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ANORTHOSITES AND THEIR ENVIRONMENT

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ABSTRACT

This joint paper, written in honour of Professor Paul Michot, explores differences in interpretation of some well-studied anorthositic terrains which are geologically similar in many respects.

The Adirondack anorthosites and the Nain complex in Labrador are considered anorogenic plutons with long fractionation histories, giving rise to a great variety of associated rock types. It is concluded that anorthosite massifs are essentially anorogenic, and related in space and time to each other and to the rapakivi plutons of Fennoscandia (D. de W.).

The Rogaland complex of southern Norway, at the other hand, is considered a synorogenic pluton, which differentiated from a parental magma to some degree hybridized by crustal material. Here the conclusion is that anorthosites are emplaced at different times in the tectomagmatic cycle, and at various levels in the earth's crust (J. C. D. and J. M.).

A joint conclusion is that the parental magma must have had a monzogabbroic to granodioritic or monzonoritic to quartz-monzonoritic composition.

PRELIMINARY REMARK

This paper was written in honour of Professor Paul Michot who devoted 40 years to the study of anorthosite in southern Norway, and who inspired with his field trips and publications much of the detailed research on anorthosite in other regions of the world.

We wrote this paper with the idea to explore common ground, and to come to joint conclusions, but it has become a study in contrast showing differences in the interpretation of geologically similar terrains. It demonstrates that, though our knowledge of anorthosite massifs has vastly increased, the Anorthosite Problem has yet to be solved in a way that satifies at least most of us.

This will briefly illustrate our differences. The Rogaland complex of southern Norway is considered a synorogenic pluton, which differentiated from a parental magma to some degree hybridized by crustal material. The conclusion is that

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The Adirondack anorthosites and the Nain complex in Labrador, at the other hand, are considered to be anorogenic plutons with long fractionation histories giving rise to a great variety of associated rock types. Here the conclusion is that anorthosite massifs are essentially anorogenic, and related in space and time to each other and to the rapakivi plutons of Fennoscandia.

We also have common ground, viz., the composition of the parental magma should be "monzogabbroic to granodioritic" and "monzonoritic to quartz-monzonoritic." Many students of anorthosite will disagree with that conclusion.

PETROLOGY AND STRUCTURE OF SOME NORTH AMERICAN ANORTHOSITE MASSIFS

D. DE WAARD

Introduction

The author began research on anorthosite in the Adirondack Mountains of New York State, but later changed to the Nain anorthosite complex in Labrador, where the rocks are unaffected by metamorphism and deformation, and much better exposed.

In the Adirondacks the study of anorthosite is hampered by the blurring effect of high-grade metamorphism and intense deformation during the Grenville orogeny. Though the cores of anorthosite bodies behaved rigidly during orogenesis, and show little internal deformation, igneous textures have been affected by metamorphic mineral reactions (de Waard, 1965*a*, 1967*b*). The border zones of the massifs are intensely sheared and recrystallized to granulites and gneisses, obscuring igneous textures and structures. The age of anorthosite formation was determined by Silver (1969) to be 1 130 m.yr. (U-Pb in zircon), whereas Spooner and Fairbairn (1970) found 1 465 m.yr. (Rb-Sr) for the same rocks. The age of the Grenville orogeny and metamorphism in the same area is 1 100-1 070 m.yr. (U-Pb in zircon) determined by Silver (1969).

Also the Nain complex forms part of the belt of anorthosite bodies which extends from Virginia and the Adirondacks to Labrador (fig. 1), and probably beyond to Greenland, Norway, and Finland (Herz, 1969). The Nain complex lies outside the Grenville province, and is unaffected by postmagmatic deformation and metamorphism. The age of the Nain anorthosite is reported to be at least 1 480 m.yr. (K-Ar; Morse, 1964). The anorthosite is intruded in a metamorphic terrain of Kenoran age (2 480 m.yr.; Stockwell, 1968). The Michikamau intrusion southwest of the Nain complex, was dated at 1 400 m.yr. (K-Ar; Emslie, 1964). Stockwell (1964) considers the anorthosite bodies in the belt to be of the same age, intruded in late Paleohelikian time, about 1 400 m.yr. ago.

