °C 2 hrs wet
SiO <sub>2</sub>	49.6	49.7	51.0	50.0	49.0	48.3	50.9	51.3
TiO <sub>2</sub>	0.8	1.2	1.2	0.7	0.9	0.9	1.1	1.9
Al <sub>2</sub> O <sub>3</sub>	9.9	12.2	10.6	9.4	10.8	12.0	10.2	13.6
FeO	6.2	8.1	6.0	5.4	5.7	5.4	4.8	8.0
MgO	16.0	12.8	14.8	15.9	14.2	14.0	14.6	10.4
CaO	16.6	15.3	16.8	16.2	16.0	15.9	17.1	15.9
Na <sub>2</sub> O	0.8	1.1	0.8	1.3	1.3	1.3	1.1	1.5
	99.9	100.4	101.2	98.9	97.9	97.8	99.8	102.6
100 Mg	82.1	73.9	81.5	84.0	81.6	82.1	84.4	69.9
Mg+Fe								
Si	1.7980	1.7956	1.8171	1.8233	1.8059	1.7796	1.8324	1.8087
Al	0.2020	0.2044	0.1829	0.1767	0.1941	0.2204	0.1676	0.1913
Al	0.2211	0.3150	0.2621	0.2275	0.2750	0.3004	0.2651	0.3736
Ti	0.0218	0.0326	0.0321	0.0193	0.0251	0.0250	0.0299	0.0504
Fe	0.1880	0.2447	0.1788	0.1648	0.1756	0.1665	0.1445	0.2358
Mg	0.8649	0.6896	0.7863	0.8647	0.7806	0.7692	0.7839	0.5469
Ca	0.6446	0.5921	0.6413	0.6330	0.6317	0.6275	0.6595	0.6005
Na	0.0562	0.0769	0.0552	0.0921	0.0930	0.0930	0.0766	0.1026
Mg	50.9	45.2	48.9	52.0	49.1	49.2	49.4	39.5
Fe	11.1	16.0	11.1	9.9	11.1	10.7	9.1	17.0
Ca	38.0	38.8	40.0	38.1	39.8	40.1	41.5	43.5

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TABLE VII

Electron microprobe analyses of plagioclases from selected runs on the high-alumina basalt composition in the pressure range 13.5–18 kb

Conditions of run	13.5 kb	13.5 kb	18 kb
	1280 °C 1 hr, dry	1240 °C 2 hrs, wet	1230 °C 2 hrs, wet
SiO <sub>2</sub>	54.3* (53.0)	53.7*	57.5* (56.0)
Al <sub>2</sub> O <sub>3</sub>	28.8	29.0	26.3
CaO	10.9	11.6	9.0
Na <sub>2</sub> O	5.4* (4.7)	5.0*	6.5* (6.1)
K <sub>2</sub> O	0.08	0.08	0.08
	99.5	99.4	99.4
<i>Mol. Prop.</i>			
Or	0.5	0.5	0.5
Ab	46.9	43.5	56.3
An	52.6	56.0	43.2

\*Denotes calculated values; measured values are shown in parentheses.

TABLE VIII

Electron microprobe analyses of garnets from selected runs on the high-alumina basalt composition at 18 kb

Conditions of run	18 kb	18 kb
	1260 °C 1 hr, dry	1230 °C 2 hrs, wet
SiO <sub>2</sub>	41.3	41.0
TiO <sub>2</sub>	0.8	1.8
Al <sub>2</sub> O <sub>3</sub>	22.8	22.0
FeO	9.1	17.7
MnO	0.4	0.4
MgO	17.9	12.6
CaO	6.7	7.8
	99.0	103.3
100 Mg	77.8	55.9
Mg+Fe		
<i>Mol. Prop.</i>		
Ti-andradite	2.1	4.7
Grossular	15.0	15.1
Pyrope	63.9	44.4
Almandine	18.2	35.0
Spessartine	0.8	0.8

separates of plagioclase can be obtained from crystallization of a parent gabbroic anorthosite magma, and the low melting liquid fractionate will be of an alkali-rich basic composition, as calculated in Table X, based on measured crystal compositions and their estimated proportions. At pressures of 27–36 kb there is a large field of crystallization of aluminous clinopyroxene which results in liquid fractionation trends away from more aluminous (or anorthositic) liquids at these pressures. This trend may be seen from the calculated liquid fractionates given in Table X.

### High-alumina Basalt

At 13.5–18 kb the large field of crystallization of clinopyroxene with an alumina content less than that of the starting composition, indicates that crystallization of this phase will result in alumina-enrichment in the low melting liquid fractionate. However, the appearance of aluminous phases, garnet and plagioclase, as the next phases to crystallize after pyroxene, prevents the alumina-enrichment trend from reaching the alumina content of a gabbroic anorthosite magma. This is clearly illustrated in the calculated compositions of the liquid fractionates given in Table XI. The most aluminous liquid obtained contains 19% Al<sub>2</sub>O<sub>3</sub> compared with greater than 22% Al<sub>2</sub>O<sub>3</sub> generally found in gabbroic anorthosite compositions. At lower pressures (e.g. 9 kb) there is also an alumina-enrichment trend, but this is terminated by the crystallization of plagioclase, and the most aluminous compositions possible at 9 kb contain 18% Al<sub>2</sub>O<sub>3</sub> (T. H. Green *et al.* 1967; T. H. Green 1967b). At higher pressures (e.g. 27 kb) garnet becomes more abundant in the partial melting field and appears closer to the liquidus, so that at these pressures a trend towards alumina-enrichment is prevented.

Experiments at 13.5–18 kb with low but significant water fugacity showed some suppression of crystallization of plagioclase, and hence some alumina-enrichment. With increasing water fugacity plagioclase may be further suppressed, but it is likely that amphibole will appear as a major crystallizing phase, and fractionation trends will be towards silica, alkali, and minor alumina enrichment of a typical calc-alkaline series, rather than towards gabbroic anorthosite compositions (cf. results at 9–10 kb; Green and Ringwood 1968).

### Geological Applications

#### Origin of Anorthositic Complexes

As indicated in the introductory section, this experimental work has been carried out in order to determine the relative merits of the two main hypotheses of magmatic origin of anorthosites involving derivation from either (1) a gabbroic anorthosite parent magma or (2) a quartz diorite parent magma.

#### (1) Gabbroic Anorthosite Parent Magma

The experimental work on the gabbroic anorthosite composition showed that the crystallization is dominated by plagioclase to pressures

TABLE IX

Calculated compositions and norms of liquid fractionates and residual crystal accumulates based on varying degrees of crystallization of the quartz diorite

