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 anatectic-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