

Genesis of Massif-Type Anorthosites — The Role of High-Grade Metamorphism

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Abstract. The genesis of massif-type anorthosites in general is discussed on the basis of data obtained on the Capivarita massif, a labradorite-type anorthosite from Southern Brazil. Massif anorthosites are thought to have originated by fractional crystallization of magmas of suitable compositions (essentially high-alumina basalt and andesite melts) that underwent extremely slow cooling under high-grade metamorphic conditions. Plagioclase is the dominant liquidus phase in the melt only over a very restricted temperature interval (10–20°C) in which water pressure ($P_{H_2O} < P_{total}$) is maintained more or less constant at a critical value. Plagioclase accumulation by gravitational sinking is operative only under a set of critical conditions that are statistically unlikely to occur or to be maintained for any length of time. Hence, anorthosites would be relatively rare. The possible influence of the total pressure on anorthosite composition is discussed.

Introduction

Massif-type anorthosites are widespread in high-grade metamorphic terrains and are normally associated with plutonic formations of almost exclusively Precambrian age. Large masses of anorthosites are, however, uncommon and limited to the Fennoscandia and Siberia (Anderson, 1969). In addition, true anorthosites (plagioclase > 90%) are only sporadically present within rock associations (*e.g.* the mangerite-charnockite and the gabbro-troctolite suites) in which their occurrence is feasible.

A considerable amount has been written about anorthosites, but their genesis remains a moot point. Any hypothesis must take into account certain peculiar features, of which the most important are: a) the relative compositional homogeneity within a single anorthosite as opposed to the variations observed between various plutons; b) their constant association with high-grade metamorphic rocks; c) their cumulate character; e) evidence of their having undergone igneous emplacement in the form of slabs rather than as a batholithic mass.

Current hypotheses (see the review of Isachsen, 1969) as to the genesis of massif anorthosites are based on: a) the fractional crystallization of a primary magma (proposed compositions include gabbroic-anorthositic, monzonitic, high-alumina basalt, andesite melts, etc.); b) the partial melting of gabbroic material (Crosby, 1969) or of sediments (De Waard, 1969; Winkler and Von Platen, 1960) leaving an anorthositic residuum.

This paper sets out to discuss the genesis of small- and medium-size massif-type anorthosites, widespread in high-grade metamorphic terrains, on the basis of observations made on the Capivarita anorthositic massif.

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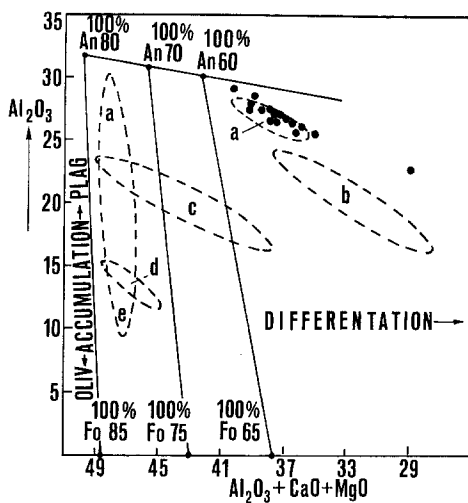


Fig. 1. Representation of samples of the Capivarita anorthosite (closed circles) on the Al_2O_3 —($\text{AlO} + \text{CaO} + \text{MgO}$) diagram. Areas delimited by dashed lines indicate the theoretical fields of: *a* anorthosite, *b* anorthosite-leuconorite, *c* cleucotroctolite, *d* troctolite, *e* dunite (from Martignole, 1974)

Outline Data on the Capivarita Anorthosite Massif

The Capivarita massif occurs in the Rio Grande do Sul State (Southern Brazil) and is at present the only known massif-type anorthosite of a certain size in the Brazilian shield. A principal ovoidal body together with three minor bodies covers an area of about 77 square kilometres. The main body is bordered on one side by a post-tectonic granite containing anorthosite xenoliths and on the other by rocks of the Precambrian basement (granite gneisses, migmatites) metamorphosed under amphibolite facies conditions. Layers of amphibolite of tholeiitic composition extend approximately N-S within the anorthosite. The petrology and chemistry of anorthosite and country rocks have been described (Formoso, 1973; Formoso *et al.*, 1975). After its emplacement, anorthosite underwent regional metamorphism in amphibolite facies that led to the formation of hydrous minerals (hornblende, chlorite). K/Ar radiometric data that give ages of about 600 m.y. (Formoso, 1973) probably date only a late thermo-metamorphic event.

