

A MODEL FOR THE GENERATION OF MASSIF-TYPE ANORTHOSITES

ANTHONY R. PHILPOTTS

*Department of Geology and Geophysics and Institute of Materials Science,
University of Connecticut, Storrs, Connecticut 06268, U.S.A.*

ABSTRACT

The relative constancy of plagioclase compositions within large anorthositic massifs is difficult to explain by simple magmatic crystallization; it can, however, be accounted for if the plagioclase was buffered by coexisting immiscible magmas that changed their proportions during the crystallization of plagioclase. Immiscible liquids in many basalts and andesites coexist with plagioclase of the composition found in anorthosites. Moreover, these liquids are compositionally similar to jotunite and quartz mangerite, two of the rock types commonly associated with anorthosites. Experiments done on a mixture of jotunite and quartz mangerite at approximately one atmosphere total pressure and under oxygen fugacities controlled by the Ni-NiO buffer reveal extensive immiscibility between liquids compositionally similar to these rocks. Plagioclase (An_{52}) first crystallizes at 1050°C from a homogeneous liquid prepared from a mixture of these rocks; then, at ten degrees lower, after only a few percent crystallization, the remaining liquid splits into iron- and silica-rich fractions. Partial melting experiments on quartz mangerite alone also result in the formation of immiscible liquids; certain textures commonly exhibited by this rock type can be interpreted as resulting from immiscibility. The following genetic model is proposed for massif-type anorthosites; they form by accumulation of plagioclase from a magma, possibly originally basaltic to andesitic in composition, that splits into immiscible fractions during the crystallization of this mineral. The separation by flotation of a light, silica- and alkali-rich, immiscible liquid from the original magma buffers the accumulating plagioclase at a relatively constant composition and enriches the upper part of the magma chamber in those components that eventually form quartz mangerite. Continued separation of plagioclase crystals and globules of immiscible silica-rich liquid from the original magma causes it to become increasingly more mafic, and eventually to crystallize as jotunite, which typically occurs between anorthosites and quartz mangerites in the field.

Keywords: anorthosite, silicate liquid immiscibility, quartz mangerite, jotunite, experimental petrology.

SOMMAIRE

On s'explique mal par simple cristallisation mag-

matique la composition relativement constante du plagioclase dans les grands massifs anorthositiques. Cette constance pourrait, par contre, résulter de la formation de magmas coexistants immiscibles qui, en variant leurs proportions, agiraient comme tampon pour le plagioclase. Dans nombre de basaltes et d'andésites, on trouve des liquides immiscibles en coexistence avec un plagioclase de composition appropriée. De plus, ces liquides ressemblent, dans leur chimisme, à la jotunite et la mangérite quartzifère, deux lithologies fréquemment associées aux anorthosites. Un mélange de ces deux roches, chauffé à environ une atmosphère et à fugacité d'oxygène fixée par le tampon Ni-NiO, montrent une grande immiscibilité entre liquides de compositions voisines de celles des deux roches de départ. Le plagioclase (An_{52}) est la première phase à cristalliser à 1050°C d'un liquide homogène formé à partir du mélange. Dès 1040°C, après le début de la cristallisation, le bain fondu résiduel subit une démixtion en fractions siliceuse et ferrifère. Des essais de fusion partielle sur la mangérite quartzifère seule donnent aussi des liquides immiscibles. De plus, certaines textures caractéristiques de ce type de roche peuvent s'interpréter comme résultat d'immiscibilité. Les anorthosites de massifs se seraient formées par accumulation de plagioclase cristallisé d'un magma, initialement basaltique ou andésitique, qui se serait séparé par la suite en deux fractions immiscibles. L'extraction du magma originel, par flottation, d'un liquide immiscible, léger, riche en silice et en alcalins tamponne le plagioclase qui cristallise à composition relativement constante et enrichit la zone supérieure de la chambre magmatique en constituants destinés à former ultérieurement la mangérite quartzifère. L'extraction continue de cristaux de plagioclase et de globules de liquide siliceux immiscible accroît le caractère mafique du magma originel, lequel finit par cristalliser comme jotunite, roche typique des contacts entre anorthosite et mangérite quartzifère sur le terrain.

(Traduit par la Rédaction)

Mots-clés: anorthosite, immiscibilité liquide, mangérite quartzifère, jotunite, pétrologie expérimentale.

INTRODUCTION

The origin of large Precambrian anorthosite massifs remains one of the major unsolved prob-

lems of petrology. Despite their remarkably simple mineralogy and relatively easily mapped structures, several important questions remain unanswered. For instance, how are anorthosites related to associated leuconorites, jotunitites, quartz mangerites and charnockites? Why is the primary grain-size of many anorthosites so exceptionally coarse, and how did huge crystals of plagioclase and pyroxene form with no significant compositional zoning? Furthermore, many anorthosite massifs of batholithic dimensions contain plagioclase that varies only slightly in composition throughout each body. If these bodies are of igneous origin, which is now generally accepted, it is difficult to conceive why there would not have been fractionation of the magma during crystallization; in turn, fractionation should have resulted in progressive changes in the composition of the plagioclase. Perhaps the most outstanding problem of all relates to their age; most massif-type anorthosites are between 1 and 1.5 billion years old, though several recent studies have revealed both older and younger bodies.

These problems do not remain unsolved for lack of work or interest. During the past twenty years an enormous amount of petrological, geochemical, structural and geophysical data has been collected from most of the major anorthosite complexes, so that today we have reasonably accurate pictures of many of these bodies. Indeed, most anorthosite massifs, while differing in detail, are now known to conform to a general model with respect to rock types and their distributions (Isachsen 1968). Such simplicity implies that solutions to the above problems might readily be found, but this apparently has not been the case.

One particular problem, that of the formation of batholithic quantities of unzoned plagioclase crystals of very limited compositional range, has several possible solutions, one of which involves the separation of an immiscible silica- and alkali-rich liquid from the magma during crystallization of the plagioclase; this silica-rich fraction could then crystallize to form the associated quartz mangerites and other silica-rich rocks. Liquid immiscibility has been invoked by several authors to explain certain minor rock-types of anorthosite complexes (Hargraves 1962, Philpotts 1966, 1967, Wiebe 1979), but several independent lines of evidence indicate that the entire range and distribution of rock types associated with anorthosite complexes can be explained by a combination of fractional crystallization and liquid immiscibility. This paper presents evidence for such a petrogenetic process,

GENERAL CHARACTERISTICS OF ANORTHOSITE COMPLEXES

Most large anorthosite complexes form domical bodies that appear to have risen diapirically into dense, overlying high-grade metamorphic rocks (Schrijver 1975). Their internal structures provide abundant evidence of the deformation accompanying their rise, and large, negative Bouguer gravity anomalies associated with many of these bodies attest to (1) the low average density of anorthosite complexes relative to their surrounding country rocks and (2) the absence of large quantities of associated ultramafic rocks. Whereas contacts with overlying gneisses are clearly exposed, no large anorthosite body has yet revealed a floor, though some small anorthosite sheets are underlain by paragneisses. Floors of large anorthosite bodies are likely left behind in the root zones during diapiric rise.

Anorthosites and associated rocks commonly occur in a definite sequence (Fig. 1) which, because of the domical form of these complexes, appears as a succession of annular zones of different rock types. The lower member, which forms the core of most complexes, consists of relatively pure anorthosite. With increasing pyroxene content, this grades outward into leuconorite which, in many complexes, is the more abundant of the two rock types. A rather rapid increase in the content of apatite and ferromagnesian minerals, in particular of magnetite and ilmenite, brings about a transition from leuconorite to a ferrodioritic rock named jotunite. This rock marks the border zone of the anorthosite body proper, *i.e.*, the part of the body in which plagioclase is the most prominent constituent, but sharp increases in the amount of alkali feldspar and quartz continue the gradation outward into the final and, in many cases, the most abundant member of the entire series, *i.e.*, quartz mangerite. In some areas the amount of quartz in this member of the series is sufficiently great that the rock is named charnockite. A rather minor but economically important rock type, consisting of various iron-titanium oxides and apatite, is characteristically associated with these complexes and occurs in the jotunite or in the leuconorite and anorthositic rocks immediately below the jotunite.

In most complexes the contacts between these major rock-types are gradational, but in some, the quartz mangerite cross-cuts the other rocks, and in still others, both relations are found in different parts of the same body (*e.g.*, Wheeler 1968). Such apparently conflicting relations

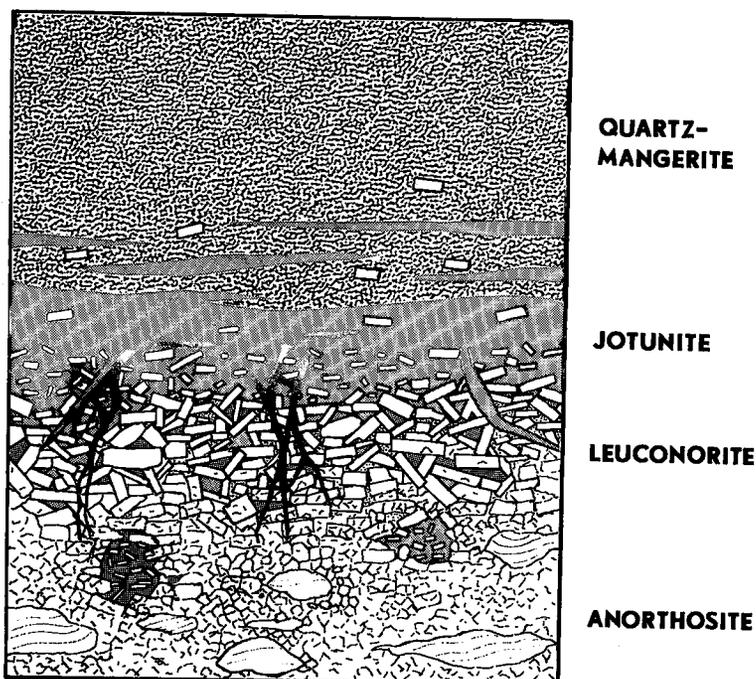


FIG. 1. Idealized stratigraphy through a typical massif-type anorthosite complex, with pure anorthosite at the base grading upward through leuconorite to jotunite, which is in turn overlain by quartz mangerite. The black dykes and lenses are rocks rich in iron and titanium oxides and apatite.

have been at the heart of many arguments concerning the origin of anorthosites and associated rocks; however, since quartz mangerite would remain molten to considerably lower temperatures than anorthosite or leuconorite, cross-cutting relations need not indicate separate origins for the different rocks, and indeed it would be surprising if such different relations did not show up in large bodies that have solidified slowly.