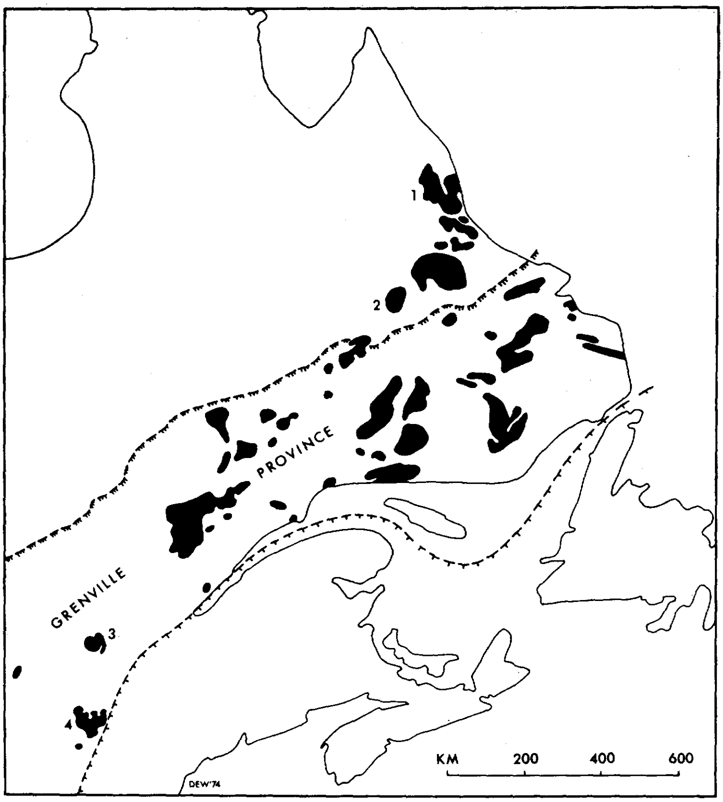

FIG. 1. — *Belt of anorthosite massifs in northeastern North America after King (1969). Massifs discussed in the text: 1, Nain complex; 2, Michikamau intrusion; 3, Morin mass; 4, Marcy massif.*

Rock types

In anorthosite massifs the anorthosite is a monotonous rock at large, but in detail it varies considerably in grain size, fabric, and composition. Map areas of anorthositic rocks thus include a variety of leucocratic plagioclase-pyroxene rocks which locally may also contain quartz or olivine.

The anorthositic rocks are invariably associated with acidic rocks. These have been given different names in the various massifs, such as quartz-syenite series, charnockite series, mangerite series, adamellite group, ferrogranodiorite group, etc. The variety in names denotes, at least to a certain extent, that there are differences in the composition of associated rocks from one massif to the other (de Waard, 1972). Though both the anorthositic rocks and the acidic rocks vary in composition from place to place, there is typically a bimodal frequency distribution of rock compositions, and a relative paucity of rocks of intermediate compositions.

In several anorthosite massifs troctolitic rocks occur as a third major rock group. In the Michikamau intrusion of Labrador (fig. 2) the leucotroctolite group forms the predominant rock type exposed in the intrusion (Emslie, 1970). In areal extent it is followed by anorthositic rocks, and by a ferrogranodiorite group as the least common rock type. In the Nain anorthosite complex (fig. 3) troctolitic rocks are less common. They occur in at least five layered structures which are lopolithic or

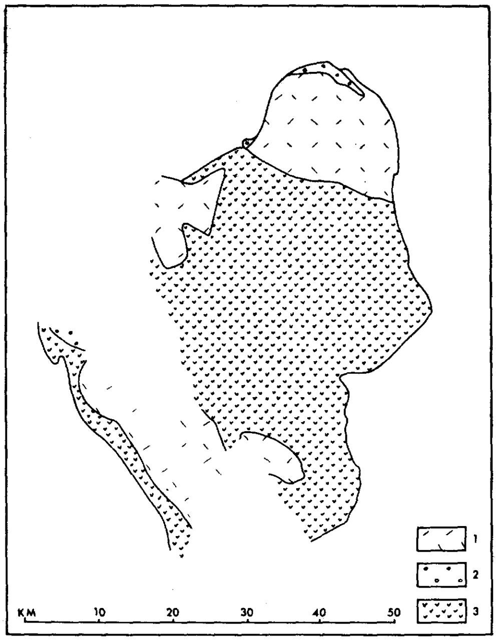

FIG. 2. — *Distribution of rock types in the Michikamau intrusion, Labrador, after Emslie (1970). 1, anorthosite group; 2, ferrogranodiorite group; 3, leucotroctolite group.*