Pressure	Composition of experimental liquid fractionates						Synthetic residual crystal accumulates				
	13.5 kb	13.5 kb	13.5 kb	9 kb	9 kb	9 kb	0 kb	13.5 kb gabbroic	9 kb anorthosite	13.5 kb anorthosite	9 kb anorthosite
Details of crystallization	10% plag	20% plag 5% cpx 2% opx	38% plag 9% cpx 3% opx	10% plag	20% plag 5% cpx 2% opx	38% plag 9% cpx 3% opx	10% plag	76% plag 18% cpx 6% opx	76% plag 18% cpx 6% opx	90% plag 8% cpx 2% opx	90% plag 8% cpx 2% opx
SiO <sub>2</sub>	62.7	64.5	68.2	62.8	64.9	69.0	63.3	56.2	55.4	57.0	56.0
TiO <sub>2</sub>	1.2	1.4	1.9	1.2	1.4	1.9	1.2	0.3	0.3	0.1	0.1
Al <sub>2</sub> O <sub>3</sub>	16.3	15.7	12.7	16.1	15.6	12.3	15.9	21.9	22.3	24.5	25.4
Fe <sub>2</sub> O <sub>3</sub>	7.0	7.4	9.8	7.0	7.2	9.1	7.0	2.6	3.3	1.1	1.4
FeO											
MnO	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	—	—
MgO	2.7	1.4	0.1	2.7	1.5	0.5	2.7	4.7	4.3	1.9	1.7
CaO	5.0	4.1	2.1	4.7	3.6	0.7	4.5	8.3	9.7	8.3	9.7
Na <sub>2</sub> O	3.0	2.7	1.6	3.1	2.9	2.1	3.2	5.0	4.4	5.8	5.2
K <sub>2</sub> O	2.4	2.9	4.0	2.4	2.9	4.0	2.5	0.6	0.6	0.7	0.7
TOTAL	100.4	100.2	100.5	100.1	100.1	99.7	100.4	99.7	100.4	99.4	100.2
Norm											
Qz	16.5	21.0	32.1	16.5	21.3	31.8	18.7	—	—	—	—
Or	14.2	17.1	23.6	14.2	17.1	23.6	15.0	3.5	3.5	4.1	4.1
Ab	25.4	23.7	13.5	26.2	25.4	19.5	27.5	44.0	38.1	49.9	44.0
Ne	—	—	—	—	—	—	—	—	—	—	—
An	23.9	20.3	10.4	22.9	17.9	3.5	16.9	34.6	38.9	38.3	43.9
Aug	0.7	—	—	0.3	—	—	4.5	5.3	7.5	2.3	3.4
Hyp	17.4	14.9	15.3	17.6	14.8	15.0	15.5	7.4	9.6	2.5	3.4
Ol	—	—	—	—	—	—	—	4.5	2.4	2.2	1.1
Mt	—	—	—	—	—	—	—	—	—	—	—
Ilm	2.3	2.7	3.6	2.3	2.7	3.6	2.3	0.6	0.6	0.2	0.2
Cor	—	0.5	1.9	—	1.0	2.9	—	—	—	—	—
Norm Plag. (Mol. Prop.)	An <sub>47.0</sub>	An <sub>44.6</sub>	An <sub>41.5</sub>	An <sub>45.1</sub>	An <sub>39.8</sub>	An <sub>15.0</sub>	An <sub>36.5</sub>	An <sub>42.5</sub>	An <sub>49.1</sub>	An <sub>42.0</sub>	An <sub>48.5</sub>

TABLE X

Calculated compositions and norms of liquid fractionates based on varying degrees of crystallization of the gabbroic anorthosite

Pressure Temperature Details of Crystallization	9 kb 1330 °C 15% plag	9 kb 1300 °C 25% plag	18 kb 1375 °C 10% plag	18 kb 1350 °C 20% plag	27 kb 1340 °C 30% cpx*	36 kb 1450 °C 10% cpx
SiO <sub>2</sub>	53.7	53.8	53.4	53.2	57.2	54.3
TiO <sub>2</sub>	1.2	1.3	1.1	1.3	0.9	1.0
Al <sub>2</sub> O <sub>3</sub>	21.2	20.1	21.8	20.9	21.7	22.0
Fe <sub>2</sub> O <sub>3</sub>	1.1	1.2	1.0	1.1	1.3	1.0
FeO	5.5	6.3	5.2	5.9	4.7	4.9
MnO	0.1	0.1	0.1	0.1	0.1	0.1
MgO	2.5	2.8	2.3	2.6	0.9	1.8
CaO	9.4	9.1	9.8	9.7	6.8	9.2
Na <sub>2</sub> O	3.6	3.5	3.6	3.3	4.2	3.7
K <sub>2</sub> O	1.2	1.4	1.2	1.3	1.6	1.2
	99.5	99.6	99.5	99.4	99.4	99.2
<i>Norm</i>						
Qz	2.8	2.7	2.1	2.9	7.9	2.4
Or	7.1	8.3	7.1	7.7	9.4	7.1
Ab	30.4	29.7	30.5	27.9	35.5	22.7
An	38.1	35.0	39.8	38.4	33.8	32.8
Aug	7.0	8.5	7.4	8.1	—	3.9
Hyp	10.2	11.3	9.1	10.4	9.9	7.0
Mt	1.6	1.7	1.5	1.6	1.9	1.5
Ilm	2.3	2.5	2.1	2.5	1.7	1.9
Cor	—	—	—	—	0.7	—

\*Denotes liquid fractionate determined from calculated compositions closely based on the micro-probe analyses of crystal phases in the experimental runs.

TABLE XI

Calculated compositions and norms of liquid fractionates based on varying degrees of crystallization of the high-alumina basalt in the pressure range 13.5–18 kb

Pressure Temperature Details of crystallization	13.5 kb 1300 °C 10% cpx	13.5 kb 1280 °C 20% cpx 10% plag	13.5 kb 1240 °C 25% cpx 5% plag	18 kb 1340 °C 10% cpx	18 kb 1320 °C 20% cpx	18 kb 1300 °C 30% cpx	18 kb 1260 °C 20% cpx 2% ga	18 kb 1230 °C 30% cpx 15% ga 5% plag wet
	dry	dry	wet	dry	dry*	dry*	wet	wet*
SiO <sub>2</sub>	50.4	49.9	49.8	50.3	50.4	50.8	50.4	52.9
TiO <sub>2</sub>	1.8	2.1	2.0	1.8	1.9	2.0	1.9	1.8
Al <sub>2</sub> O <sub>3</sub>	17.8	16.7	18.4	17.8	18.5	19.0	18.6	16.7
Fe <sub>2</sub> O <sub>3</sub>	1.7	2.1	2.1	1.7	1.9	2.1	1.9	3.0
FeO	7.8	8.5	8.7	7.8	8.0	8.5	8.3	6.3
MnO	0.18	0.23	0.23	0.18	0.2	0.23	0.19	0.2
MgO	6.9	7.5	5.9	6.9	6.1	5.0	5.8	5.6
CaO	10.8	10.4	9.7	10.9	10.2	9.3	10.1	9.9
Na <sub>2</sub> O	3.0	3.1	3.4	3.0	3.2	3.4	3.3	4.0
K <sub>2</sub> O	0.2	0.25	0.25	0.2	0.23	0.26	0.23	0.3
	100.6	100.8	100.5	100.6	100.6	100.6	100.7	100.7
<i>Norm</i>								
Qz	—	—	—	—	—	—	—	0.8
Or	1.2	1.5	1.5	1.2	1.3	1.6	1.3	1.8
Ab	25.4	26.2	28.8	25.3	27.1	28.8	27.9	33.9
An	34.5	30.8	34.2	34.5	35.4	35.7	35.2	26.7
Aug	15.4	16.8	11.4	15.9	12.3	8.6	12.2	18.1
Hyp	13.2	10.3	10.4	12.3	14.1	18.8	13.1	11.7
Ol	4.9	8.0	7.4	5.4	4.0	0.3	4.6	—
Mt	2.5	3.0	3.0	2.5	2.8	3.0	2.8	4.4
Ilm	3.4	4.0	3.8	3.4	3.6	3.8	3.6	3.4

\*Denotes liquid fractionate determined from calculated compositions closely based on the microprobe analyses of crystal phases in the experimental runs.

of 22.5 kb and the low melting fraction approximates an alkali-rich basic composition. Thus anorthosites and rock types such as kenningite could in theory be derived from a gabbroic anorthosite parent magma at all depths down to about 80 km. However, there still remains the problem of deriving the gabbroic anorthosite magma. As indicated in the previous section there is no major alumina enrichment trend in the high-alumina basalt composition leading to such compositions as gabbroic anorthosite under dry conditions from 0–36 kb, or under hydrous conditions at 9–18 kb.

The experimental work on the fractionation of gabbroic anorthosite and high-alumina basalt at 27 and 36 kb is relevant to the hypothesis that anorthositic magmas originated at great depth (e.g. 200 kms) by the "differential fusion of feldspathic peridotite" (Turner and Verhoogen 1960). The existence of a large field of crystallization of sodic, aluminous clinopyroxene in the gabbroic anorthosite at 27–36 kb and the presence of a large field of crystallization of garnet and aluminous clinopyroxene in the high-alumina basalt at the same pressures indicate that the fractionation trends at depths of greater than 100 km are away from anorthositic compositions. Hence it is unlikely that gabbroic anorthosite magmas can be derived at great depths as envisaged by Turner and Verhoogen.