The descriptions of the gradational contacts between anorthositic and mangeritic rocks from areas of good exposure are worthy of close scrutiny, for here major changes in composition occur over distances of as little as several tens of metres, with SiO_2 changing from 48 to 68%, K_2O from 1 to 5% and iron oxide from 15 to 5%. The relations between jotunite and quartz mangerite are clearly exposed in some of the anorthosite complexes of southern Quebec, which have been described by the author (Philpotts 1966). Most jotunites in these bodies are fine- to medium-grained rocks, but near contacts with quartz mangerite they contain large phenocrysts (megacrysts) of plagioclase and alkali

feldspar that steadily become more numerous and cluster together to form lenses as the quartz mangerite is approached. As these lenses become thicker and more abundant, the rock grades into a quartz mangerite containing lenses of jotunite, and then, with further diminution in the amount of jotunite, the gradation continues into a massive quartz mangerite. The interlayering of these two rock types occurs over tens of metres, but isolated lenses of jotunite occur throughout bodies of quartz mangerite, even at great distances from contacts. Schrijver (1975) has described similar relations in the zone between the leuconorite and quartz mangerite of the Lac-Croche plutonic complex of southern Quebec. In addition to jotunite, he describes this zone as containing "a heterogeneous discontinuously interlayered assemblage of rocks including leuconorite, augen gneiss, fine-grained pyroxene granulite, pyroxenite, fine-grained schistose biotite gneiss, and medium-grained apatite-magnetite-rich rock" (Schrijver 1975). Schlieren-like zones of jotunite are also present throughout the quartz mangerite of this body.

It is noteworthy that of all rock types associated with anorthosite complexes, jotunite is the only one that commonly forms dykes; these can be found cutting all other associated rock types. Many of the iron-titanium-oxide apatite-rich ores also form dykes, but these are restricted mostly to occurrences in the leuconorite. Jotunite dykes are intimately associated with most of these ores and, in some cases, even form composite dykes with them (Philpotts 1967).

The gradational variation between the major rock types of anorthosite complexes is shown by the mineralogy of the rocks. Plagioclase, the most abundant mineral of the entire series, is generally between An_{60} and An_{30} in composition. The plagioclase in the anorthosite of any particular complex exhibits no more than a few percent variation in its anorthite content (Buddington 1968, Isachsen 1968, Wiebe 1979). For example, the plagioclase in the Lac-St-Jean anorthosite massif of Quebec, the world's largest such body, all falls within the labradorite range, and this occurs over the enormous area of 25,000 km². On the other hand, the plagioclase in the Morin anorthosite of southern Quebec is all of andesine composition. Plagioclase becomes slightly more sodic with the gradation from anorthosite to leuconorite, reaching compositions of An_{45} in jotunites associated with labradorite-bearing anorthosites, and An_{30} in jotunites associated with andesine-bearing anorthosites (Anderson & Morin 1968). Little increase (if any) in the sodium content of the plagioclase accompanies the change to quartz mangerite; the major change in rock composition here is due to a sharp increase in the amount of potassium feldspar, a mineral that in the anorthosites and leuconorites occurs only as antiperthitic blebs in the margins of some plagioclase laths.

The pyroxenes, while being only minor constituents in most rocks of the series, range from relatively magnesium-rich compositions in anorthosites to iron-rich compositions in quartz mangerites. Clinopyroxenes, for example, typically range from $Ca_{47}Mg_{48}Fe_{10}$ to ferroaugite, and orthopyroxenes from En_{75} to En_{30} , and in some silica-rich rocks the assemblage fayalite + quartz is also found (Wheeler 1968).

Ilmenite and magnetite occur interstitially throughout the series, even in the jotunites where they are extremely abundant. The amount of apatite appears to be closely related to the abundance of these opaque oxides, being very low in the anorthosites and leuconorites, high in the jotunites, and low in the quartz mangerites.

Textures exhibited by these rocks are mainly the products of deformation, but some relict

primary textures are preserved in most complexes, and these provide evidence of the igneous origin of the rocks. The anorthosites are the coarsest-grained members of the series, with primary grain-sizes being measured in centimetres or even tens of centimetres. The primary plagioclase grains, which are invariably dark owing to abundant minute, oriented opaque inclusions, are commonly surrounded by finer-grained recrystallized plagioclase, which may also be dark (recrystallization presumably occurred at a high temperature prior to the exsolution of the opaque inclusions), but is mostly white and free of inclusions. Unrecrystallized leuconorite typically consists of centimetre-long plagioclase laths subophitically enclosed in pyroxene or ilmenite-magnetite intergrowths. Primary layering is common and due to both alignment of plagioclase laths and variations in mineral proportions. The jotunites are texturally the most peculiar member of the series, since their grain size is at least an order of magnitude less than that of any other associated rock. Moreover, they do not exhibit a subophitic texture, but instead are granular, a feature that may be due to recrystallization but is thought to be primary, since megacrysts of plagioclase are commonly preserved whole in this granular matrix (Fig. 1). The quartz mangerites are commonly the most deformed of all the rocks and many form augen gneisses with large strained feldspar augen surrounded by quartz, pyroxene, magnetite, ilmenite and apatite. Many quartz mangerites that have escaped deformation and recrystallization have a striking texture in which the quartz and feldspar occur in multigrained clusters that are separated from each other by aggregates of pyroxene, magnetite, ilmenite and apatite. Finally, large megacrysts (xenocrysts?) of andesine are found in some quartz mangerites near contacts with anorthositic and leuconoritic rocks.

Though differences exist among anorthosite complexes, the above general description encompasses those features that most complexes have in common and that should be accounted for in any satisfactory petrogenetic model for the origin of massif-type anorthosites.

THE PROBLEM OF GROWTH OF LARGE UNZONED PLAGIOCLASE CRYSTALS

The manner in which plagioclase crystallizes from a magma is well understood from the phase relations in various experimentally investigated systems, and from the common normal zoning found in the natural mineral. Plagioclase crystals

are always enriched in anorthite relative to the liquid with which they are in equilibrium. With falling temperature, the compositions of both liquid and crystals become more sodic, and if equilibrium is maintained, each crystal must, in addition to changing its composition, become homogeneous throughout. Whereas this is possible for small crystals in slowly cooled bodies, it becomes increasingly difficult the larger the crystal or the more rapid the cooling, because of the slow diffusion rates in solids. As a result, zoned plagioclase crystals tend to be the rule rather than the exception.

Whereas considerable data exist on diffusion rates in alkali feldspars, the author is unaware of such data for the plagioclase feldspars; however, since homogenization of plagioclase involves diffusion of aluminum and silicon in addition to sodium and calcium, the diffusion rates in plagioclase must be considerably slower than those in alkali feldspars, which need involve only the diffusion of alkalis. By using values for the diffusion coefficient in plagioclase that are somewhat smaller than those for alkali feldspar, we can estimate the likely rate of diffusion in plagioclase. Such calculations reveal that the large crystals of the size common in anorthosites, if initially zoned, would take more than all of geological time to become essentially homogeneous, even at elevated temperatures. It is only reasonable to conclude, therefore, that they must have grown in a relatively unzoned state, a conclusion supported by the rare occurrence of steep compositional gradients in the marginal zones of some otherwise unzoned plagioclase megacrysts; diffusion was apparently unable to homogenize these zones, despite the steepness of the compositional gradients.

Crystals of plagioclase could grow in an unzoned state in several ways, perhaps the most obvious of which involves the separation of a small amount of plagioclase from a large quantity of magma at constant temperature. Plagioclase grown in this manner would be of essentially one composition. As long as the quantity of crystals remains small relative to the volume of magma, there would be no significant change in magma composition, and thus there would be no change in the composition of the crystals either. Some anorthosite layers of constant composition in layered gabbroic intrusions may well have formed in this manner, but surely not massif-type anorthosites, since the volumes of magma would have had to be enormous. For instance, it is difficult to conceive of a body of magma sufficiently large that no significant fractionation would have resulted from the sepa-

ration of the 25,000 km² of homogeneous Lac-St-Jean anorthosite. And if such a magma body did exist, certainly no evidence of it remains today.

Unzoned plagioclase could also form if the plagioclase liquidus, under high pressures, developed a minimum such as that found in the alkali feldspar system. Lindsley's (1968) experimental investigation of the system albite-anorthite, however, shows that, apart from raising liquidus temperatures, increased pressure does not significantly change the phase relations in this system.

There remains another way in which plagioclase could crystallize with constant composition from a cooling magma, and this can be illustrated by referring to the system diopside-albite-anorthite (Fig. 2). The plagioclase liquidus in this system can be contoured with lines joining liquid compositions in equilibrium with specific plagioclase compositions. One such line, that for liquids in equilibrium with plagioclase of An₅₀ composition, is shown in Figure 2. These lines can be drawn using the experimental data for coexisting liquid and crystal pairs (Bowen 1915) or can be calculated using thermodynamic data (Barron 1972).