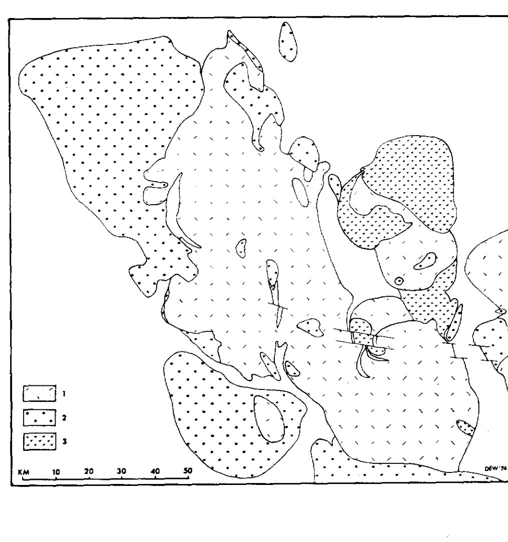

FIG. 3. — *Distribution of rock types in the Nain anorthosite complex, Labrador, after Wheeler (1969) with changes described in the Nain Anorthosite Project Field Reports. 1, anorthositic rocks; 2, adamellitic rocks; 3, troctolitic rocks.*

trough-shaped, and which show intrusive relations against the anorthositic rocks. In the Morin anorthosite massif in Quebec (fig. 4) troctolite occurs in a single, thin sill-like body (Martignole and Schrijver, 1970*a*). No troctolite is known from the Adirondack anorthosite massifs.

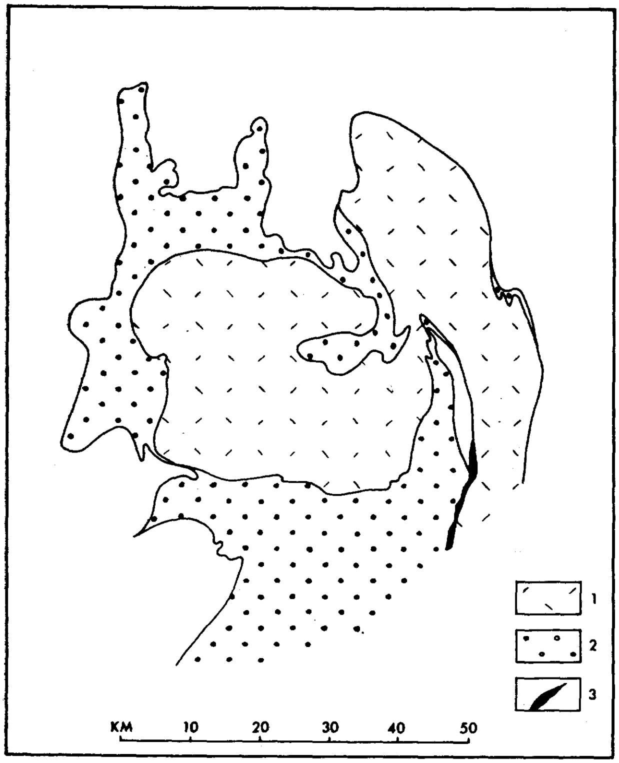

FIG. 4. — *Distribution of rock types in the Morin anorthosite massif, Quebec, after Martignole and Schrijver (1970*a*) and Wynne-Edwards* et al. *(1966). 1, anorthosite; 2, jotunite and mangerite; 3, troctolite.*

Models for the origin of anorthosite

Bowen (1917) explained the Adirondack anorthosite by gravitational differentiation from a single gabbroic parental magma, which resulted in a stratified mass consisting of pyroxenite, anorthosite, and syenite-granite in ascending order. Buddington (1939, 1972) favours two independent magmatic events in the Adirondacks, giving rise to a gabbro-anorthosite differentiation series and a subsequent quartz-syenite or quartz-mangerite differentiation series. De Waard (1970, 1972) postulates a single parental magma of dioritic to granodioritic composition which fractionated by floatation of plagioclase into the anorthosite-charnockite suite of rocks of the Adirondacks.

For the Morin anorthosite complex in Quebec, Philpotts (1966) suggests that dioritic parental magma assimilated large amounts of granitic material, and differentiated by crystal settling in the gradational series of the anorthosite-mangerite suite of rocks. Also Martignole and Schrijver (1970*a*) consider the anorthosite and the associated jotunites and mangerites of the Morin massif comagmatic, and they note that the troctolite possibly represents an early differentiate of the parental magma.