### (2) *Quartz Diorite Parent Magma*

The experimental work on the quartz diorite composition showed that from 0–13.5 kb a large field of crystallization of plagioclase occurs. Subordinate phases crystallizing are pyroxenes and opaque minerals, and the low melting point liquid fraction is acidic in composition. These results point to two different models for the genesis of anorthositic complexes from a parent quartz diorite ( $\approx$  andesite) composition, either by (a) fractional crystallization of a quartz diorite or andesite magma, or, (b) partial melting of crustal rocks of bulk composition approximating to a quartz diorite or andesite. In both these models plagioclase is left behind as the dominant mineral component of a crystalline residuum. This is similar to the conclusion reached by De Waard (1966) after consideration of structural, modal, and chemical data for several large masses of anorthosites.

(a) *Fractional Crystallization*—A model involving fractional crystallization of a quartz

diorite parent magma giving rise to complementary anorthositic and acidic rocks was proposed by Barth (1936). However, a difficulty in this hypothesis was reconciling the sodic character of the plagioclases found in massive anorthosite complexes with the more calcic composition of feldspars crystallizing from quartz diorite in the early stages of crystallization. The present high pressure experimental work solves this problem since it has shown that with increasing pressure an increasingly sodic feldspar will crystallize from quartz diorite as the liquidus phase (up to pressures of at least 13.5 kb, corresponding to depths of 45 kms).

The details of the model envisaged have been given elsewhere (T. H. Green 1969). Briefly, it is proposed that the combined effect of difference in density of the crystallizing phases (plagioclase, pyroxenes, and opaque minerals) and a temperature gradient across a crystallizing andesite magma in a chamber at depth, may cause segregation of a partly crystalline mass into anorthositic, gabbroic anorthositic, and opaque mineral-rich fractions. Subsequent deformation, through filter pressing action, separates the acidic (granodiorite to adamellite) liquid from the crystals, giving rise to a residual anorthositic complex and a complementary acidic liquid fractionate, which may or may not remain spatially associated with the residuum. Locally, where the acidic liquid has been removed and where the temperature is high enough, it is possible that a crystal separate of plagioclase (anorthosite) could occur in an alkali-rich gabbroic (approximately dioritic) liquid. This produces a mush of gabbroic anorthosite composition similar to the kenningite dikes of Sweden.

A typical form for an anorthositic complex derived from the crystalline separate of a partly crystallized andesite or quartz diorite magma may be a core-like body of true anorthosite (< 10% femics) surrounded by, and grading into, gabbroic anorthosite, anorthositic gabbro, and gabbro. In some cases the gradational change in composition may proceed right through to the low melting acidic fractionates in the outermost regions of the complex, depending on the efficiency of the deformation mechanism in separating crystalline residuum from liquid. If no separation of crystals and liquid from the parent quartz diorite magma occurred, then a deep level quartz diorite pluton would result.

Philpotts (1966) has recently studied an anorthosite complex together with associated acid rocks (mangerites) forming the Morin Series of southeastern Quebec. Several observations and conclusions made by Philpotts provide a very useful link between the fractional crystallization of quartz diorite (or andesite) model outlined and the petrogenesis of a natural anorthositic complex, as interpreted from a detailed field and laboratory investigation. In particular Philpotts concluded that: (1) the anorthosite-mangerite series was derived by very dry differentiation of a calc-alkaline parent magma giving rise to a strong iron-enrichment trend; (2) anorthosite formed from an early accumulation of plagioclase from the parent magma due to increase in size of the field of crystallization of intermediate and sodic plagioclase under high pressure; and (3) deformation appeared to govern the extent of differentiation, and where deformation was less intense complete gradation between anorthositic and more acid (lower melting) fractions has been preserved.

Each of these conclusions agrees closely with the model proposed in this paper for anorthosite origin. However, Philpotts favored a fairly basic parent magma (dioritic) for the series and was confronted with the volume problem involved in explaining the proportions of rock types observed in the Morin Series, and concluded that a more acidic parent magma, approximating in composition to quartz diorite, would be needed. Philpotts considered that the diorite parent magma was modified in composition by assimilation of acid material, thus accounting for the more acid nature of the bulk composition of the complex. The experimental work on the fractionation of quartz diorite (andesite) from 0–13.5 kb has indicated a way of deriving such complexes from a parent quartz diorite. Field observations from other areas also support this mode of origin (e.g. Thirteenth Lake complex—Letteney 1966; Nain complex—Wheeler 1966).

(b) *Partial Melting*—A similar mechanism to this second model has been proposed by Winkler and Von Platen (1960), based on results of work on the partial melting of calcite-bearing illitic clays, but was not actually demonstrated experimentally. They suggested that anorthosites are the crystalline remainder not liquefied in the course of anatexis of such clays during ultrametamorphism. Berg (1966) has also postulated an anatexis-type of origin for anorthosites. In the present paper

this model is envisaged to involve partial melting of lower crustal rocks of bulk composition approximating to quartz diorite or andesite. The similarity between an average andesite composition and proposed average compositions for continental crustal rocks has been pointed out by Taylor and White (1965), so that it is feasible that lower crustal rocks have the bulk composition required for this model. Applying the experimental results, partial melting of an andesite composition at pressures of 0–13.5 kb will result in formation of a low melting granitic liquid fraction, and a residuum of plagioclase and subordinate pyroxene and opaque minerals. As in the fractional crystallization model the depth at which the process operates will govern the albite : anorthite ratio of the plagioclase, and also in a similar manner the interaction of temperature gradient, gravity differentiation, and deformation may give rise to various spatial relationships between anorthosites, gabbroic anorthosites, gabbros, iron-titanium ore bodies of the residuum, and the acidic rocks of the melt fraction.

A corollary of this model is that if such partial melting has occurred on a large scale over a long period of time, then an overall segregation of the crust into an upper granodioritic fraction and a lower gabbroic anorthosite fraction may occur. Thus gabbroic anorthosite may form a significant portion of the lower crust. Most exposures of anorthositic rocks occur in conjunction with high-grade granulitic rocks generally considered to have been derived by metamorphism under the pressure-temperature conditions found deep within the crust, so that this evidence supports a deep origin or emplacement of anorthosites.

Comparison of the calculated liquid fractionates and crystalline residua (Table IX) with the composition of natural anorthositic plutons and associated acid rocks indicates close parallels in composition. This is emphasized when  $K_2O/Na_2O$  and  $CaO/Na_2O$  ratios are considered (as mentioned earlier in this section under the subheading "Quartz diorite").

#### *Crystallization of Calc-alkaline Magmas*

The chosen quartz diorite composition is similar to andesites of the calc-alkaline igneous rock series, so that comparison of calculated fractionation trends in the quartz diorite composition over the 0–13.5 kb pressure range may be made with trends observed in natural calc-alkaline rock series. The typical acid members of

many of the rock series (e.g. Taupo, New Zealand (Grange 1937; Steiner 1958; Ewart 1965) and the Southern Californian batholiths (Larsen 1948)) are broadly similar to the calculated acid liquid fractionates from the quartz diorite at 0–9 kb (see Table IX), particularly in  $K_2O/Na_2O$  ratios.

Rare corroded plagioclase phenocrysts with albite-rich cores occur in some andesites where most of the plagioclase phenocrysts contain cores more calcic than rims (Williams 1932). These corroded albite-rich cores may represent early crystallization of the andesite at depth, where a more albite-rich plagioclase composition would be the equilibrium liquidus phase, in contrast to the more calcic composition obtained at shallower levels from the same parent.

Similarly, pyroxene phenocrysts with high-alumina contents may also indicate early crystallization at a deep level.

### Conclusions

The experimental results on the anhydrous high pressure fractional crystallization of high-alumina basalt and gabbroic anorthosite effectively preclude any simple means of deriving highly aluminous magmas at depth, and it is unlikely that magmas with compositions as rich in plagioclase as gabbroic anorthosite are obtainable by hydrous fractional crystallization of a parent basaltic composition. However, the experimental results on the fractional crystallization of quartz diorite ( $\approx$ andesite) at 0–13.5 kb point to two possible geological models for obtaining anorthositic rocks, either by fractional crystallization or partial melting of a parent quartz diorite composition at lower crustal depths. In both cases the anorthositic rocks form as a crystalline residuum deep within the crust, and are essentially 'frozen' in their position of formation, except possibly for minor movement as a semi-solid crystal mush. This explains the association of anorthosites with charnockitic and granulitic rocks typically found in Precambrian metamorphic terrains. Anorthosites may well occur in younger rocks where these have been buried deep within the crust, but processes of orogenesis and erosion have not exposed these younger high-grade metamorphic terrains extensively at the earth's surface.