Liquid of composition *X* in Figure 2 (it is not implied that *X* represents the composition of the parental magma of anorthosites) will, on cooling, follow some liquid line of descent between the two extreme cases of complete

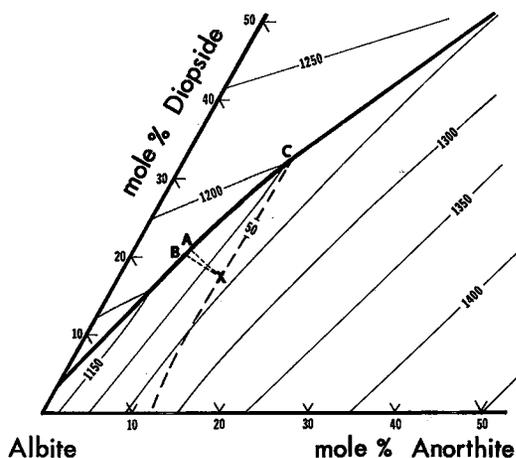


FIG. 2. Part of the system diopside-albite-anorthite showing liquidus temperatures. A heavy dashed line joins liquid compositions that are in equilibrium with plagioclase of An₅₀ composition (after Barron 1972).

equilibrium crystallization (XA) and complete fractional crystallization (XB). If the crystals were to grow large, equilibrium would be more difficult to achieve, and zoned crystals would result. If, however, the liquid's composition could be constrained to cool along line XC , the plagioclase formed would all be of An_{50} composition. Such a liquid line of descent would be unusual and would require exceptional fractionation. For example, it could be achieved by adding diopside to the system as cooling proceeded. In nature, this would require the assimilation of large quantities of pyroxenite, but there is certainly no evidence of this having occurred around anorthosite complexes.

On the other hand, this same line of descent could be achieved by subtracting material during cooling. If during crystallization of plagioclase there was a simultaneous separation of an appropriate amount of an albitic fraction, the liquid could follow line XC , crystallizing plagioclase of An_{50} composition as it cooled. But the subtracted albitic fraction could not be crystalline at this temperature, and thus would have to be an immiscible liquid. Of course, it would be extremely fortuitous for the primary liquid to follow exactly the line XC , but the important point is that the separation of a sodic immiscible liquid could prevent the normal enrichment in sodium that typically accompanies the crystallization of plagioclase from a melt. During the unmixing, equilibrium would require that the same composition of plagioclase exist in both liquids; however, the more sodic liquid, after coalescence and separation from the other liquid, would continue cooling to lower temperatures; the plagioclase in this melt would then become more sodic, although relics of the earlier-formed, more calcic plagioclase could persist.

There is, of course, no known liquid immiscibility field in the system diopside-albite-anorthite that could effect this unusual liquid line of descent, although the diopside liquidus does exhibit strong deviations from ideality towards the albitic part of this system. In the more complicated natural system, however, such a field could exist, and the albitic-rich immiscible liquid could separate by floating upward, eventually crystallizing as quartz mangerite. The denser conjugate liquid would either sink to form interstitial ferromagnesian patches in the anorthosite and leuconorite or eventually accumulate to form jotunite.

The evidence for the existence of this hypothesized immiscibility field will now be presented, based on naturally occurring immiscible liquids and ones synthesized in experiments on

mixtures of natural rocks from the anorthosite-quartz mangerite series (Philpotts 1978a).

COMPARISON OF COMPOSITIONS OF IMMISCIBLE LIQUIDS IN ANDESITES WITH ROCKS OF THE ANORTHOSITE-QUARTZ MANGERITE SERIES

The glassy residues of many fresh tholeiitic basalts consist of two chemically distinct glasses, one iron-rich and the other silica-rich, both of which form globules in each other (Roedder & Weiblen 1971, De 1974, Philpotts 1978b, 1979). The author has found that the glassy residues of many andesites exhibit similar evidence of silicate liquid immiscibility, and that the immiscible glasses have compositions similar to those of quartz mangerite and jotunite.

Analyses of pairs of glasses and coexisting crystalline phases have been obtained for sam-

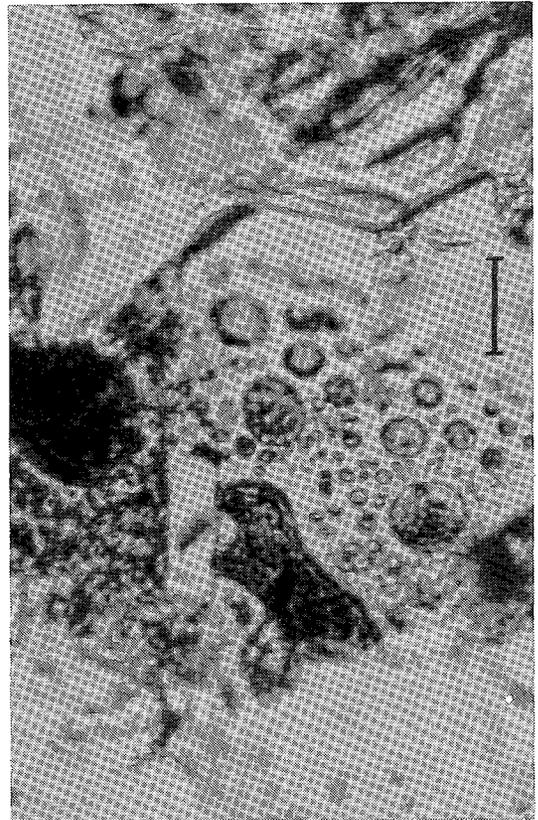


FIG. 3. Immiscible globules of iron-rich silicate glass in silica-rich glass in a patch of mesostasis between plagioclase and pyroxene crystals in an andesite from Nisi Yama, Japan. Scale bar is 10 μ m.

TABLE 1. COMPARISON OF COMPOSITIONS OF IMMISCIBLE GLASSES IN TWO ANDESITES WITH JOTUNITE AND QUARTZ MANGERITE, AS WHOLE ROCKS AND WITH PLAGIOCLASE SUBTRACTED

	Usu Volcano, Japan		Steinerne Mann, Germany		Jotunite	Grenville Twp. Quebec		
	Fe-rich	Si-rich	Fe-rich	Si-rich		Q Mangerite	Jotunite -33% An ₃₅	Q Mangerite -20% An ₃₅
	1	2	3	4	5	6	7	8
SiO ₂	44.8	74.1	42.2	71.1	48.0	68.6	43.5	71.4
TiO ₂	4.8	0.7	3.5	1.4	3.3	1.0	4.9	1.2
Al ₂ O ₃	3.5	10.6	2.9	13.6	10.9	13.1	4.0	10.4
Fe ₂ O ₃					6.2	1.0	9.3	1.2
FeO	28.0	3.0	21.2	3.0	10.7	3.6	16.0	4.5
MnO	0.6	0.0	0.4	0.0	0.1	0.1	0.1	0.1
MgO	0.0	0.0	8.3	1.3	3.7	0.7	5.5	0.9
CaO	10.8	0.7	12.4	2.5	9.1	2.8	10.2	1.8
Na ₂ O	0.7	1.5	0.9	2.8	2.2	3.1	0.5	2.5
K ₂ O	1.8	5.4	0.3	1.0	2.6	5.4	2.7	6.0
P ₂ O ₅	2.3	0.0	5.0	0.0	2.5	0.3	3.7	0.4
Total	97.3	96.0	97.1	96.7	99.3	99.7	100.4	100.4

ples of andesite from Steinerne Mann, Germany, and the Usu and Osima volcanoes, Japan. These samples all consist of large plagioclase crystals of andesine to labradorite composition with smaller crystals of augite and pigeonite (or hypersthene), between which occur pale brown glassy residues containing globules of dark brown, iron-rich glass (Fig. 3). Electron-probe analyses of glasses in the samples from the Usu volcano and Steinerne Mann are given in Table 1 as examples of conjugate liquids formed from the splitting of liquid residues in these rocks.

The conjugate liquids have compositions corresponding approximately to iron-rich calcium pyroxene and granite. Titanium, manganese, magnesium, calcium and phosphorus all partition strongly into the iron-rich liquid, whereas aluminum and the alkalis partition into the silica-rich granitic liquid. The granitic liquids contain between 70 and 74% silica and the calcium, sodium and potassium proportions vary between the two extremes given in columns 2 and 4 of Table 1. Whereas this immiscibility is found mostly in iron-enriched residues, it can occur in less fractionated liquids containing considerable magnesium, as in the German andesite.

Analyses of a jotunite and quartz mangerite from Grenville Township, Quebec (columns 5 and 6, Table 1), are included for comparison with these natural immiscible liquid pairs, though the similarities may not be readily apparent. For example, the jotunite contains more silica, alumina and alkalis than the iron-rich glasses in the andesites, and the quartz mangerite contains slightly less silica than the silica-rich glasses. These two rocks most likely do not correspond exactly to liquids, however, for they are distinctly porphyritic, containing phenocrysts (and

megacrysts) of antiperthitic andesine. By removal of antiperthitic plagioclase of the composition typically found in these rocks (Phillipotts 1966, Table 1), compositions are obtained that correspond closely with those of the immiscible glasses in andesites, as is shown by columns 7 and 8 in Table 1. Jotunite and quartz mangerite are, therefore, assumed to have compositions that are comparable to naturally occurring immiscible liquids with admixtures of plagioclase phenocrysts.

The similarities in these compositions are brought out by plotting the analyses in the triangular diagram FeO + Fe₂O₃ + MnO + TiO₂ + CaO + P₂O₅ - MgO + Al₂O₃ + Na₂O + K₂O - SiO₂ (Fig. 4). This diagram, which is similar to that used by Weiblen & Roedder (1973) to plot lunar immiscible liquids, is particularly useful in that comparisons can be made between rock compositions and the low-temperature immiscibility field in the system fayalite-leucite-silica (Roedder 1951). The particular diagram used here, however, differs from that of Weiblen and Roedder in one important respect: MgO is plotted with alumina and the alkalis, rather than with the other divalent oxides. With this particular grouping, magnesium-rich compositions that do not develop immiscibility, owing to the increased liquidus temperatures of the ferromagnesian minerals, plot separately from the more iron-rich ones that do.