For the Michikamau intrusion in Labrador, Emslie (1969, 1970) considers an initial magma of basaltic liquid in which plagioclase crystals were suspended. The plagioclase accumulated at the roof to form a thick layer of anorthosite. Layered troctolite formed later by bottom accumulation of crystals. Finally, residual liquids were squeezed from below the collapsing anorthosite layer to the upper part of the intrusion, where they crystallized to ferrogranodioritic rocks.

For the Nain anorthosite complex Morse (1969) suggested that anorthosite formed from basaltic parental magma by floatation of plagioclase at the roof, and settling of mafic crystals at the bottom of the chamber. Orogenic deformation of the magma chamber caused residual liquid to intrude the overlying anorthosite and country rock, and crystallize to rocks of the adamellite group. The troctolitic bodies in the complex are considered to be the result of a later intrusion of basaltic magma.

De Waard and Wheeler (1971) proposed a model in which a single parental magma differentiated into all rock types of the Nain complex. Fractional crystallization in the magma chamber is considered to result in a density-stratified mass in which anorthosite was underlain by troctolitic magma, and overlain by residual acidic magma. Subsequent deformation of the magma chamber caused local intrusive relationships between anorthosite and the residual liquid, which further differentiated into members of the adamellite group.

Morse (1972) offered an alternative two-parent model for the Nain complex, in which a basaltic magma gives rise to the anorthositic and troctolitic rocks, and a later andesitic magma generates the adamellitic rocks. Another possibility, suggested by Morse (1974), is that the various rock types in the Nain complex represent separate magma batches derived from the mantle by the process of fractional melting (Yoder, 1973).

To summarize, anorthositic rocks are commonly associated with acidic rocks, and to a lesser extent with troctolitic rocks. Models for the evolution of these three rock groups postulate either a single parental magma, or two independent parental magmas by assuming that two of the three groups are comagmatic, or possibly a multiple magmatic origin, with one magma for each rock group.

Age and spatial relationships between the three rock groups

In the Nain complex as well as in other anorthosite bodies it has been observed that the anorthositic rocks are intruded by all other rocks, and thus are the oldest rocks of the massifs. Basaltic magma or troctolitic crystal mush invaded the anorthosite to form layered intrusions of troctolitic rocks. Troctolitic rocks of the Nain complex are associated with ferrodioritic and ferrosyenitic differentiates (Morse, 1969*b*), but also with jotunitic, opdalitic, and farsunditic rock types (de Waard and Mulhern, 1973).

The adamellitic rocks are the youngest group of rocks in the Nain complex. The group includes jotunitic, opdalitic, farsunditic, and charnockitic rocks, as well as ferrogranodiorites and ferroadamellites. Transgressive relationships between troctolite and adamellite are known from only one contact in the Nain complex. The paucity of intrusive contacts between the two strongly suggests that the residual adamellitic magma developed at a level in the magma chamber above that of the troctolitic rocks. Other contacts between the two groups are transitional, showing that troctolite is overlain by jotunite, opdalite, and farsundite, in that order (de Waard and Mulhern, 1973).

Adamellitic rocks intruding anorthosite have commonly a jotunitic contact zone, forming a zone of transition between the adamellitic and anorthositic rocks (de Waard, 1974). Adamellite forms large bodies which intruded, in many instances, between the anorthosite masses and the country rock of the Nain complex (Wheeler, 1969). In those large bodies the rock is predominantly a hornblende adamellite with large ovoidal feldspar, thus strongly resembling rapakivi in texture and composition (Wheeler, 1974).

Field observations thus indicate that anorthosite was formed at a high stratigraphic level in the magma chamber, for instance, by the process of roof accumulation of plagioclase and adcumulus growth. Troctolitic rocks were formed at a low stratigraphic level in the chamber, presumably by the process of bottom accumulation. Adamellitic rocks crystallized from a residual magma that evolved at a level above the troctolite, and below the anorthosite. The residuum intruded the overlying anorthositic rocks and country rock of the massif, and thus tended to reverse its stratigraphic position with that of anorthosite. A similar conclusion was reached by Emslie (1970) for the Michikamau intrusion.

The composition of the parental magma

Reflections on the composition of the parental magma require the following inferences: (1) which of the groups of rocks are comagmatic, and (2) what is the volumetric proportion of those rocks. For the Nain complex Morse (1969*a*) suggested that the areal percentage of adamellitic rocks, as appears from geologic maps, is much higher than the volumetric percentage that may be expected for the entire body. Assuming this, Morse postulated that a basaltic magma could have been the parent of anorthositic and adamellitic rocks, as well as of ultrabasic rocks which are assumed to have formed at the bottom of the magma chamber. De Waard and Wheeler (1971) considered the areal distribution to reflect volumetric proportions, and they favoured a granodioritic parental magma for the formation of the anorthositic, troctolitic and adamellitic groups of rocks. Also Emslie (1970) suggested for the Michikamau intrusion a single parental magma for the origin of anorthositic, troctolitic and acidic rocks, but, because of the high areal proportion of troctolitic rocks, and low areal proportion of acidic rocks, postulated an aluminous basaltic liquid as the parental magma.