The models also explain the sodic nature of the plagioclase typically found in the massive

anorthosite complexes, since the soda content of the plagioclase crystallizing from a parent quartz diorite composition increases with increasing pressure. Rock types related genetically to anorthosites and gabbroic anorthosites may range from granite to gabbro, depending on the degree and nature of the separation of the crystalline residuum from the parent intermediate composition magma. Spatial association of these varied, but genetically related, rocks need not necessarily be maintained.

Finally, it should be pointed out that there will be a range of compositions in the calc-alkaline series from which a large field of crystallization of sodic plagioclase will occur in the pressure range of 0–13.5 kb. Accordingly there will be some variation in plagioclase composition and the relative proportions of genetically related rock types, depending on the nature of the parent magma.

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## HIGH PRESSURE EXPERIMENTAL STUDIES ON THE MINERALOGICAL CONSTITUTION OF THE LOWER CRUST

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Diorite and gabbroic anorthosite have been proposed as two possible overall compositions constituting the lower crust. The mineral assemblages stable in these compositions under anhydrous conditions at temperatures of 900-1200 °C and pressures of up to 36 kb have been determined. The low pressure mineralogy is dominated by plagioclase, with subordinate pyroxene and minor quartz. With increasing pressure garnet appears, and garnet, quartz and clinopyroxene form at the expense of plagioclase. Finally at pressures greater than 20 kb at 900-1200 °C

plagioclase disappears and the high pressure assemblage consists of clinopyroxene + quartz (coesite) + garnet + K-feldspar ± kyanite(?). Extrapolating the experimental results to *P-T* conditions predicted for a stable, anhydrous lower crust and calculation of compressional wave velocities for these compositions supports the models of a lower crust composed of diorite or gabbroic anorthosite, where the mineralogy of these compositions consists of clinopyroxene, sodic plagioclase and subordinate quartz, garnet.

### 1. Introduction

Previous experimental investigations on natural rock systems have established the mineral assemblages formed in basaltic and granitic (adamellite) rocks at high pressures and temperatures under anhydrous conditions (GREEN and RINGWOOD, 1967; GREEN and LAMBERT, 1965). These results, complemented by data of other workers on relevant simple systems (BIRCH and LECOMTE, 1960; KUSHIRO and YODER, 1966), have been used to interpret the mineralogy expected in natural rocks under the pressure-temperature conditions predicted for the lower crust. The present investigation provides data on high pressure mineral assemblages in diorite and gabbroic anorthosite compositions, which fall between the extremes of basaltic and granitic rocks previously studied.

Recently proposed crustal models indicate that the earth's continental crust has an overall composition approximating to diorite or andesite (TAYLOR and WHITE, 1965). In crustal areas where there has been a long history of metamorphism and igneous activity (e.g. Precambrian shield) the crust may be differentiated into an upper granodioritic fraction underlain by a more basic fraction (TAYLOR, 1968; HARRIS, 1967). This basic fraction would approximate to gabbroic anorthosite if

the initial overall composition was dioritic or andesitic (GREEN, 1968). Thus rocks of diorite or gabbroic anorthosite composition may well be major constituents of the lower crust, and determination of their mineralogies under lower crustal pressure-temperature conditions is important in enabling comparison of the properties of these compositions with the geophysically determined data for the lower crust. Accordingly this paper describes an experimental investigation of the mineral assemblages found in diorite and gabbroic anorthosite with increasing pressure, followed by estimates of the geophysical properties of these assemblages and finally a comparison with the available geophysical data for the lower crust in order to qualitatively evaluate the merits of these models.

It should be emphasized that from a detailed petrological point of view it is unlikely that the lower crust consists of a homogeneous layer of diorite or gabbroic anorthosite. Rather it is more likely to be composed of a mixture of rock types (cf. DEN TEX, 1965) among which diorite and gabbroic anorthosite may dominate. Alternatively, when viewed on a gross scale (e.g. by geophysical methods) the varied rock types combine to give characteristics expected of a rock of uniform intermediate composition (RINGWOOD and GREEN, 1966).

## 2. Experimental

The high pressure experimental work has been conducted using a solid medium piston-cylinder high pressure apparatus of the type described by BOYD and ENGLAND (1960a, 1963). The detailed experimental procedure has followed that of BOYD and ENGLAND (1960b, 1963) and GREEN and RINGWOOD (1967). Loss of pressure transmitted to the sample due to friction effects and non-uniform distribution of pressure in the solid medium pressure cell is allowed for by applying a -10% correction to the nominal pressure values for a single stage, instroke run (i.e. approaching the desired  $P$ - $T$  values with the piston moving in), and the resulting pressures are believed to be accurate to  $\pm 3\%$  for the range 15-40 kb (GREEN *et al.*, 1966). For pressures lower than 15 kb the results are probably accurate to  $\pm 5\%$ . In two-stage runs where the piston has been retracted a -4.5% pressure correction has been applied, based on the results of GREEN *et al.* (1966) for similar two-stage runs, and the probable accuracy is  $\pm 5\%$ . Temperature is measured with a Pt/Pt 10% Rh thermocouple and is believed accurate to  $\pm 15^\circ\text{C}$ . No corrections for any pressure effect on the e.m.f. of the thermocouple have been made.

The compositions were carefully prepared by thoroughly mixing highest purity Fisher chemical compounds in the requisite proportions (table 1). The gabbroic anorthosite composition is based on the average of 7 analyses of gabbroic anorthosite from the Adirondack anorthosite complex (BUDDINGTON, 1939). A crushed glass of this composition was held in a sealed, evacuated silica tube with an iron pellet at  $900^\circ\text{C}$  for 24 hours, then chemically analyzed for FeO and  $\text{Fe}_2\text{O}_3$  to check the oxidation state. This procedure resulted in devitrification of the glass to a finely crystalline mix of feldspar and pyroxene which was used for the experimental work. The diorite composition is based on the average andesite composition proposed by TAYLOR (1968). It was prepared as a reacted mix, held in an evacuated silica tube with an iron pellet at  $900^\circ\text{C}$  for 24 hours. Subsequent chemical analysis of the diorite indicated that the iron was present as FeO, with negligible  $\text{Fe}_2\text{O}_3$ .

In this project it was necessary to carry out runs at as low temperature as possible while still allowing equilibrium to be obtained in a reasonable time, in order to

TABLE 1

Composition and CIPW norms of synthetic diorite and gabbroic anorthosite used in the experimental work.

	Diorite	Gabbroic anorthosite
$\text{SiO}_2$	59.9	53.5*
$\text{TiO}_2$	0.7	1.0*
$\text{Al}_2\text{O}_3$	17.3	22.5*
$\text{Fe}_2\text{O}_3$	—	0.9†
FeO	6.3†	4.7†
MnO	—	0.1
MgO	3.4	2.1*
CaO	7.1	9.9*
$\text{Na}_2\text{O}$	3.7	3.7*
$\text{K}_2\text{O}$	1.6	1.1*

\* denotes content determined by electron microprobe analysis of a glass fragment.

† denotes content chemically determined.

CIPW norms	Diorite	Gabbroic anorthosite
Qz	9.2	2.1
Or	9.4	6.5
Ab	31.3	31.3
An	25.8	41.5
Diop	7.8	6.3
Hyp	15.0	8.5
Mt	—	1.3
Ilm	1.3	1.9
Density ( $\text{g}/\text{cm}^3$ )	2.84	2.84
$V_P$ (km/s) approx.	6.6	7.0

simulate as closely as possible the  $P$ - $T$  conditions of the lower crust. Experience showed that reaction rates were extremely slow under anhydrous conditions at temperatures less than  $1000^\circ\text{C}$ . The presence of water provides a catalytic effect for silicate reactions, but only a low water content as a catalyst could be tolerated in the present work otherwise hydrous phases crystallized, and it is unlikely that in general the activity of water in the lower crust is sufficient to produce such phases (RINGWOOD and GREEN, 1966). Thus the experiments were carried out under conditions of low water activity in the subsolidus fields of the two compositions for the temperature range  $900$ - $1200^\circ\text{C}$  at pressures up to 36 kb. Even at these temperatures, times of up to 72 hours were needed to enhance attainment of equilibrium. The results of the runs were then extrapolated to  $P$ - $T$  conditions of the lower crust.