Freestone (1978) has demonstrated that the immiscibility field in the system fayalite-leucite-silica is significantly enlarged by the addition of small amounts of titanium and phosphorus. The field resulting from the addition of 3 wt. % TiO₂ and 1 wt. % P₂O₅ is included in Figure 4 for comparison, as these compositions approxi-

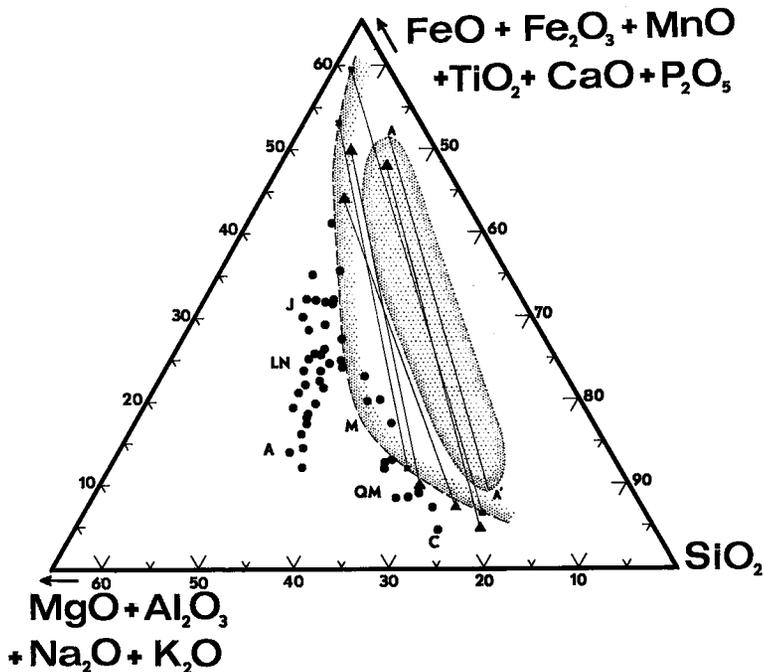


FIG. 4. Weight % plot of immiscible liquids in andesite (this paper, triangles), in the system fayalite-leucite-silica (A-A', Roedder 1951) and in the same system but with 3 wt. % TiO_2 and 1 wt. % P_2O_5 added (squares, Freestone 1978). Also shown are rocks of typical anorthositic complexes (circles), including anorthosite (A), leuconorite (LN), jotunite (J), mangerite (M), quartz mangerite (QM) and charnockite (C). See text for locations. The boundaries of the immiscibility field in the system fayalite-leucite-silica (oval stippled area) and in the same system with TiO_2 and P_2O_5 added (Freestone 1978, larger stippled area) are also shown.

mate more closely those of many of the rocks associated with anorthosite complexes than do those compositions in the simple system.

Analyses of the immiscible glasses in the andesites are indicated in Figure 4 as triangles. Whereas the silica-rich fractions plot close to the boundary of the immiscibility field in the titanium- and phosphorus-spiked system,

the iron-rich glasses are less enriched in ferromagnesian constituents than are the synthetic iron-rich glasses, although the tielines between conjugate pairs are essentially parallel. The presence of calcium and sodium in the natural glasses may be responsible for these differences, but so, too, could a lack of equilibrium in the rapidly cooled andesites. The plagioclase

TABLE 2. COMPOSITIONS OF PLAGIOCLASE COEXISTING WITH IMMISCIBLE GLASSES IN BASALTS AND ANDESITES

Rock Type	Sample No.	Locality	Mol. %		
			An	Ab	Or
Hypersthene Andesite	1445	Steinerne Mann, Nahe Valley, Germany	63.2	34.1	2.7
Fe-rich Basalt	79869	Nisi-yama volcano, Izu Islands, Japan	60.2	39.8	0.0
Olivine Basalt	67733	McGregor Point, W. Maui, Hawaii	59.3	39.2	1.5
Basalt	79856	Osima volcano, Izu Islands, Japan	58.0	37.9	4.1
Basalt	65301	Southbury, Connecticut, U.S.A.	55.5	43.2	1.3
Andesitic Basalt	11712	Eerie Port, Great Cumbrae, Scotland	50.8	47.0	2.2
Basalt	57363	1859 lava, Mauna Loa, Hawaii	48.6	50.3	1.1
Tholeiite	67668	Nanakuli Valley, Oahu, Hawaii	46.5	51.8	1.7
Basalt	84315	Great Thjorslava, Thjorsarbru Bridge, S. Iceland	41.8	56.3	1.9
Basalt	54204	1947 lava, Hekla, Iceland	40.9	57.4	1.7
Olivine Basalt	75612	Robertson Island, Graham Land, Antarctica	39.3	57.5	3.2
Andesite	102001	Usu volcano, Hokkaido, Japan	37.8	57.2	5.0

*Sample numbers refer to Cambridge University collections

that coexists with these liquids has a composition typically found in massif-type anorthosites. Table 2 lists electron-probe analyses of plagioclase in both andesitic and basaltic rocks containing immiscible glasses. Clearly, plagioclase has an intermediate composition at the stage of crystallization where immiscibility sets in.

Quartz mangerites (QM in Fig. 4) and charnockites (C) plot along the silica-rich side of the immiscibility field in the titanium- and phosphorus-bearing synthetic system, whereas the jotunitites (J) plot along the iron-rich side. If the jotunitites do represent mixtures of liquid and plagioclase phenocrysts (plagioclase plots near A in Fig. 4), their liquid fractions would plot at more ferromagnesian compositions, possibly approaching those of the iron-rich immiscible liquids in the system fayalite-leucite-silica or in andesites. If quartz mangerites contain plagioclase phenocrysts, their liquid fractions, too, would plot farther from A in Figure 4. Though the amounts of plagioclase phenocrysts in both rock types are uncertain, Figure 4 reveals that variable amounts of phenocrysts would simply result in the plotted positions moving along the boundaries of the immiscibility field rather than into or away from it. Quartz mangerites and jotunitites therefore have compositions that appear to correspond closely with silica-rich and iron-rich immiscible liquids, respectively, from both synthetic systems and natural rocks.

Analyses of all rock types associated with anorthosite complexes form an interesting forked trend in the plot of Figure 4, with branches following both sides of the immiscibility field. Rocks from the Morin series of southern Quebec (Papezik 1965, Philpotts 1966, Schrijver 1975) and from the Nain area of Labrador (Wheeler 1968, Deuring 1977) are plotted in Figure 4 as typical examples of rocks of anorthosite complexes. Pure anorthosites (A) plot well away from the immiscibility field, but with an increase in pyroxene content and gradation to leuconorite (LN) the rocks trend towards the immiscibility field, at which point the jotunitites (J) follow the iron-rich side of the immiscibility field and the mangerites (M), quartz mangerites (QM) and charnockites (C) follow the silica-rich side. Such a trend is similar to that followed by the Skaergaard magma which, during its final stages of fractionation, is thought to have split into immiscible fractions, the iron-rich one having given rise to the ferrodiorites, and the silica-rich one, to the granophyres (McBirney 1975).

The trend in Figure 4 suggests that rocks of an anorthosite complex are formed from a

fractionating magma that, upon crystallizing plagioclase and pyroxene, encounters an immiscibility field and splits into iron-rich and silica-rich fractions. Because of their density differences, these fractions separate from each other prior to complete solidification. The stage of fractionation at which this unmixing first occurs cannot be determined from Figure 4 because of the uncertainty in the correlation of rock analyses with magma compositions. Leuconorites, the earliest crystallizing rocks to plot up against the immiscibility field, are mostly plagioclase cumulates; thus their analyses represent a mixture of plagioclase and a liquid that is more iron-rich than the whole-rock analysis. This liquid could well lie on the boundary of the immiscibility field, even when the whole-rock analysis falls well away from it. Therefore, it is possible only to speculate from these data that the magma may reach the immiscibility field at some stage during the crystallization of leuconorites.

EXPERIMENTAL EVIDENCE

To investigate the possible existence of a miscibility gap between magmas of jotunitic and quartz mangeritic compositions, experiments were performed on a melt prepared from a mixture of equal weights of the jotunitite and quartz mangerite of Table 1. The starting material was a homogeneous glass formed by the repeated alternate crushing and fusion of the mixture at 1150°C under an oxygen fugacity controlled by the Ni-NiO buffer. All experiments were performed in evacuated silica glass capsules, with charges that weighed approximately 0.02 g, suspended on platinum wire loops immediately above the Ni-NiO buffer. The platinum loops were reused in subsequent experiments in order to saturate the wire with iron and minimize the loss of this element from the experimental charges. The wire-loop method does, however, result in considerable loss of alkalis, in particular sodium, a problem that is discussed below. The charges (plus buffer) were less than 1 cm in length, and were positioned in the furnace at the middle of a 4-cm-long section over which the temperature gradient varied by less than 2°C. Temperatures of the experiments were attained by cooling the charges at a rate of ¼° per hour, using a Data Track programmable temperature controller. This slow cooling resulted in the formation of small numbers of nuclei, which greatly facilitated phase identification. Liquidus temperatures were obtained by first lowering the temperature to the point of crystal

TABLE 3. EXPERIMENTAL RUN CONDITIONS AND PRODUCTS

Temp. °C	Duration hrs	-log f _{O₂}	Phases	Plag. % An	Pyroxene		
					Ca	Mg	Fe
1055	60	9.4	G1				
1050	65	9.5	Plag G1				
1035	45	9.7	Plag Aug G1				
1025	146	9.8	Plag Aug Mt G1 (+ minor 2nd G1)	52.3			
1020	144	9.9	Plag Aug Mt G1 1 G1 2		48.1	36.1	15.8
1015	189	10.0	Plag Aug Mt G1 1 G1 2				
1012	190	10.0	Plag Aug Mt G1 1 G1 2	54.3 - 50.9	41.9	38.2	19.9 (core)
1010	110	10.1	Plag Aug. Mt G1 1 G1 2		46.2	33.8	20.0 (rim)
1008	97	10.1	Plag Aug Mt G1 1 G1 2				
1006	72	10.1	Plag Aug Mt G1 1 G1 2	54.1 - 51.0	43.9	31.2	24.9
1003	164	10.2	Plag Aug Mt Ap G1 1 G1 2	53.1 - 51.4	40.6	33.0	26.4
995	290	10.3	Plag Aug Pig Mt Ap G1 1 G1 2	53.2 - 49.2	39.7	36.8	23.6
					10.6	53.3	36.1