Estimates of possible compositions of parental magmas thus largely depend on one's opinion of what was removed by erosion, and what underlies the present surface. This two-dimensional view may be improved somewhat by geophysical methods. Gravity survey demonstrated, for instance, that the layer of ultrabasic rocks, which should be present below the anorthosite in Bowen's model, is absent in the Adirondacks (Simmons, 1964).

Another possibility to develop a three-dimensional image of an anorthosite complex is to assume that massifs have basically the same construction, but are now exposed at different levels. The lowest level may be represented by the Michikamau intrusion, in which troctolitic rocks predominate, and acidic rocks have the smallest areal distribution. A higher level may be represented by the Nain complex, having a lower areal distribution of troctolitic rocks, and a considerably higher one of acidic rocks. The Morin massif may represent a still higher level with very little

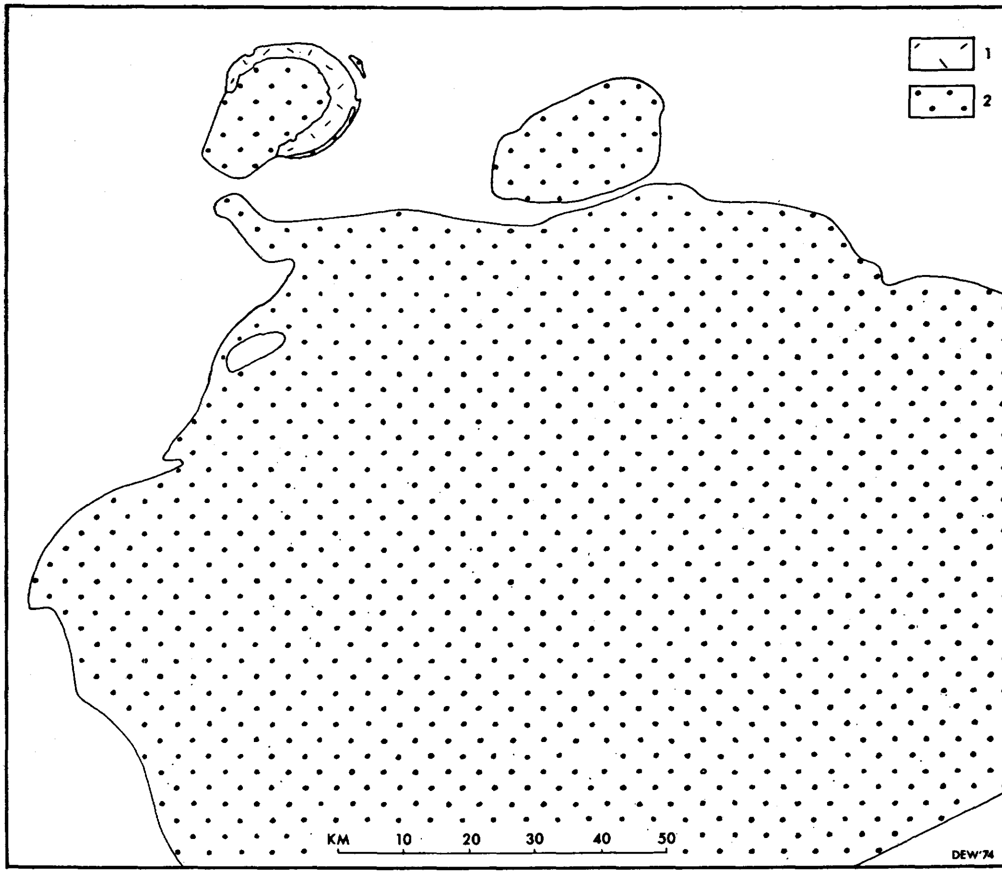

FIG. 5. — *Distribution of rock types in the Ahvenisto and Wiborg massifs of Finland, after Simonen (1960) and Savolahti (1956, 1966). 1, anorthositic rocks; 2, rapakivi.*

troctolite, and a large area of acidic rocks. The Marcy massif in the Adirondacks may be similar to the Morin massif, but without troctolite.