A relative compositional homogeneity is found throughout the body. Plagioclase composition (An normally 49–63%) indicates that Capivarita is a typical labradorite anorthosite. The main compositional variations within the body are represented in the diagram of Fig. 1. According to Martignole (1974), this diagram illustrates variations caused by the two main processes guiding the evolutive patterns of anorthositic suites genetically correlated to mafic magmas, *i.e.* crystal fractionation in the normal manner and formation of crystal cumulates. Both these processes seem to have been active during the formation of anorthosite. The absence in the area both of mafic plutons and of rock types typical of anorthositic associations poses severe problems when it comes to discussing the genesis of anorthosites. Gradational contacts with the amphibolite layers (increasing: An content of plagioclase up to bitownitic composition and progressive increase of mafics towards amphibolite) suggest that gabbroic tholeiitic rocks and anorthosites are co-magmatic.

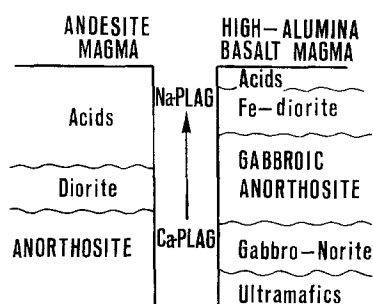


Fig. 2. Rock sequences originating according to Ryder (1974) from the fractional crystallization of andesite and high-alumina basalt magmas under granulite facies conditions

The Production of Anorthosites by Fractionation of Mafic Magmas

On account of the unreasonably high temperature required for the crystallization of a pure anorthite magma some form of fractionation from possible parent magmas is generally proposed for the genesis of anorthosites. Abundant experimental data relating to magmas of varied composition illustrate the great difficulty with which anorthositic liquids are derived from other magmas. The parent magmas most often suggested include andesite, monzonitic, calc-alkali basalt, high-alumina basalt and gabbroic anorthositic compositions (Isachsen, 1969). In general, in order to obtain a liquid of anorthositic composition, a high water content in the primary magma undergoing fractional crystallization is assumed; this is on account of the wellknown effect of water in the experimental crystallization of the diopside-anorthite system. Some Authors, however, argue that the shift towards anorthite composition produced by water is not sufficient to produce liquids of suitable composition from which, at a given stage, pure plagioclase can crystallize and later accumulate. Lindsley (1969) pointed out that, in the system diopside-albite-anorthite, high total pressure may shift the boundary curve towards the plagioclase join, providing a mechanism for the generation of gabbroic anorthosite magma at depth. Most Authors, however, favour the idea that large massifs of anorthosite and gabbroic anorthosite are an accumulation of magmatically-differentiated plagioclase crystals formed from a liquid at crustal levels or near the mantle-crust boundaries.

The ubiquitous association of anorthositic rocks with granulite facies rocks (typical is the mangerite-charnockite suite) recently led Ryder (1974) to suggest that the genesis of massif-type anorthosites might be correlated with the fractional crystallization of high-alumina basalt and andesite magmas under high-grade metamorphic conditions. Two different vertical sequences of rock types would form (Fig. 2). Early fractionation of high-alumina basalt liquids would give ultramafic and gabbro-norite crystallized products, and labradoritic plagioclase would be removed (by gravitational sinking) from the remaining liquid crystallizing under granulite-facies pressure. Such a sequence is not very dissimilar from that proposed by Bowen (1917). Andesine-type anorthosites, on the other hand, would originate in the early stages of the fractional crystallization of an andesite magma. The schemes proposed by Ryder (1974) offer a plausible and relatively simple model for the genesis of massif-type anorthosites. Nevertheless, the influence of the metamorphic conditions on the genesis of the anorthosites is not

discussed in detail, nor is it explained why anorthosites occur only sporadically among the crystallization products of mafic magmas whose crystallization under high-grade metamorphic conditions should, it is thought, have afforded anorthosites. These points will be considered in the present model, which represents an extension of the ideas of Ryder.

Discussion of the Crystallization Patterns of Some Magmas

Field evidence shows that, under a wide range of pressure conditions, olivine is the dominant phenocryst phase in the fractional crystallization of a normal basalt magma. Plagioclase does not usually appear at an early stage of fractionation. Abundant experimental data (Yoder and Tilley, 1962; Green and Ringwood, 1964, 1967; etc.) confirm that, except at very low pressure and zero water content, plagioclase is absent from the liquidus of various basalt magmas. Experiments on high-alumina basalts show that plagioclase is produced at or close to the liquidus up to about 6.8 kilobars at low water pressure, but is usually accompanied by both pyroxene and olivine (Green *et al.*, 1967). Finally, it is well known that plagioclase is the most abundant phenocryst phase in the calc-alkaline andesites, an observation which is also confirmed by experimental data over wide pressure ranges (Green, 1969, 1972). Water in liquids of varying composition (from basaltic to andesitic) generally serves to delay the crystallization of plagioclase, in some cases by reducing the plagioclase crystallization temperature to slightly below that of mafic phases. From the foregoing it can be deduced that anorthositic accumulations, brought about by the selective settling out of plagioclase crystals over pressure ranges found in high-grade metamorphism, may take place only from andesite liquids. However, as pointed out by Ryder (1974), anorthosites generated by andesite liquids would only be of the more sodic andesine-type, the labradorite-type requiring a more mafic melt for their formation. On the basis of experimental results, early fractional crystallization under high water pressure of a high-alumina basalt magma would generate an ultramafics-gabbroic sequence (see Fig. 2), the remaining liquid being enriched in water, plagioclase and salic components. If this liquid crystallizes at least partially in the deep crust under granulite facies conditions, and under certain conditions plagioclase is the only liquidus phase, gravitational sinking of plagioclase crystals may lead to anorthositic accumulations. In order to ascertain whether these conditions may be realised, the main features of high-grade metamorphic environments are discussed.