Phases identified include: G1-single homogeneous glass; G1 1 and G1 2 - two immiscible glasses; Plag - plagioclase; Aug - augite; Mt - magnetite; Ap - apatite; Pig - pigeonite

TABLE 4. COMPOSITIONS OF GLASSES PRODUCED IN EXPERIMENTS

	Starting Glass	1050°C		1025°C		1012°C		1006°C		1003°C		995°C	
		1 Glass	Si-rich	Fe-rich	Si-rich	Si-rich	Fe-rich	Si-rich	Fe-rich	Si-rich	Fe-rich	Si-rich	
SiO ₂	61.31	63.56	64.49	43.48	67.39	69.86	41.50	72.24	39.09	73.90			
TiO ₂	0.86	0.77	0.53	2.43	0.79	0.61	2.61	0.62	3.68	0.81			
Al ₂ O ₃	13.35	13.37	12.38	7.94	12.95	11.86	7.74	11.76	7.50	12.19			
FeO ^t	10.31	10.43	10.39	22.78	8.09	7.24	22.11	6.20	21.13	5.08			
MnO	0.11	0.08	0.00	0.38	0.05	0.00	0.20	0.00	0.46	0.06			
MgO	0.81	1.04	0.90	2.80	0.79	0.69	4.02	0.50	4.83	0.33			
CaO	6.72	6.05	6.57	12.20	4.12	4.01	13.37	3.41	13.95	2.61			
Na ₂ O	1.90	1.43	1.43	0.66	1.97	1.73	0.60	1.60	0.59	1.48			
K ₂ O	3.54	2.19	2.14	0.95	2.84	2.99	0.90	2.82	0.37	2.85			
P ₂ O ₅	0.94	1.08	1.17	6.43	1.00	1.02	6.53	0.77	7.69	0.52			
ZrO ₂	0.00	0.00	0.00	0.22	0.00	0.00	0.40	0.09	0.71	0.07			

formation and then raising it to the desired temperature. Thermocouples were calibrated periodically against the melting point of gold, and the temperature gradients in the furnace were measured regularly so that the positioning of the samples could be optimized. Typically, the experiments lasted approximately one week; temperatures are considered accurate to $\pm 1^\circ\text{C}$. Though the silica glass capsules collapsed slightly during the experiments, their residual strength at the temperatures of the experiment probably resulted in the total pressure within the capsule being somewhat less than one atmosphere. The experimental results are listed in Table 3.

Preparation of the starting glass from the rock mixture resulted in a 30% loss of sodium and a 12% loss of potassium. The composition of the resulting glass is given in the first column of Table 4. Further loss of alkalis occurred during the experiments, to the extent that all of the experimental glasses contain normative corundum. But the loss of alkalis is believed to have occurred slowly at the lower temperatures of the experiments, and only became significant because of the long durations used to coarsen im-

miscible globules, where present. The crystalline phases, which form in large part during the first few hours of each run, do not reflect the peraluminous nature of the liquids; that is, the plagioclase does not become enriched in anorthite, and calcium-rich pyroxene is accompanied by pigeonite in only the lowest temperature experiment. The growth of crystalline phases is, therefore, considered to have occurred prior to further substantial alkali loss.

Plagioclase is the first crystalline phase on the liquidus at 1050°C, and by 1035°C it is joined by augite. At 1025°C, in addition to magnetite, a second liquid makes its appearance, forming small, dark brown immiscible spheres in a pale brown glass. These globules are, unfortunately, too small and too few to analyze by electron probe, but the composition of the main glass (Table 4) is taken as one boundary of the immiscibility field for this bulk composition and temperature. Further cooling results in the rapid development of large numbers of immiscible globules, so many, in fact, that each is too small to analyze. Thus it is necessary to hold charges at temperature for considerable

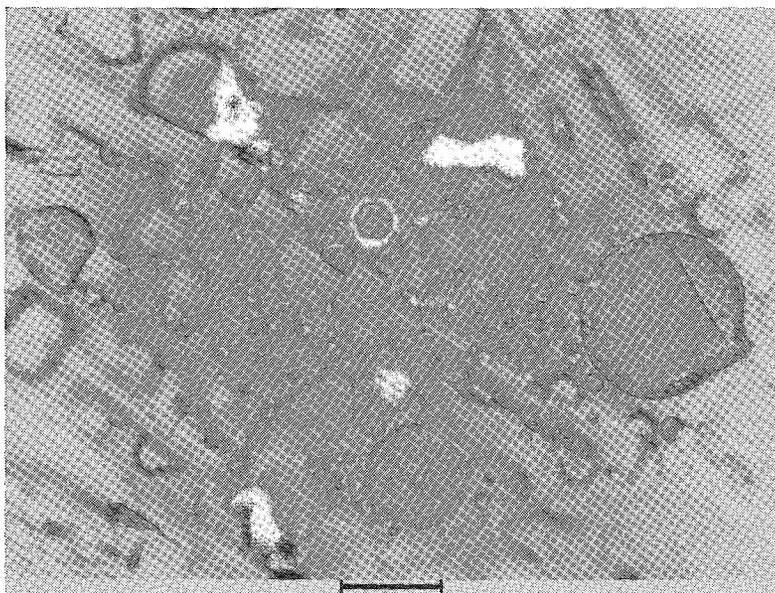


FIG. 5. Immiscible globules of iron-rich liquid in silica-rich liquid in contact with plagioclase, clinopyroxene and magnetite formed at 995°C under an oxygen fugacity buffered by nickel – nickel oxide. The starting material was a homogeneous glass formed from a fused mixture of jotunite and quartz mangerite (Table 4). Note that the iron-rich globules contain extremely small quench globules of silica-rich liquid. Scale bar is 10 μm .

periods of time in order to effect coalescence and coarsening of the globules. It is during this stage that alkalis are believed to escape, particularly from the pale brown silica-rich glass. The crystalline phases and the two liquids, however, form in the first few hours of an experiment, before much loss of alkalis can have occurred. The phase identification and temperatures are therefore considered reliable for this particular bulk composition, even though analyses of the final glasses may be in error owing to loss of alkalis. Continued cooling brings about further crystallization of plagioclase, augite and magnetite, and silica-rich glass becomes essentially colorless owing to decreasing iron content with falling temperature. At 1003°C apatite is present amongst the run products, and at 995°C, the lowest temperature investigated, pigeonite joins the augite already formed at higher temperatures. At 995°C two liquids are still present and in contact with all of the crystalline phases (Fig. 5).

The experimental products resulting from the programmed cooling are not sufficiently evenly textured to allow accurate estimations to be made of the proportion of phases in each exper-

iment based on the small amount of sample included in the polished thin section taken from each charge. Certain generalizations can, however, be made. Plagioclase, which is the first phase to crystallize on cooling, is more abundant than pyroxene in all of the experiments. Also, in those experiments where two liquids are present, the iron-rich liquid is less abundant than the silica-rich one. In Figure 6, a very approximate bulk-liquid line of descent is indicated joining the starting composition (*X*) with the estimated bulk composition of the immiscible liquids in the 995°C experiment. Also plotted in this diagram is the range of compositions of calcium-rich pyroxenes and plagioclases formed in the experiments.

The compositions of plagioclase and pyroxene in those experiments where crystals are large enough for electron-probe analysis are given in Table 3. No significant difference in plagioclase compositions can be detected between each of the experiments; anorthite contents are between 54 and 49%. The pyroxene, although also limited in its compositional range, does become more iron-rich with falling temperature, varying from $\text{Ca}_{48.1}\text{Mg}_{38.1}\text{Fe}_{15.8}$ at 1020°C to

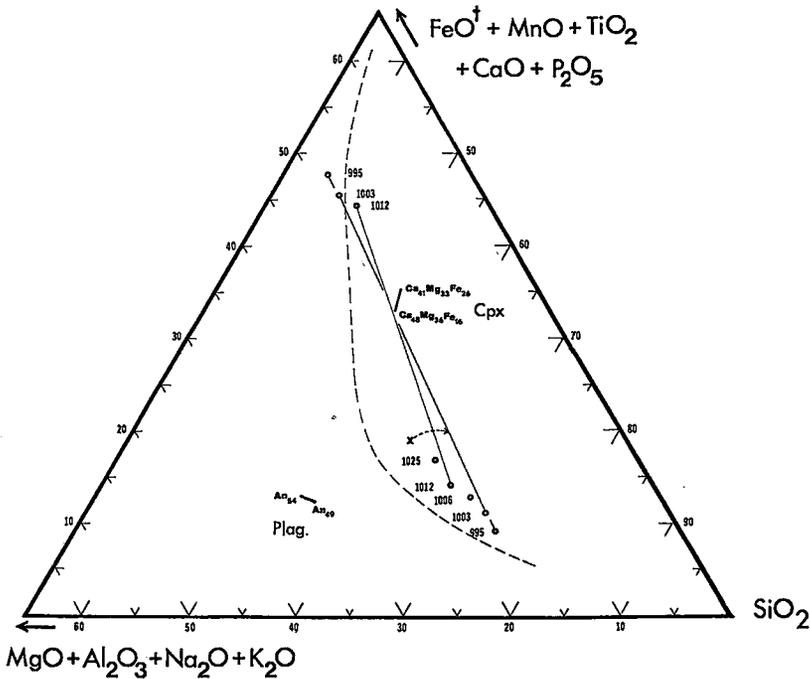


FIG. 6. Weight % plot of compositions of conjugate liquids formed in experiments on a mixture of jotunite and quartz mangerite. Temperatures of experiments are indicated by numbers beside points. The expanded immiscibility field in the titanium- and phosphorus-spiked fayalite-leucite-silica system (Freestone 1978) is included as a dashed line for comparison with Figure 4.