At  $900$ - $1000^\circ\text{C}$  unsealed gold capsules were generally used, though in a few cases silver-palladium capsules

TABLE 2  
Results of experimental runs on the diorite composition at 900 °C

Pressure (kb)	Temperature (°C)	Time (hrs)	Type of sample capsule	Phases present*				Comments
{ 27	900	48	Au	px	plag	qtz	—	Well crystallized; uncommon laths of orthopyroxene distinguishable; plag ≫ px > qtz
then 4	900	67						
{ 27	900	48	Au	px	plag	qtz	—	Medium grainsize; plag ≫ px > qtz
then 6.5	900	64						
{ 27	900	48	Au	px	plag	qtz	<u>ga</u>	Medium grainsize; laths of orthopyroxene distinguishable; plag ≫ px > qtz > ga
then 9	900	62						
	900	24	Au	px	plag	qtz	—	Fine grained; no evidence for garnet; plag ≫ px > qtz
	11.3	24	Au	px	plag	qtz	—	Medium grainsize; no evidence for garnet; plag ≫ px > qtz
{ 18	1100	6	Ag-Pd	px	plag	qtz	<u>ga</u>	Medium grainsize; plag ≫ px > qtz > ga
then 11.3	900	50						
	900	6	Ag-Pd	px	plag	qtz	—	Fine grained; no garnet evident; plag ≫ px > qtz
	900	20	Ag-Pd	px	plag	qtz	<u>ga</u> ?	Fine grained; uncertain, rare garnet; plag ≫ px > qtz
	900	48	Au	px	plag	qtz	<u>ga</u>	Medium grainsize; plag ≫ px > qtz > ga
	900 ± 50	48	Au	px	plag	qtz	<u>ga</u>	Medium grainsize; plag > px > qtz > ga
{ 27	900	48	Au	px	plag	qtz	ga	Medium grainsize; px ≫ qtz > plag, ga; definite growth of plag compared with 27 kb 900 °C run
then 22.1	900	64						
	900	48	Au	px	plag	qtz	ga	Medium grainsize; px ≫ qtz, plag > ga
{ 22.5	1000	16	Au	px	plag	qtz	ga	Medium grainsize; px ≫ plag, qtz > ga; slightly more garnet than 22.5 kb 900 °C run
then 22.5	900	71						
	900	48	Au	px	felds	qtz	ga	Medium grainsize; px ≫ qtz > ga > felds; trace of feldspar, probably K-feldspar not plag
	900	48	Au	px	felds	qtz	ga	Fine grained; px ≫ qtz > ga > felds
	900	48	Au	px	felds	qtz	ga	Fine grained; px ≫ qtz > ga > felds

\* Underlines denote phase identified by optical means alone.

px = pyroxene; plag = plagioclase; qtz = quartz; ga = garnet; felds = feldspar (K-rich).

were substituted. Runs at 1100 °C were conducted in silver-palladium capsules and at 1200 °C platinum capsules were used, with reduced experiment time to minimize iron loss from the sample to the platinum capsule. At this higher temperature equilibrium was reached in much shorter times. The pressure cell components were not dried, except for runs on the andesite composition at 1100 °C in the lower pressure range where a dried pyrophyllite spacer was used, in order to prevent excessive melting resulting from access of water to the sample. No boron nitride sleeve was used in the pressure cell. This procedure allowed minor access of water to the sample to promote reaction, but the amount present did not result in observable crystallization of hydrous phases.

Even with runs of 48 hours duration, difficulty in nucleating garnet was experienced in both compositions at 900 °C. Accordingly the incoming of garnet with increasing pressure was determined by two-stage runs. In the first stage the charge was taken into the garnet field and held under conditions where it was known from previous runs that garnet formed in the allowed time, then the *P-T* conditions were changed to those desired for the particular run and held for 2-3 days. Finally the charge was removed and examined to determine whether garnet remained stable or had reacted away. This procedure was, in effect, a type of reversal of reaction by a two stage experiment. The final disappearance of plagioclase was studied in a similar manner.

TABLE 3  
Results of experimental runs on the diorite composition at 1000–1200 °C

Pressure (kb)	Temperature (°C)	Time (hrs)	Type of sample capsule	Phases present †					Comments
18	1000	24	Ag-Pd	px	plag	qtz	—	—	Well crystallized; uncommon orthopyroxene laths distinguishable; plag ≳ px > qtz
then 9.3	1000	70	Ag-Pd	px	plag	qtz	ga	—	Medium grainsize; plag ≳ px > qtz > ga
11	1000	31	Ag-Pd	px	plag	qtz	ga	—	Medium grainsize; px > plag > qtz > ga
22.5	1000	16	Au	px	plag	qtz	ga	—	Medium grainsize; px ≳ qtz > ga > felds; possible trace of plag remaining
25	1000	10	Au	px	felds	qtz	ga	—	Medium grainsize; px ≳ qtz > ga > felds; possible trace of plag remaining
25	1000	48	Au	px	felds	qtz	ga	—	Medium grainsize; px ≳ qtz > ga > felds; possible trace of plag remaining
36	1000	17½	Au	px	felds	coes	ga	—	Medium grainsize; px ≳ coes > ga > felds
12.2	1100	4	Ag-Pd	px	plag	qtz	—	<u>glass</u>	Well crystallized; minor glass; plag ≳ px ≳ qtz
12.2	1100	24	Ag-Pd	px	plag	qtz	—	<u>glass</u>	Well crystallized; common glass; plag ≳ px > qtz
13.5	1100	4	Pt	px	plag	qtz	<u>ga?</u>	—	Medium grainsize; plag ≳ px > qtz; uncertain, rare garnet
14	1100	4	Ag-Pd	px	plag	qtz	<u>ga</u>	—	Fine grained; plag ≳ px > qtz > ga
14	1100	12	Ag-Pd	px	plag	qtz	<u>ga</u>	<u>glass</u>	Well crystallized, very minor melting; plag ≳ px > qtz > ga
15.8	1100	5	Ag-Pd	px	plag	qtz	<u>ga</u>	<u>glass</u>	Medium grainsize; minor melting; plag ≳ px > qtz > ga
18	1100	6	Ag-Pd	px	plag	qtz	ga	<u>glass</u>	Medium grainsize; minor melting; px > plag > qtz > ga
22.5	1100	10	Ag-Pd	px	plag	qtz	ga	—	Fine grained; px > plag > qtz > ga
24.8	1100	10½	Ag-Pd	px	plag	qtz	ga	—	Fine grained; px > plag, qtz > ga
27	1100 ± 30	24	Ag-Pd	px	felds	qtz	ga	—	Fine grained; px ≳ qtz > ga > felds
31.5	1100	24	Ag-Pd	px	felds	qtz	ga	—	Fine grained; px ≳ qtz, ga > felds
36	1100	4½	Ag-Pd	px	felds	qtz	ga	—	Fine grained; px ≳ coes, ga > felds
36	1200	4	Pt	px	felds	coes/	ga	—	Medium grainsize; px ≳ coes, qtz > ga > felds
36	1200	11½	Pt	px	felds	coes	ga	—	Medium grainsize; px ≳ coes > ga > felds

† Underlines denote phases identified by optical means alone.

px = pyroxene; plag = plagioclase; qtz = quartz; ga = garnet; felds = feldspar (K-rich); coes = coesite.

### 3. Results

#### 3.1. Diorite

The detailed experimental results for this composition are given in tables 2 and 3 and are summarized in fig. 1.