Role of High-Grade Metamorphism

Pressure and temperature values normally accepted for granulite facies metamorphism vary in certain intervals. Assuming that the earth's thermal regime has remained unvaried from the Precambrian to the present day (higher heat flows may typify conditions of Archean metamorphisms, according to Brown and Fyfe, 1972) normal pressures of about 6–10 kilobars and temperatures up to 850–900°C are considered. The temperature of a liquid derived from an early fractionated high-alumina basalt melt cannot be known with precision, but it is unlikely to much exceed 1100–1200°C. Several sets of experimental data suggest

that andesine-type anorthosites crystallize at temperature of about 1000–1100°C (see *e.g.* Luth and Simmons, 1969). The limited difference between the probable temperature of the magma and that of the surrounding environment suggests that, if the metamorphic conditions remain unvaried, cooling and consequent crystallization of the magma would take place very slowly, particularly in view of the low thermal conductivity of plagioclase-rich magmas (Isachsen, 1969). This signifies that, at least during certain stages, crystallization of magma occurs under quasi-static thermal conditions. In the evolutive course of granulite facies metamorphism partial water pressure in the general environment is lowered by dehydration reactions and similar effects should be present in the crystallizing magma. The latter would be submitted to conditions of progressive decrease in water pressure with respect to total pressure, while total pressure and temperature remain unvaried, or at least vary only very slightly. This evolving set of conditions characterized by decreasing P_{H_2O} must have a strong effect on the sequence of crystallization of the various phases, as demonstrated by experimental data. The sequence of crystallization in the Hawaiian tholeiites deduced by MacDonald (1949) is olivine-plagioclase-pyroxenes and iron oxides. Experimental results with $P_{H_2O} = \text{total pressure}$ on the same rocks (Yoder and Tilley, 1962) indicate that olivine is the first silicate phase to form, while pyroxene precedes plagioclase. Recent experiments on the same liquid with P_{H_2O} lower than P_{total} (Holloway and Burnham 1972) show that the upper stability of plagioclase is increased by about 100°C and that plagioclase and clinopyroxene co-exist in part of the P - T field. Experimental crystallization of andesite magma under different water pressure shows similar effects. For low water content (from zero to 2% by weight), plagioclase is the liquidus phase and mafics commence crystallizing about 10–20°C below the liquidus, which lies above 1100°C (Green, 1972; Eggler, 1972). These observations support the hypothesis that, at a certain stage, plagioclase becomes the dominant liquidus phase in a plagioclase-rich magma crystallizing under decreasing partial water pressure. By analogy with andesite liquids the mafic phase would join the plagioclase at temperatures slightly below the liquidus. Thus, because of its extremely slow cooling, the temperature of the magma could remain steady for lengthy periods at critical values, *i.e.* in the temperature interval in which plagioclase is the only liquidus phase. If removal of plagioclase crystals by gravitational sinking is operative, anorthosite accumulations will be formed (Fig. 3). The size of the plagioclase cumulate would depend on the plagioclase crystallization rates (*i.e.* melt composition) and above all, on the persistence over long periods of the critical temperature and partial water-pressure conditions. The interval of critical temperatures may be estimated by analogy with andesite liquids as being 10–20°C. Data on oxide minerals (Kretchsmar and McNutt, 1971) and the low structural state and general lack of compositional zoning of plagioclase are consistent with a crystal growth type within a very restricted temperature interval. Furthermore, since water not only influences the crystallization sequence of the main phases but also sharply lowers the absolute plagioclase crystallization temperature (Yoder, 1969), water pressure must not vary to much when the liquid is in the critical temperature interval. The small variation in the An content of plagioclase seems to be the result of the close approach to “equilibrium” achieved under very slowly changing conditions during the crystallization