$\text{Ca}_{40.6}\text{Mg}_{33.0}\text{Fe}_{26.3}$ at 1003°C . The pigeonite present in the run at 995°C has the composition $\text{Ca}_{10.6}\text{Mg}_{53.3}\text{Fe}_{38.1}$.

At 1025°C , where the immiscible liquids are first developed, less than 5% of the bulk composition has crystallized. Thus, almost no fractionation of the starting liquid is necessary to develop immiscibility. This is evident from the similarities in the analyses of the glasses in the experiments at 1050 and 1025°C (Table 4).

With the particular starting composition used in these experiments, the immiscibility field is first encountered on its silica-rich side. Small globules of iron-rich melt nucleate in the more viscous silica-rich melt and commonly on the surface of plagioclase crystals. Aluminum, sodium and potassium partition into the silica-rich fraction, whereas the other elements strongly partition into the iron-rich fraction; with falling temperature the compositional differences between the two liquids become greater, as indicated in Table 4 and Figure 6. Liquids are produced that are compositionally similar to the jotunite and quartz mangerite of Table 1.

The tielines between coexisting liquids are approximately parallel to those between pairs of immiscible liquids in basalts, andesites and the system fayalite-leucite-silica (Fig. 4). The boundary of the immiscibility field in the titanium- and phosphorus-bearing synthetic system (Freestone 1978) is included in Figure 6 for comparison. The apparent rotation of the tielines with falling temperature may be real, but could result from the loss of alkalis. Prior to this loss, all the silica-rich liquids (also alkali-rich) would have plotted at compositions that were more alkali-rich than those presently shown in Figure 6. Moreover, it is likely that the lower temperature experiments, which are also of the longest duration, would be the most affected.

The systematic change in the composition of the immiscible liquids, with decreasing temperature is brought out by examining the variation in the weight fraction of $\text{SiO}_2/\text{SiO}_2 + \text{FeO} + \text{MnO} + \text{TiO}_2 + \text{CaO} + \text{P}_2\text{O}_5$ (Fig. 7). The composition of each liquid, based on ten to fifteen analyses, is plotted with error bars (\pm one standard deviation). Clearly the compositions

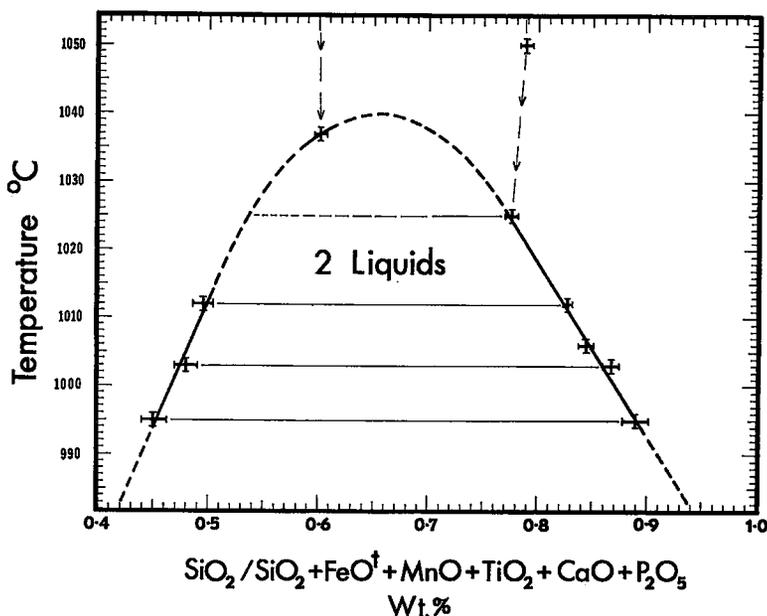


Fig. 7. Field of liquid immiscibility found in the experiments projected in terms of the weight ratio of $\text{SiO}_2/\text{SiO}_2 + \text{FeO}^\dagger + \text{MnO} + \text{TiO}_2 + \text{CaO} + \text{P}_2\text{O}_5$ and temperature. Uncertainty bars on plotted compositions represent \pm one standard deviation based on multiple analyses, and $\pm 1^\circ\text{C}$.

of the immiscible liquids are strongly dependent on temperature. On the silica-rich side of the immiscibility field, where there are more data points, this dependence is almost linear; the equation of best fit is temperature (in $^\circ\text{C}$) = $1224.8 - 258 \times \text{wt. fraction SiO}_2$, with a coefficient of determination (r^2) of 0.990.

A few experiments were done using a glass prepared from the jotunite itself. This composition, on cooling, develops globules of immiscible liquid at 1037°C ; these continue to form at lower temperatures, but none could be grown large enough for analytical purposes. The 1037°C temperature does, however, provide a point in Figure 7 that is useful in delineating the immiscibility field, which appears to have a maximum temperature of approximately 1040°C .

The experiments indicate that a melt having a composition intermediate between that of jotunite and quartz mangerite will, with essentially no crystal fractionation, enter an immiscibility field on cooling to temperatures below 1040°C (at least under the conditions of the experiments). Furthermore, the compositional similarity between the immiscible liquids in the experiments and the jotunite and quartz mangerite, and the spatial relation between these rock

types in the field, strongly imply that liquid immiscibility played a role in the formation of these rocks. In addition, the plagioclase and pyroxene formed in equilibrium with the immiscible liquids in the experiments are compositionally similar to those typically found in anorthosites and leuconorites.

If the compositions of jotunite and quartz mangerite are determined by immiscibility, then the formation of sizeable bodies of these rocks must involve large-scale separation and segregation of the two liquids; however, these liquids would continue to exsolve small amounts of the other liquid as cooling progressed because of the slopes on the limbs of the immiscibility field (Fig. 7). When sufficient numbers of crystals had formed, the late-separating globules would be unable to escape from their surroundings, and would thus have to crystallize in place along with the minerals crystallizing from the major immiscible phase. For example, if quartz mangerite crystallizes from the silica-rich liquid, late-separating globules of the iron-rich liquid would most likely crystallize to form ferromagnesian minerals amongst the more abundant quartz and feldspar. Such a quartz mangerite might be expected, when heated in the laboratory, to generate small amounts of iron-rich

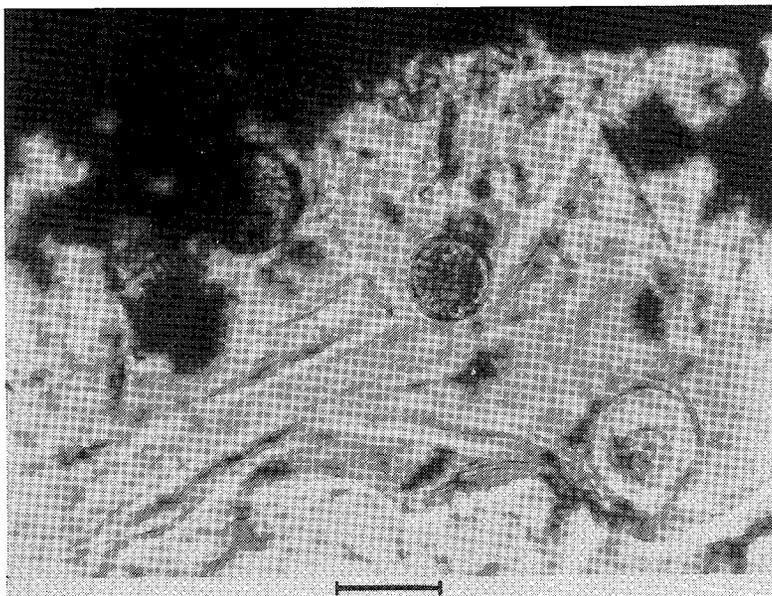


FIG. 8 Immiscible globules of iron-rich liquid (containing quench globules) in a silica-rich liquid formed by partial melting of quartz mangerite at 1037°C with the oxygen fugacity buffered by nickel - nickel oxide. Opaque above is magnetite, with apatite in lower centre, and partially melted iron-rich clinopyroxene in lower right. Scale bar is 10 μm .

immiscible liquid on first melting. This, of course, assumes that differences in pressure between the conditions under which the rock formed and those in the experiments do not significantly change the immiscibility field.

To test this, uncrushed samples of the quartz mangerite of Table 1 were suspended in platinum wire coils in evacuated silica-glass capsules and buffered with Ni-NiO. Melting experiments were done, each for one week, at 1010, 1034 and 1079°C. No attempt was made to achieve equilibrium in these runs. To do so, in a reasonable time, would have required crushing the rock to a fine grain-size; however it was decided to preserve the textural integrity of the rock so that features developed during the beginning of melting could be seen clearly.

In the sample run at 1010°C, a narrow zone of clear glass separates all quartz and feldspar grains, but no evidence of melting was found around any of the ferromagnesian minerals (ferroaugite, inverted pigeonite and ilmenite). At 1034°C, however, clear glass separates all major minerals of the rock, and where pyroxene, ilmenite and apatite are juxtaposed, this glass contains sphere-like globules of a dark brown immiscible glass (Fig. 8). The central regions of

these globules are crowded with extremely fine beads of the clear glass, which were most likely formed on quenching. In the 1079°C experiment, considerable glass is present, which ranges gradually in color from clear to dark brown, depending on the associated grains. No evidence of liquid immiscibility was found at this temperature, but when this sample was reheated to 1010°C, abundant small, dark brown globules formed in the iron-rich parts of the glass.

These experiments demonstrate that quartz mangerite, by itself, can generate a small amount of iron-rich immiscible liquid on first melting; this is to be expected if this rock formed from a silica-rich liquid in equilibrium with a conjugate iron-rich liquid. Little significance can be attached to the temperatures in the experiments, as in each case the melting process did not go to completion. The temperatures are, however, consistent with the results from the previous experiments.