At 900 °C garnet first appeared stable at 6.5 kb after a two-stage run, but was not obtained in a single stage run until 13.5 kb (48 hour run), pointing to the difficulty in nucleating garnet in this composition at 900 °C. Garnet, quartz and clinopyroxene increased in amount with increasing pressure, while plagioclase decreased, until at 24.8 kb only a trace of feldspar remained. This amount of feldspar remained unchanged with further increase in pressure and was probably potash feldspar.

At 1000 °C garnet first appeared at 11 kb in a single stage run and was unstable in a two-stage run at 9.3 kb. In a similar fashion to the 900 °C series of runs, garnet, quartz and pyroxene increased in amount with increasing pressure while plagioclase decreased, until at 25 kb only a trace of feldspar (K-rich) remained. In the experiments at 1100 °C minor glass occurred in the lower pressure runs. Garnet first appeared at 14 kb and plagioclase disappeared by 27 kb. Kyanite was not observed in any of the runs.

#### 3.2. Gabbroic anorthosite

The detailed experimental results for this composition are given in table 4 and are summarized in fig. 2.

In a series of two-stage runs at 900 °C garnet was

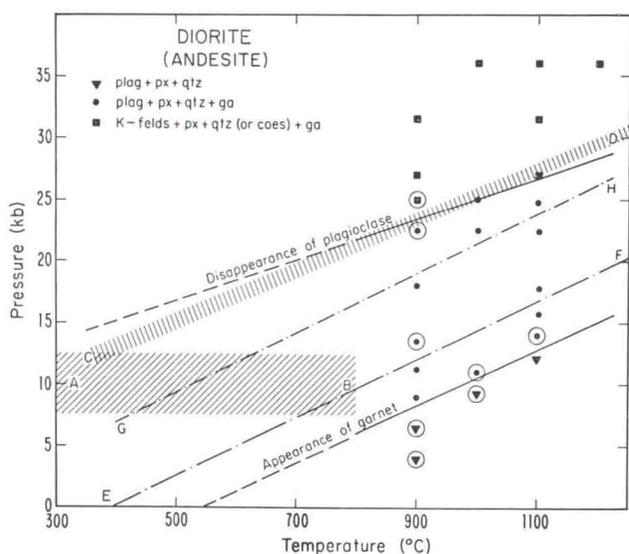


Fig. 1. Results of high pressure experimental runs on the diorite composition.

Shaded area AB: Postulated  $P$ - $T$  conditions for the lower crust (BIRCH, 1955; CLARK, 1961, 1962; CLARK and RINGWOOD, 1964). Shaded area CD: Experimental determinations of the albite  $\rightleftharpoons$  jadeite + quartz equilibrium plot in this field (BIRCH and LECOMTE, 1961; BOETTCHER and WYLLIE, 1968; NEWTON and KENNEDY, 1968; NEWTON and SMITH, 1967).

EF: Kyanite-sillimanite equilibrium (RICHARDSON *et al.*, 1968). GH: Experimental determination of the anorthite  $\rightleftharpoons$  grossular + kyanite + quartz equilibrium (HAYS, 1966) — extrapolated.

Encircled points represent experiments where a low pressure assemblage has reacted to form a high pressure assemblage, or alternatively a high pressure assemblage has reacted to a low pressure assemblage after a two-stage run.

unstable at 4.3 and 6.6 kb but became stable at 7.7 kb. It first appeared at 10.1 kb in a single stage run, again pointing to the difficulty in nucleating garnet in experimental runs at temperatures as low as 900 °C. Only a trace of feldspar (probably *K*-feldspar) was present at 25 kb and higher pressures, but plagioclase was stable to 22.5 kb. At 1000 °C plagioclase disappeared between 25 and 27 kb. In a similar fashion to the diorite composition garnet, quartz and clinopyroxene appeared at the expense of plagioclase with increasing pressure at temperatures of 900–1200 °C. As reported previously (GREEN, 1967) kyanite occurred in some runs at 1200 °C but it was not positively identified at 900–1100 °C in the present work, though it may have been present in amounts of the order of 5%. Overlapping peaks on the diffractometer charts from other phases in the runs preclude definite identification of small amounts of

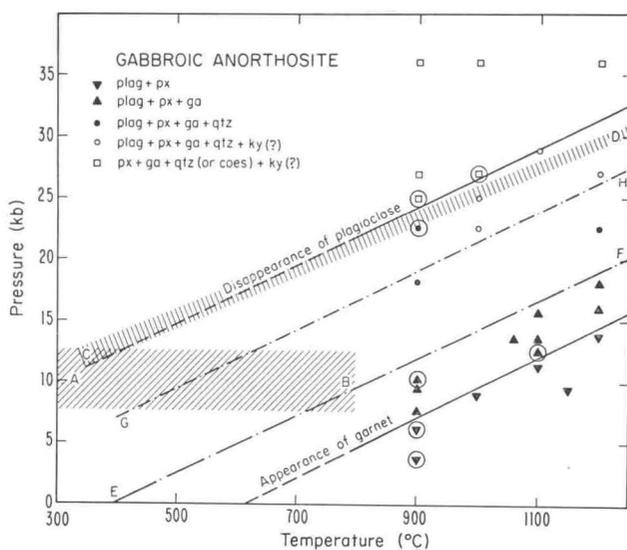


Fig. 2. Results of high pressure experimental runs on the gabbroic anorthosite composition.

Shaded area AB: Postulated  $P$ - $T$  conditions for the lower crust (BIRCH, 1955; CLARK, 1961, 1962; CLARK and RINGWOOD, 1964). Shaded area CD: Experimental determinations of the albite  $\rightleftharpoons$  jadeite + quartz equilibrium plot in this field (BIRCH and LECOMTE, 1961; BOETTCHER and WYLLIE, 1968; NEWTON and KENNEDY, 1968; NEWTON and SMITH, 1967).

EF: Kyanite-sillimanite equilibrium (RICHARDSON *et al.*, 1968). GH: Experimental determination of the anorthite  $\rightleftharpoons$  grossular + kyanite + quartz equilibrium (HAYS, 1966) — extrapolated.

Encircled points represent experiments where a low pressure assemblage has reacted to form a high pressure assemblage, or alternatively a high pressure assemblage has reacted to a low pressure assemblage after a two-stage run.

kyanite. The garnet cell size increased significantly with increasing pressure ( $a = 11.66 \text{ \AA}$  at 18 kb to  $a = 11.76 \text{ \AA}$  at 36 kb) reflecting a marked increase in grossular content (cf. GREEN, 1967).

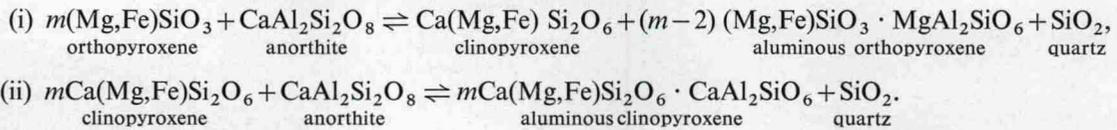
In the highest pressure runs the silica phase identified was coesite, rather than quartz.

#### 4. Discussion and application of results

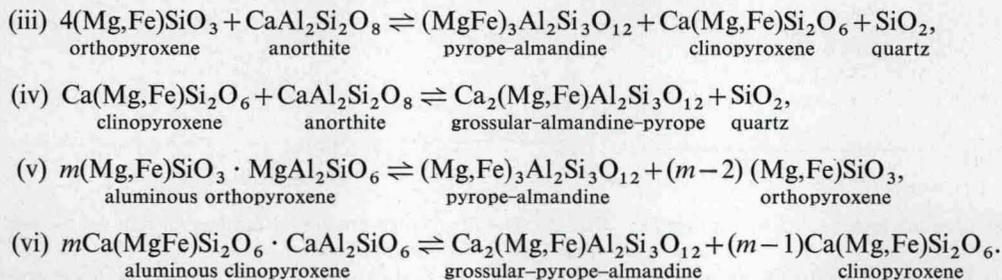
##### 4.1. Mineralogical changes and reactions

The mineralogical changes observed result from a series of pressure dependent reactions. These reactions are complex, involving members of feldspar, pyroxene and garnet solid solution series. Prior to the first appearance of garnet there is a small decrease in the proportion of plagioclase relative to pyroxene, particularly in the gabbroic anorthosite composition. This

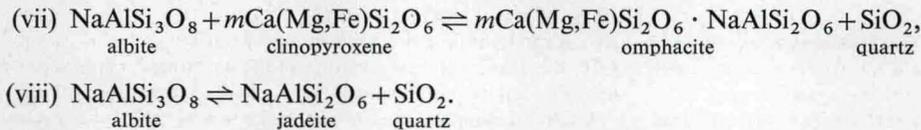
effect is attributed to reactions of the type (i) and (ii) resulting in the formation of aluminous pyroxenes and quartz, with the co-existing plagioclase becoming more sodic:



The first appearance of garnet, and its subsequent increase in amount with increasing pressure may result from the reaction of pyroxene with the anorthite component of plagioclase, and also in the later stages at higher pressure, from the breakdown of aluminous pyroxene, e.g.