Upper levels of anorthositic complexes may be represented by the rapakivi plutons of Finland and Sweden, most of which are closely associated with relatively small occurrences of anorthositic rocks (Sobral, 1913; Wahl, 1925; Sederholm, 1934; von Eckermann, 1938; Hietanen, 1947; Savolahti, 1956) (fig. 5). Kranck (1939, 1967, 1969) draws attention to the similarity between the Finnish rapakivi and the acidic rocks of anorthosite massifs, which suggests a genetic relationship between the anorthosite suite and the rapakivi suite. Several rapakivi bodies are associated with volcanic rocks of the same composition, which indicates that the rapakivi was emplaced at shallow depth in the earth's crust (Kranck, 1929; von Eckermann, 1936). Wheeler (1942, 1974) emphasizes the rapakivi nature of adamellitic rocks in the Nain complex. Both are massive and coarse-grained, have ovoidal feldspar, may contain fayalite and have the green color of charnockitic rocks, and both have commonly an adamellitic composition. Emslie (1973) points out the chemical similarity between rapakivi suites and the silica-rich members of the anorthosite suites. It is of interest to note that the rapakivi bodies occur in a broad belt which extends to the Norwegian anorthosite bodies (fig. 6), and which may be the continuation of the belt of anorthosite massifs in North America (Herz, 1969).

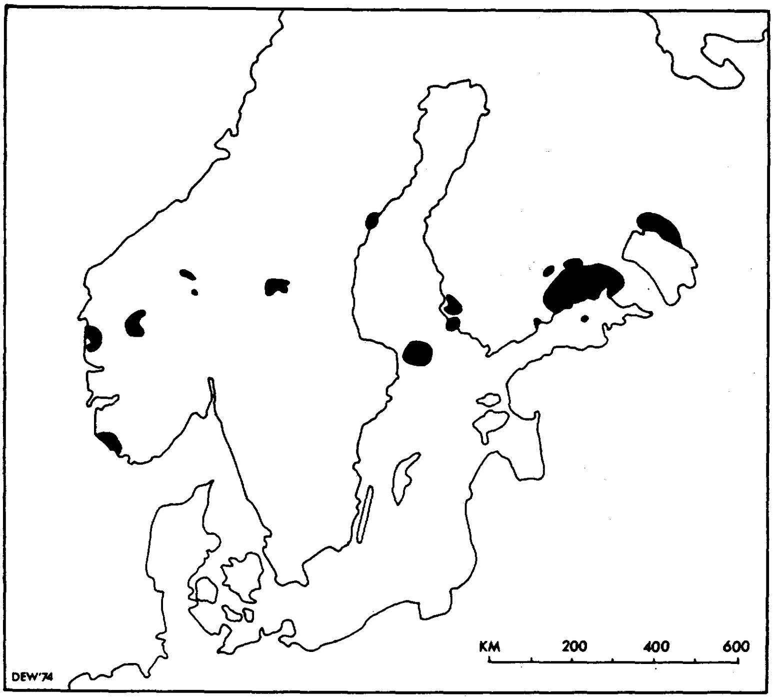

FIG. 6. — *Belt of anorthosite and rapakivi massifs in northwestern Europe after Kranck (1969), Simonen (1960), and Holtedahl (1960). Those in Norway are predominantly anorthositic, those in Finland predominantly rapakivi.*

Hence, if anorthositic, troctolitic and acidic rocks fractionated from a single parental magma, and if the sequence Michikamau intrusion, Nain complex, Morin complex, and rapakivi plutons depict ascending levels of the average anorthosite complex, then the volume of acidic rocks will be too high for a basaltic parental magma. The parent will have to be monzogabbroic or granodioritic, depending on how the proportions between rock groups are estimated.

Conclusions

Based on observed age and spatial relationships between rock units in the well-exposed Nain anorthosite complex, and on structures indicative of movements during fractionation, a tentative model evolved, shown as a flow chart in figure 7.