TEXTURAL EVIDENCE FOR IMMISCIBILITY

The evidence from the melting experiments on quartz mangerite suggests that textures indicative of immiscibility might have developed

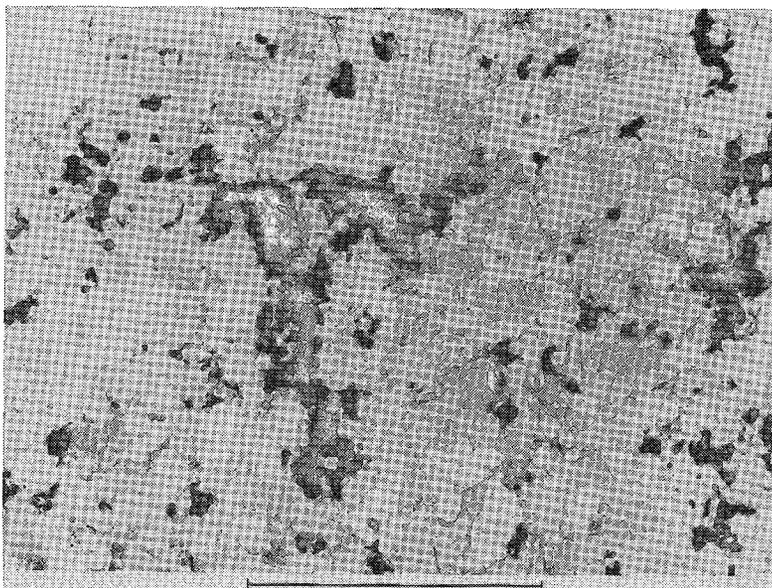


FIG. 9. Typical texture of undeformed quartz mangerite showing clustered nature of ferromagnesian minerals (inverted pigeonite, iron-rich augite, magnetite and ilmenite) between even-grained aggregates of perthite and quartz with minor plagioclase. Scale bar is 1 cm.

during the original crystallization of such rocks. Unfortunately, the typically deformed nature of these rocks reduces the chances of finding such evidence, but in those few cases where primary features are preserved, quartz mangerites do exhibit a texture that may indeed result from immiscibility.

The most prominent feature of this texture is the occurrence of quartz and feldspar grains in clusters that are separated from other clusters by stringer-like aggregates of ferromagnesian minerals (Fig. 9). Perhaps of greater significance, however, is the distribution of some of the other minerals within the rock, particularly that of apatite, which shows a close association with the ferromagnesian minerals.

The quartzofeldspathic parts of the rock are interpreted as having formed from the abundant silica-rich liquid, whereas the ferromagnesian aggregates would have crystallized from the minor immiscible iron-rich fraction that probably continued separating from the silica-rich liquid as it cooled. The distributions of the other minerals within the rock can be used to support this interpretation, as will be discussed below.

As an aid in the study of these mineral associations, maps were prepared of the grain distributions of each of the minerals within an entire

thin section of the quartz mangerite that was used in the experiments (Fig. 10, A to F). These maps, used in conjunction with a computerized image analyzer (Quantimet), were also employed to determine the accurate mode of the rock: 49.0 volume % perthitic alkali feldspar, 24.3% quartz, 11.8% plagioclase, 11.0% ferromagnesian minerals (ferroaugite, inverted pigeonite and ilmenite), 2.4% apatite and 1.5% zircon.

In interpreting the quartzofeldspathic clusters as having crystallized from the immiscible silica-rich liquid, it is important to emphasize that each cluster consists of a large number of separate grains of feldspar (Fig. 10A) and quartz (Fig. 10B), and that the proportions of these minerals remain the same throughout each cluster. This is consistent with the present interpretation and rules out the possibility that they represent recrystallized phenocrysts of feldspar or quartz. The ferromagnesian aggregates similarly consist of a variety of minerals whose proportions are essentially constant from aggregate to aggregate, as would be expected if they had formed from a homogeneous, immiscible iron-rich liquid.

Plagioclase (Fig. 10C) is the only mineral that may form phenocrysts in this section. Al-

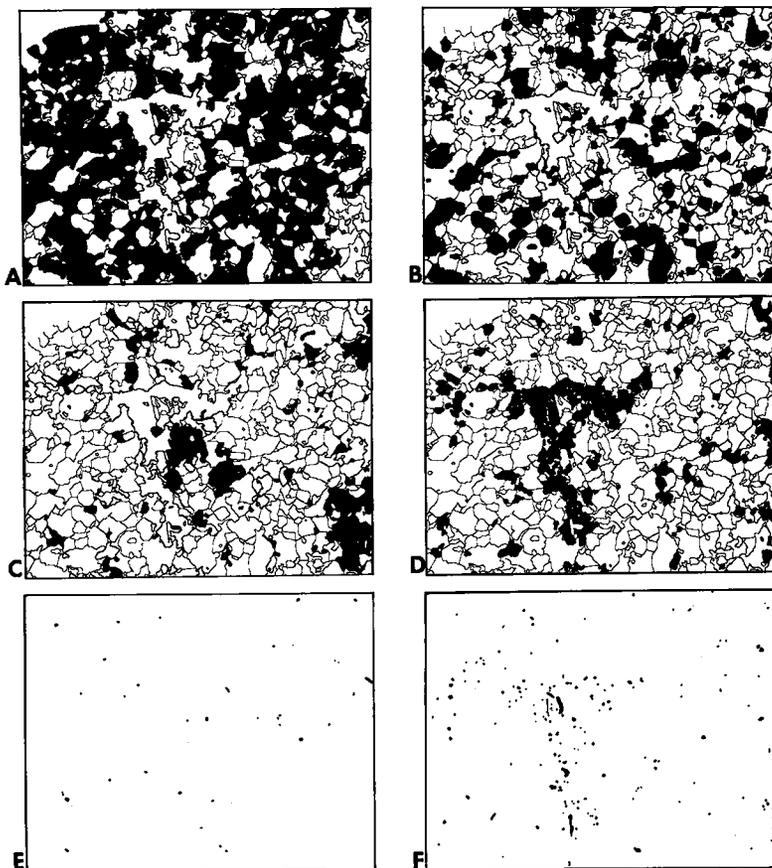


FIG. 10. Distributions of constituent grains in a thin section of Figure 9: A perthite, B quartz, C plagioclase, D ferromagnesian minerals, E zircon, F apatite.

though much of the plagioclase occurs as very small grains distributed throughout the quartzofeldspathic clusters, a few larger grains occur in contact with ferromagnesian aggregates. Also, plagioclase megacrysts measuring several centimetres in diameter do occur in the hand specimen from which the thin section was prepared, but none of these is intersected in this particular section.

The distribution of apatite grains within the rock is particularly important, because analyses of coexisting iron-rich and silica-rich immiscible liquids in synthetic systems and natural rocks (Roedder & Weiblen 1971, Philpotts 1976, Watson 1976) indicate that phosphorus is strongly fractionated into the iron-rich liquid. Thus, if immiscible liquids were present during the final stages of solidification of the quartz mangerite, any remaining phosphorus would

have preferentially entered the iron-rich liquid, which, after it had crystallized to form the ferromagnesian aggregates, would be expected to contain an abundance of apatite.

Comparison of the distributions of ferromagnesian mineral (Fig. 10D) and apatite (Fig. 10F) grains indicates that almost every grain of apatite occurs within, or is in contact with, a ferromagnesian aggregate. Moreover, within these aggregates, apatite exhibits no preference for one ferromagnesian mineral over another, ruling out the possibility that the apatite distribution is due to some epitaxial relation. The few grains of apatite in the quartzofeldspathic clusters form very fine needles, in contrast to the stubby prismatic form it has in the ferromagnesian aggregates. Thus, apatite is an extremely minor constituent of the quartzofeldspathic parts of the rock, whereas in the ferromagnesian fraction it

constitutes 16%. This distribution, then, is consistent with the strong partitioning of phosphorus between immiscible silicate liquids.

The distribution of zircon grains within the quartz mangerite is also of interest because, according to the experimental results of Watson (1976) and those reported in this paper, zirconium, like phosphorus, is strongly partitioned into the iron-rich immiscible liquid. There are, however, far fewer grains of zircon than of apatite, making it more difficult to determine whether this mineral has a special distribution. On first inspection, the distribution of zircon grains (Fig. 10E) only very slightly resembles that of apatite. Of the 34 zircon grains in the figure, 22 occur within the quartzfeldspathic part and 12 occur within the ferromagnesian aggregates. Considering the modal abundances of the major minerals, this indicates a slight concentration of zircon within the ferromagnesian aggregates, but not nearly as great as would be expected from the two-liquid partition coefficient. This apparent lack of fractionation could be accounted for if zircon were in part a cumulus phase and thus not wholly dependent on the distribution of residual patches of immiscible iron-rich liquid.

In summary, then, the texture of the undeformed quartz mangerite is thought to result at least in part from liquid immiscibility. If cooling of the silica-rich magma from which this rock formed resulted in exsolution of globules of an iron-rich liquid, these could probably have formed on the surface of plagioclase crystals, as is commonly the case in experimental run products and volcanic rocks; the liquids immediately in contact with these crystals are presumably the first to become supersaturated with the iron-rich phase (Philpotts 1978b). This could explain the juxtaposition of large plagioclase crystals (phenocrysts?) and ferromagnesian aggregates (iron-rich liquids) in the quartz mangerite. Once the iron-rich globules were formed, phosphorus in the liquid partitioned strongly into the iron-rich phase with the result that most apatite crystallized in the ferromagnesian aggregates. The silica-rich liquid most likely had a composition close to a quartz-alkali feldspar eutectic which would then have been responsible for producing the even-textured aggregates of these minerals.

THE MODEL FOR THE GENERATION OF MASSIF-TYPE ANORTHOSITE

The composition of the immiscible liquids in many andesites, the experiments on the jotunite-

quartz mangerite mixture and on the melting of quartz mangerite itself, and the uneven mineral distributions in this rock all suggest that jotunite and quartz mangerite formed from immiscible liquids. The experiments further indicate that immiscible liquids with compositions corresponding closely to those of jotunite and quartz mangerite have, as their primary liquidus phase, plagioclase with a composition similar to that found in anorthosite massifs. These facts form the basis for the following model for the genesis of massif-type anorthosites and associated rocks.