The pyroxene content also increases from the breakdown of the albite component of the feldspar solid solution at moderately high pressures, according to reactions (vii) and (viii):



At intermediate pressures, where the anorthite molecule of plagioclase is involved in reactions with pyroxene, the pyroxene solid solution becomes rich in  $\text{CaAl}_2\text{SiO}_6$ . At higher pressures, the breakdown of aluminous pyroxenes to give garnet, combined with the breakdown of the albite component of the plagioclase to form jadeite and quartz will result in a pyroxene solid solution characterized by a high jadeite content, rather than a high  $\text{CaAl}_2\text{SiO}_6$  content.

At higher pressures than those at which final breakdown of plagioclase occurs, the only change in the pyroxene-garnet-quartz(-kyanite?) assemblage is in the gabbroic anorthosite composition where there is an increase in grossular content of the garnet, probably resulting from the further breakdown of  $\text{CaAl}_2\text{SiO}_6$ -rich pyroxene with increasing pressure.

#### 4.2. Comparison of results with natural rock mineralogies

As pointed out by GREEN and LAMBERT (1965) and RINGWOOD and GREEN (1966) the pressure-temperature

conditions under which basaltic compositions transform to eclogitic assemblages (garnet + clinopyroxene  $\pm$  quartz  $\pm$  kyanite, but no plagioclase) correspond to conditions at which clinopyroxene, garnet, quartz and sodic plagioclase form in more acid compositions. This holds for both the diorite and gabbroic anorthosite compositions investigated in the present work, since plagioclase is still stable above 25 kb at 1100 °C in these two compositions but it has disappeared by 25 kb at 1100 °C in each basaltic composition studied at high pressure (GREEN and RINGWOOD, 1967; GREEN, 1967).

The pyroxene-garnet-quartz-sodic plagioclase ( $\pm$  kyanite?) assemblage obtained at high pressure corresponds to some garnet granulites found in high grade metamorphic terranes. There are several recorded occurrences of assemblages analogous to those obtained in the experimental work in natural rocks of overall andesite or gabbroic anorthosite composition. Thus BUDDINGTON (1939, 1952) describes garnet-bearing gabbroic anorthosite (garnet moderately rich in grossular,

TABLE 4

Results of experimental runs on the gabbroic anorthosite composition at 900–1200 °C (note: additional results depicted in fig. 2 are taken from GREEN, 1967)

Pressure (kb)	Temperature (°C)	Time (hrs)	Type of sample capsule	Phases present†							Comments
11.3	900	13	Ag-Pd	px	plag	—	—	—	—	—	Fine grained; plag ≫ px
then 4.3	900	24		px	plag	—	—	—	—	—	Fine grained; plag ≫ px
11.3	900	11½	Ag-Pd	px	plag	—	—	—	—	—	Fine grained; plag ≫ px
then 6.2	900	24		px	plag	ga	qtz?	—	—	—	Medium grainsize; plag > px > ga, qtz? uncertain X-ray evidence for quartz
11.3	900	12	Ag-Pd	px	plag	—	—	—	—	—	Fine grained; plag ≫ px; no garnet observed
then 7.7	900	24		px	plag	—	—	—	—	—	Fine grained; plag ≫ px > ga, qtz? uncertain X-ray evidence for quartz
9	900	4	Ag-Pd	px	plag	—	—	—	—	—	Fine grained; plag ≫ px ≫ trace garnet
11.3	900	12½	Ag-Pd	px	plag	ga	qtz?	—	—	—	Fine grained; plag ≫ px > ga, qtz? uncertain X-ray evidence for quartz
then 9.6	900	25		px	plag	ga	qtz?	—	—	—	Fine grained; plag ≫ px > ga, qtz? uncertain X-ray evidence for quartz
10.1	900	4	Ag-Pd	px	plag	—	—	—	—	—	Fine grained; plag ≫ px ≫ trace garnet
10.1	900	12	Ag-Pd	px	plag	ga	qtz?	—	—	—	Fine grained; plag ≫ px > ga, qtz? uncertain X-ray evidence for quartz
18	900	48	Au	px	plag	ga	qtz	—	—	—	Medium grainsize; plag > px > ga > qtz; $a_{ga} = 11.66 \pm 0.01 \text{ \AA}$
22.5	900	48	Au	px	plag	ga	qtz	—	—	—	Medium grainsize; px, plag ≫ ga > qtz; $a_{ga} = 11.76 \pm 0.02 \text{ \AA}$
22.5	1000	48	Au	px	plag	ga	qtz	—	—	—	Medium grainsize; px > plag ≫ ga > qtz (c.w. 22.5 kb 1000 °C run, plag content lower; ga, qtz higher)
then 22.5	900	64		px	plag	ga	qtz	—	—	—	Well crystallized; px > plag > ga > qtz; plag definitely grown compared with 36 kb 1000 °C run
36	1000	48	Au	px	plag	ga	qtz	—	—	—	Medium grainsize; px ≫ ga > qtz > felds > ky? minor amphibole also present; $a_{ga} \approx 11.72 \pm 0.02 \text{ \AA}$
then 22.5	900	72		px	plag	ga	qtz	—	—	—	Fine grained; px ≫ ga > qtz > felds > ky?; evidence for kyanite not definitive, felds (trace only) probably K-felds, no plag
25	900	48	Au	px	felds	ga	qtz	ky?	(amph)	—	Medium grainsize; px ≫ ga > qtz > felds > ky?; felds trace amount only; $a_{ga} \approx 11.76 \pm 0.02 \text{ \AA}$
27	900	30½	Ag-Pd	px	felds	ga	qtz	ky?	—	—	Medium grainsize; px ≫ ga > qtz > felds > ky?; felds trace amount only; $a_{ga} \approx 11.76 \pm 0.02 \text{ \AA}$
27	900	48	Au	px	felds	ga	qtz	ky?	—	—	Medium grainsize; px ≫ ga > qtz > felds > ky?; felds trace amount only; $a_{ga} \approx 11.76 \pm 0.02 \text{ \AA}$
36	900	48	Au	px	felds	ga	coes	ky?	—	—	Medium grainsize; px ≫ ga > coes > felds > ky?; felds trace amount only; $a_{ga} \approx 11.76 \pm 0.02 \text{ \AA}$
9	1000	11½	Ag-Pd	px	plag	—	—	—	—	glass	Fine grained; minor glass; plag ≫ px
22.5	1000	48	Au	px	plag	ga	qtz	ky?	—	—	Medium grainsize; px > plag, ga > qtz > ky?; $a_{ga} = 11.71 \pm 0.01 \text{ \AA}$
25	1000	24	Au	px	plag	ga	qtz	ky?	—	—	Medium grainsize; px ≫ plag, ga > qtz > ky?
27	1000	48	Au	px	felds	ga	qtz	ky?	—	—	Medium grainsize; px ≫ ga > qtz > felds, ky?; felds trace amount only; $a_{ga} = 11.74 \pm 0.01 \text{ \AA}$
36	1000	48	Au	px	felds	ga	coes	ky?	—	—	Medium grainsize; px ≫ ga > coes > felds, ky?; felds trace amount only; $a_{ga} = 11.76 \pm 0.02 \text{ \AA}$
13.5	1060	3	Au	px	plag	ga	—	—	—	—	Fine grained; plag ≫ px > ga
11.3	1100	4	Ag-Pd	px	plag	—	—	—	—	—	Fine grained; plag ≫ px
12.4	1100	4	Ag-Pd	px	plag	ga	—	—	—	—	Medium grainsize; plag ≫ px > ga
13.5	1100	2	Ag-Pd	px	plag	ga	qtz?	—	—	—	Medium grainsize; plag ≫ px > ga > qtz?; uncertain X-ray evidence for quartz
28.8	1100	23	Ag-Pd	px	plag	ga	qtz	ky?	—	—	Medium grainsize; px ≫ ga > qtz ≫ plag > ky?
16.0	1200	2½	Pt	px	plag	ga	—	—	—	glass	Medium grainsize; minor glass, plag ≫ px > ga

† Underlines denote phases identified by optical means only.

px = pyroxene; plag = plagioclase; qtz = quartz; ga = garnet; felds = feldspar (K-rich); coes = coesite; ky = kyanite; amph = amphibole.