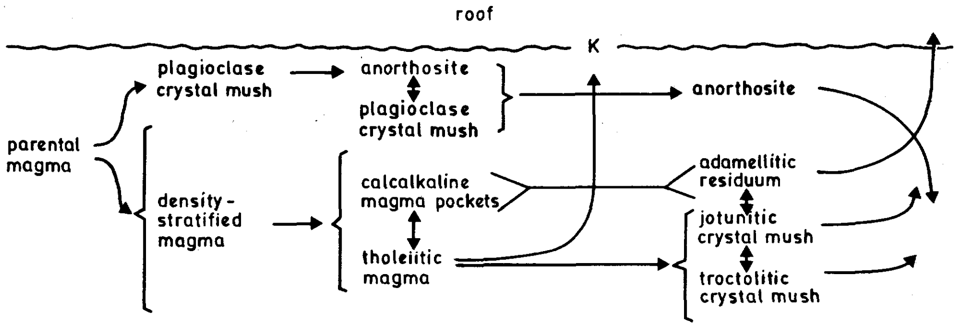

FIG. 7. — *Flow chart showing a model for the evolution of an anorthosite complex from a single parental magma fractionating into anorthosite by plagioclase floatation, troctolite by bottom accumulation, and acidic residuum in between the two. Tholeiitic magma intruding anorthosite fractionated into the troctolite-ferrosyenite suite of the Kiglapait layered intrusion (K). Density overturn in the final stage resulted in roof collapse, subsidence of anorthosite blocks, and intrusion of adamellitic magma and locally of jotunitic crystal mush.*

In parental magma of monzogabbroic or granodioritic composition fractional crystallization begins with the floatation of plagioclase and growth at the roof by the adcumulus process. Crystallizing olivine sinks, and melts at greater depth, which results in the formation of a density-stratified magma, grading upward from a tholeiitic to a calcalkaline composition. Possibly at this stage intrusion occurs of the tholeiitic magma into the anorthosite layer, where it fractionates separately into the troctolite-ferrosyenite suite of the Kiglapait layered intrusion.

In the main magma chamber bottom accumulation begins, forming a troctolitic crystal mush which grades upward into a jotunitic crystal mush and into a layer or pockets of adamellitic magma. Due to the gradually decreasing density of the fractionating magma a density inversion developes between the residuum and the overlying plagioclase cumulate, and a period of roof collapses follows. Blocks of anorthosite subside, and residual liquid and crystal mush intrude between and above anorthosite blocks, and in the roof of the magma chamber. Depending on the local cooling history and the local strength of the roof, density overturn occurs at different times in different places, resulting in intrusions which differ in composition from place to place.

This model is similar to Emslie's (1970), except for the composition of the parental magma, and it resembles in many respects Morse's (1969, 1972) models, but differs in the parent and in which of the rock groups fractionated from it.

Acknowledgements

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THE ANORTHOSITE PROBLEM WITH RESPECT TO THE NORVEGIAN PLUTONS

J. C. Duchesne and J. Michot

Introduction

Anorthosites and related rocks may be considered the most important basic plutonic phenomena in the deep zones of the earth's crust. They constitute massifs that may reach considerable dimensions (e.g. 20 000 km^2 for the Lake St-John anorthosite) and represent a large areal proportion of the Precambrian crystalline terrains (e.g. 20 % of the Grenville province) (fig. 1). In the northern hemisphere they form a belt extending from Virginia and the Adirondacks to Labrador and possibly even through Greenland and Northern Scotland, to Norway (Anderson, 1969; Herz, 1969).

For a number of years the origin of the anorthosite massifs and the closely related charnockitic rocks has been discussed by various authors on the basis both of field relationships and petrogenetic data (J. Michot, 1972). Experimental and geochemical approaches have also contributed to a better definition and clearer understanding of the problem.

The present authors report here on some of the results arrived at since 1966 when a symposium was held on the Anorthosite Problem at Plattsburg (edited in 1969 by Y. Isachsen).

They have focussed their research on Rogaland to which Paul Michot has since 1935 devoted the major part of his activities as a field geologist and as a petrologist. His studies have permitted the unravelling of the geological evolution of that region in its greatest detail and served as a frame for further field and petrological studies and also for geochemical investigations on trace elements and isotopes.

Anorthosite in the tectomagmatic cycle

The Rogaland anorthosites (fig. 8) are considered to be intruded during the orogenic stage of the tectomagmatic cycle. Their synorogenic character has been demonstrated by P. Michot (1951, 1952, 1956, 1957*a*, 1960, 1969). The emplacement of the various massifs appears intimately related to the major phases of the deformation which affected the metamorphic envelope on a regional scale. The Egersund-Ogna massif, which is the older one, was emplaced during a first pennine-style tectonic phase with north-south axes (P. Michot, 1957*b*). The crystallization of the Bjerkrem-Sogndal lopolith began during the second tectonic phase of the same style but with east-west axes, and continued during the third phase with vertical axial planes (P. Michot, 1960). The Haaland-Helleren and Aana-Sira massifs were emplaced some time between the formation of these two massifs.