The primary magma was probably of andesitic composition, but could initially have been more basic, if later contaminated by partial melts from within the crust. Early crystallizing sodic labradorite or calcic andesine separated from this magma to form relatively pure anorthosite. The plagioclase was soon joined by minor pyroxene and, in some areas, olivine, to form leuconorite and troctolite. Crystallization of these minerals enriched the residual magma in silica, alkalis and iron, which in turn should have brought about progressive changes in the composition of the minerals. Although pyroxenes do exhibit such a change, plagioclase does not. It is at this stage, therefore, that the residual magma is thought to have split into immiscible fractions, with alkalis and alumina preferentially entering the silica-rich liquid and, by so doing, buffering the composition of the plagioclase. This composition could vary from one intrusion to another, depending on the degree of fractionation of the magma at the time of unmixing. The silica-rich liquid, being of low density, floated to the top of the magma chamber. The immiscible iron-rich fraction, being denser, sank and accumulated with the plagioclase, and later crystallized to form the typical interstitial ferromagnesian minerals of the leuconorite. The main constituent of this fraction is pyroxene, which is distinguishable from earlier-crystallized pyroxene in having associated apatite, magnetite and ilmenite, minerals formed from elements that partition strongly into the iron-rich liquid. Further accumulation of this iron-rich liquid gave rise to the jotunite, whereas the overlying silica-rich liquid crystallized to form quartz mangerite.

The proportions of the two liquids are dependent on the composition of the original magma, the degree of contamination by crustal rocks and, as discussed below, the degree of oxidation of the magma. The amount of iron-rich melt that actually forms jotunite is typically a small fraction of the total anorthosite-quartz mangerite association. The amount of

this liquid that crystallizes to form interstitial ferromagnesian minerals in the leuconorite and quartz mangerite is uncertain, although it could be substantial. In areas where there are sufficient accumulations of the iron-rich liquid, fractional crystallization of pyroxene from this melt would give rise to even more iron- and phosphorus-enriched melts that, because of their high density, would intrude downward into the underlying rocks. This, then, could be the origin of the iron-titanium oxide and apatite deposits associated with anorthosites (Philpotts 1967).

The amount of silica-rich liquid produced from the original magma is difficult to gauge from the abundance of rock types and their major-element chemistry, because partial melting of crustal rocks could give rise to granitic melts that do not differ drastically from those produced by immiscibility from a more basic

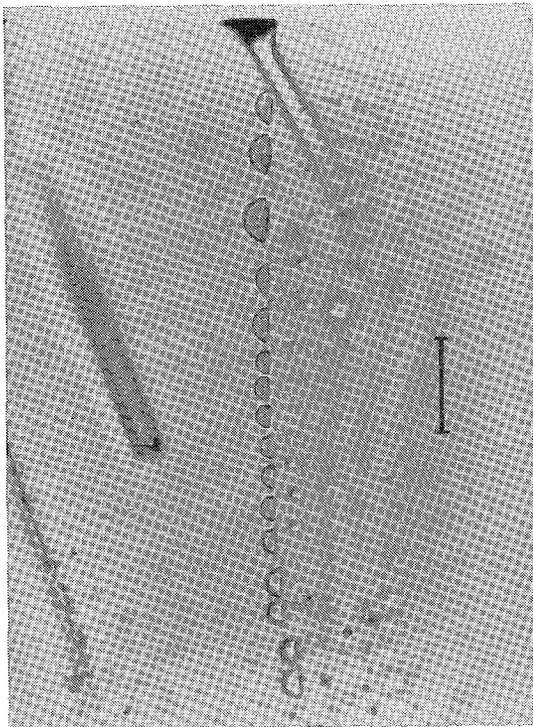


FIG. 11. Silica-rich glass containing immiscible globules of iron-rich liquid that nucleated and grew on the surface of a plagioclase crystal in an experiment at 1020°C. Each globule has caused the plagioclase to grow more rapidly beneath it, thus producing a lobate crystal face. High relief needles are pyroxene. Scale bar is 10 μm .

melt. It is important, in fact, to emphasize that evidence of immiscibility between silica-rich and iron-rich magmas associated with anorthosites (Wiebe 1979) is not necessarily proof of the comagmatic nature of these melts, because silica-rich melts produced by the partial melting of crustal rocks would likely bear an immiscible relation with the iron-rich residues produced from the fractional crystallization of more basic mantle-derived magmas.

The initial aim of the model was to provide an explanation for the restricted compositional range of plagioclase in anorthosites; however, the immiscible liquids that were found in the experiments also provide an explanation for the compositions and distribution of the main rock types associated with anorthosites. It is interesting to consider whether other peculiar features of anorthosite massifs can be explained by the model.

The rather restricted age of anorthosites, which is certainly one of their outstanding features, can be explained by arguing that in only a few instances have magmas been intruded into sufficiently dry rocks to permit the generation of anorthosite. At all other times, the presence of water has prevented the formation of immiscible liquids which, according to this model, are crucial to the development of anorthosites; instead, the typical calc-alkaline suite of rocks may have been developed.

Water can prevent unmixing in a magma by depolymerizing the melt and, more importantly, by oxidizing it. Experiments by the author on the residual liquid of a tholeiitic basalt indicate that immiscibility is extremely sensitive to changes in the oxidation state of the magma. Whereas an increasing ferric/ferrous iron ratio tends to expand the immiscibility field, there comes a stage where it brings about the early crystallization of magnetite, which prevents iron enrichment in the residual melt; this, in turn, prevents the fractionating magma from encountering the immiscibility field.

The coarse grain-size of anorthosites and leuconorites still remains a puzzle, but some interesting results that may have some bearing on this problem were obtained in the experiments relating to the rate of plagioclase growth. Immiscible globules of iron-rich liquid typically form firstly, both in experiments and in many volcanic rocks (Philpotts 1978b), on the surface of plagioclase crystals, presumably because it is the liquid surrounding these crystals that first becomes supersaturated with the components of the iron-rich phase. Thus, once the immiscibility field is reached, the surface of the plagioclase

clase crystals becomes coated with small hemispheres of iron-rich liquid (Fig. 11). Continued cooling brings about further crystallization of the plagioclase, but instead of occurring across the crystal faces, it occurs preferentially beneath the iron-rich hemispheres. The result is the formation of pillars of plagioclase beneath each immiscible globule (Fig. 11).

This feature can be interpreted as resulting from differences in the diffusion rates in the two liquids, those in the iron-rich liquid being much greater than those in the silica-rich liquid. Indeed, if diffusion rates are related to viscosities, the rates in these two melts could differ by a factor of 25,000; this figure is based on viscosities calculated according to the method of Bottinga & Weill (1972). As long as diffusion controls the growth of plagioclase, the immiscible globules on the crystal surfaces will be the sites of most rapid growth, despite the fact that the components necessary for plagioclase growth are concentrated in the silica-rich melt. Each hemisphere, with its ability to rapidly diffuse material, acts as a collection zone extending out into the silica-rich liquid in front of the growing face of the crystal.

It is not suggested that textures such as these would form in anorthosites, but if plagioclase crystals, which have accumulated by sinking, grow in part or entirely in an immiscible iron-rich melt that has also accumulated by sinking, their grain size could be expected to be coarser than if they had grown in a more viscous melt. Even basaltic magma is significantly more viscous than the iron-rich immiscible liquid. For example, at 1150°C a basalt's viscosity is of the order of 10^3 poise, whereas the calculated viscosity of the iron-rich liquid is 10^2 poise. This growth method does not, however, explain the extremely coarse grain-size of pure anorthosite where there is no evidence of any interstitial liquid.

An interesting result can be expected if the amount of immiscible iron-rich liquid that sinks to the bottom of a magma chamber produces a layer of significant thickness on top of earlier accumulated crystals. The calculated density of this melt, according to the method of Bottinga & Weill (1970), is 3.2 g cm^{-3} ; hence this melt is significantly denser than plagioclase. It is likely that any layer of crystal mush containing a large proportion of plagioclase crystals would become gravitationally unstable under such conditions, and diapiric rise of the mush would result. Even in the case in which the underlying material is solid, blocks might rise into the dense liquid if there were means by

which they could break loose. This might, then, be the origin of the common block structure in anorthosites.

Formation of a layer of immiscible iron-rich liquid would certainly prevent any further sinking of plagioclase crystals to the floor of a magma chamber. Crystals that sank through an overlying immiscible silica-rich liquid would accumulate at the interface between the two liquids where, because of the more rapid diffusion rates in the iron-rich melt, further growth would take place predominantly downward into the underlying melt. Such growth might be expected to trap patches of the iron-rich melt, into which plagioclase crystals would project in pegmatitic fashion. Such patches are, in fact, common in anorthosites, and it would be interesting to see if they possess other features that would support the hypothesis.

The test of the model probably lies in careful geochemical studies of anorthosites and associated rocks, for the partitioning of elements between immiscible liquids should produce rock types with minor-element chemistries different from those produced solely by fractional crystallization. The results to date, however, provide a rather confused picture, with different results being obtained for similar rock types in different areas (*e.g.*, Philpotts *et al.* 1966, Green *et al.* 1972, Simmons 1976, Seifert *et al.* 1977, Duchesne *et al.* 1974, Duchesne & Demaiffe 1978, Ashwal 1978, Higgins 1979, Raman & Hewins 1979). Undoubtedly, many factors contribute to this variation, including the use of samples that represent mixtures of cumulus crystals and liquid, and of rocks that have been affected by contamination. Furthermore, difficulties can arise if the element distributions are interpreted in terms of liquid-crystal partitioning only, where actually liquid-liquid partitioning also is involved. Future geochemical studies should focus on the petrography of the analyzed rocks in order to avoid some of these problems.

This model, whether correct or not, should stimulate a fresh examination of anorthosites and associated rocks, and provide a new set of criteria by which to evaluate the old data and collect the new.

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