>20 mol%) from the Adirondacks. Dioritic gneisses of similar chemical composition to andesite also occur, but contain little or no garnet. The garnet tends to be lowest or absent in rocks with the highest quartz content, the rocks most closely approaching the diorite of this paper in composition. Both the gabbroic anorthosite and diorite assemblages are dominated by plagioclase with subordinate clinopyroxene and minor garnet. Comparison with the experimental results indicates probable  $P$ - $T$  conditions of about 750 °C and 5 kb. DE WAARD (1966) suggests pressures as high as 10 kb and temperatures up to 800 °C for the metamorphism in the Adirondacks, in which case garnet would be expected in rocks of intermediate composition under anhydrous conditions.

DAVIDSON (1943) refers to a garnet-bearing anorthositic gneiss (plagioclase dominant, with subordinate garnet and minor clinopyroxene and hornblende) on South Harris. In the same area DEARNLEY (1963) describes tonalites (approximately equivalent to andesite in composition) with the assemblage orthopyroxene-clinopyroxene-plagioclase. Also in basic rocks there is a reaction relation between olivine and plagioclase (producing garnet and quartz). Conditions satisfying these 3 features would be 3-5 kb at 700-800 °C as indicated by the present work and work of GREEN and RINGWOOD (1967).

DEN TEX and VOGEL (1962) and ESKOLA (1952) record intermediate rocks with assemblages orthopyroxene-clinopyroxene-plagioclase-quartz indicating  $P$ - $T$  conditions in the field below the incoming of garnet in fig. 1. QUENSEL (1951) and GROVES (1935) refer to intermediate composition rocks with the assemblage: -2 pyroxenes-plagioclase-garnet-quartz-hornblende, indicating metamorphism under  $P$ - $T$  conditions within the garnet field of fig. 1. GROVES (1935) also notes reaction rims involving hypersthene-plagioclase reacting to form diopside and garnet and indicates that the pyroxene becomes increasingly omphacitic in composition. Similarly KOZLOWSKI (1958) reports an intermediate rock with the assemblage garnet (grossular 22%), omphacitic pyroxene, plagioclase (oligoclase), quartz and minor microcline, biotite, amphibole and rutile. Kozlowski's conclusion that this assemblage was formed under conditions which would have produced eclogites from basalts is consistent with the present experimental results.

#### 4.3. Lower crustal mineralogy

Assuming a linear extrapolation of the incoming of garnet and the final disappearance of plagioclase to probable temperatures in the stable lower crust (300-700 °C; BIRCH, 1955; CLARK, 1961, 1962) an indication of the mineralogy of an anhydrous lower crust of overall andesite and/or gabbroic anorthosite composition may be obtained. As mentioned in section 2, RINGWOOD and GREEN (1966) have argued that large areas of stable continental crust are essentially dry, and it is emphasized that the present results are only applicable to a consideration of the mineralogy of a dry crust.

For an andesitic composition the highest pressure assemblage obtainable below the quartz to coesite transition (coesite is only known to have formed naturally in association with meteorite impact) consists of clinopyroxene, quartz, garnet and K-feldspar, but for likely  $P$ - $T$  conditions in the lower crust, the final breakdown of plagioclase in this composition is not attained, so that some sodic plagioclase will occur as well. This is similar to the assemblage proposed by RINGWOOD and GREEN (1966) except for the absence of kyanite. This phase was not identified in any of the experimental runs on andesite, but it may have occurred in amounts up to about 5% (see section 3.2), but not 15% as calculated by Ringwood and Green. This suggests that the high pressure assemblage obtained experimentally is probably richer in aluminous pyroxenes, quartz and garnet than the assemblage calculated.

Similarly, in the case of the gabbroic anorthosite, the mineralogy expected under stable lower crustal  $P$ - $T$  conditions would consist of plagioclase, pyroxene, minor garnet, minor quartz and possibly minor kyanite. The grossular content of the garnet would be significant, and for any given bulk composition, increase with increasing pressure of formation.

#### 4.4. Experimental results and geophysical models for the lower crust

Seismologists generally recognize compressional wave velocities of 5.8-6.3 km/s as characteristic of the upper crust, increasing to 6.6-7.4 km/s in the lower crust (GUTENBERG, 1955, 1959; RICHARDS and WALKER, 1959; STEINHART and MEYER, 1961; JAMES and STEINHART, 1966). The nature of the downward increase in velocity is controversial (for a summary see JAMES and

STEINHART, 1966); in some regions it is argued to be discontinuous at the Conrad discontinuity (e.g. RICHARDS and WALKER, 1959), whereas in other areas it is considered to be continuous (e.g. TATEL and TUVE, 1955). Early crustal models proposed to explain this increase have attributed it to a granitic upper crust overlying a basic lower crust. PAKISER and ROBINSON (1966) have given estimates of the average composition of three super-provinces of the North American continental crust, based on seismic evidence. Their conclusion is that the overall composition is intermediate, though they assume that there is a composition change from granitic to basic with depth, rather than a mineralogical change in a single bulk composition.

However RINGWOOD and GREEN (1966) have argued, using experimental results on high pressure assemblages in basic compositions, that an anhydrous lower crust of basic composition could not give rise to the observed seismic properties of this region. RINGWOOD and GREEN (1966) further suggested that rocks approaching diorite ( $\approx$ andesite) in average chemical composition would best fit the physical properties of the lower crust. The present experimental work supports these conclusions. Garnet is stable in diorite under conditions equivalent to high-pressure granulite facies and eclogite facies (i.e. conditions expected in the lower crust) and so in an anhydrous lower crust, the presence of relatively dense phases garnet and aluminous pyroxene may be responsible for increasing seismic velocity with depth, rather than a compositional change (cf. GREEN and LAMBERT, 1965). A gabbroic anorthosite composition would behave in a similar fashion to diorite.

The density of the high pressure mineral assemblage has been measured directly on two experimental runs using a Berman balance. The gabbroic anorthosite composition at 25 kb, 900 °C has a density of 3.15 g/cm<sup>3</sup> while the diorite composition at 18 kb, 900 °C has a density of 2.88 g/cm<sup>3</sup>. Using solutions 6 and 7 of the equation given by BIRCH (1961) ( $V_p = a + b\rho$  where  $V_p$  is the compressional wave velocity in km/s at 10 kb and  $\rho$  the density in g/cm<sup>3</sup>) the calculated compressional wave velocities at 10 kb confining pressure for these assemblages are 7.4 km/s (gabbroic anorthosite) and 7.0 km/s (diorite). The particular gabbroic anorthosite run represents a mineral assemblage stable at  $P$ - $T$  conditions greater than those generally considered likely in the lower crust, so that the calculated seismic veloc-

ities may be regarded as the upper limit for a lower crust of this composition. The diorite run represents a mineral assemblage likely for intermediate  $P$ - $T$  conditions predicted in the lower crust (e.g. extrapolated to 550 °C at 10 kb), so that the calculated seismic velocity may be regarded as a median value for a lower crust of dioritic composition. The compressional wave velocities should be somewhere between 6.8 and 7.4 km/s for gabbroic anorthosite or 6.6 and 7.2 km/s for diorite, where the lower values are those predicted for the low pressure mineralogy (table 1).

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