

# High-pressure experimental studies on the origin of anorthosite

TREVOR H. GREEN

*Hoffman Laboratory, Harvard University, 20 Oxford St., Cambridge, Mass. 02138, U.S.A.*

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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).