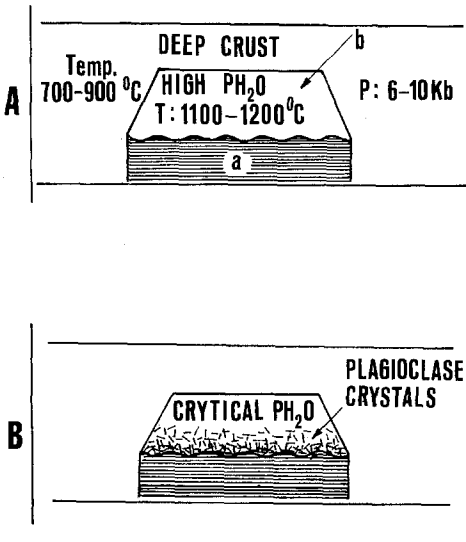


Fig. 3 A and B. Schematic model for the genesis of massif-type anorthosites. (A) Early fractional crystallization under granulite facies conditions of an high-alumina basalt magma. *a* ultramafic-gabbroic differentiates, *b* residual liquid enriched in water and feldspar components. (B) Appearance and gravitational sinking of plagioclase under quasi-static temperature conditions at a critical water pressure

of anorthosites (Yoder, 1969). The maintenance of critical water pressure is more difficult to envisage than that of critical temperatures, since regional granulite-facies metamorphism tends to cause a relatively rapid and generalized decrease of water pressure. It may be that the water pressure in the crystallizing liquid is maintained at critical values by means of a process of compensation, the water accumulating as a result of progressive crystallization of anhydrous plagioclase making up for the water lost in the normal course of events in granulite facies metamorphism. It is clear that the attainment and above all maintenance of critical levels of temperature and water pressure are statistically unlikely ever to be realised. A slight variation of one of the variables considered would presumably cause the contemporaneous crystallization of plagioclase and mafic phases, driving the magma towards usual fractional crystallization patterns. Hence anorthosite formation will be only a sporadic event in the fractional crystallization of a mafic magma under granulite facies conditions.

Critical water pressure values during the stage of plagioclase crystals accumulation can only be roughly estimated. According to Crosby (1969), water vapour pressure must be lower than 5 kilobars. Some observations (coarse grain size and marked cumulative character undoubtedly favoured by low viscosity conditions of the melt) seem to indicate conditions of relatively high water pressure. Some Authors argue that these conclusions are against the absence of hydrous minerals precipitated from the interstitial liquids trapped within plagioclase crystals. At this point, Yoder (1969) remarked that the persistence of hydrous phases would depend on the retention of volatiles after complete crystallization of the magma. In our opinion, the lack of hydrous phases may simply mean the maintenance of "dry" granulite facies conditions after the formation of plagioclase cumulate. In this case, eventual hydrous phases present in anorthosites would be eliminated by dehydration reactions. According to the model proposed, the composition of the original melt would seem to play the

major role in determining the An content of plagioclase. Nevertheless, the possible influence of pressure and temperature conditions of metamorphism must also be evaluated. In particular, pressure was found experimentally (Green, 1969) to influence the composition of the early crystallizing plagioclase from a quartz-diorite liquid. At low pressure labradorite plagioclase prevails, while above 9 kilobars the first plagioclase to appear is andesinic. Thus, two distinct sets of total pressure (high- and low-pressure) could account for the two main types of anorthosites. If this is true, a certain correlation must exist between pressure conditions of metamorphism and anorthosite composition. The association of andesine-anorthosites with high-pressure granulitic rocks is well documented (Isachsen, 1969). Much less precise and detailed information exists about the generalized association of labradorite-anorthosites with metamorphic pressure conditions of the country rocks. The apparent association of the Capivarita labradorite anorthosite with amphibolite facies rocks is not indicative because it seems to be the result of secondary processes.

Problems Concerning the Magmatic Origin of Anorthosites

In the light of the foregoing, and in accordance with the proposals of the majority of Authors, it would seem most likely that anorthosites derive from high-alumina basalt and andesite liquids through the intervention of high-grade metamorphism. Nevertheless, other magmas that in their crystallization processes give rise to residual liquids enriched in plagioclase components may be thought to account for anorthositic accumulates. High-alumina basalt is considered as a special primary mantle-derived magma by Kuno (1960) or a liquid derived under particular conditions from tholeiitic or calc-alkali basalt melts (Yoder and Tilley, 1962; Chayes, 1966). If this last hypothesis is true, normal tholeiitic or calc-alkali basalt magmas that have been subjected at depth to early fractionation of dominant mafic phases under certain conditions may be the true starting material for anorthosites. It is clear that also this interpretation is subject to all the criticisms applicable in the case of the genetic correlation of anorthosites with the evolution of a mafic magma. The two fundamental criticisms are a) the normal absence of large quantities of associated mafic and ultramafic differentiates, and b) the supposed high water content of a primary magma derived from an almost anhydrous mantle. In spite of the numerous interpretations proposed (see Isachsen, 1969), these two points remain the more puzzling aspects of anorthosite genesis.

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