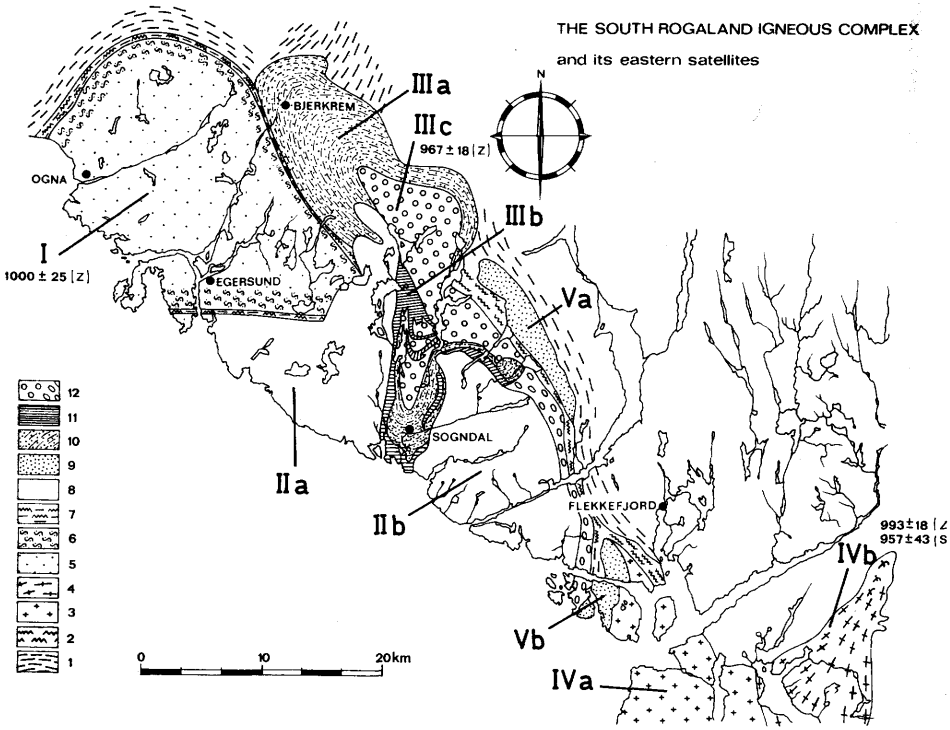

FIG. 8. — *General geological map of the South Rogaland igneous complex and their south-eastern satellites (after Jean Michot and Paul Michot, 1969). I, Egersund-Ogna body. — IIa, Haaland-Helleren massifs; IIb, Aana-Sira body. — III, Bjerkrem-Sogndal lopolith: a, anorthosito-noritic phase; b, Eia-Rekefjord intrusion; c, mangeritic phase. — IVa, Farsund charnockite; IVb, Lygndal Hb-granodiorite. — Va, Garsaknatt body; Vb, Hydra body. — 12, circle: mangerite and quartz-mangerite; oval: norito-mangeritic complex; 11, quartz-monzonorite of the Eia-Rekefjord intrusion; 10, anorthosite, leuconorite, norite and monzonorite of the Bjerkrem-Sogndal lopolith (anorthosito-noritic and monzonoritic phases); 9, coarse-grained leuconorite and anorthosite; 8, anatectic leuconorite and paraanatectic anorthosite; 7, migmatitic norite of the Lakssvelefjeld-Koldal intrusion; 6, anorthositic and leuconoritic gneiss; 5, coarse-grained anorthosite; 4, Lygndal Hb-granodiorite; 3, Farsund charnockite; 2, norito-granitic banded gneiss; 1, surrounding gneisses (metasedimentary gneiss, noritic gneiss, charnockitic migmatitic gneiss). — Radiometric ages of the principal igneous bodies are reported on the map (Z, zircon; S, sphene). Age of the Egersund-Ogna body is deduced from isotopic data obtained on the intruded gneisses (see text).*

The 'farsundite' (1) massif and the two small anorthosite bodies of Hidra and Garsaknatt appeared later, the first one probably during the final phase of deformation (Pasteels *et al.*, 1970) and the other two still later (Demaiffe *et al.*, 1973). The ages of these various magmatic events were determined by radiometric dating.

(1) The term "farsundite" refers to an igneous body described by Middlemost (1968) and which actually comprises two distinct units; the first one is a charnockite (hypersthene granite) —see Streckeisen (this volume)—, the second one is a hornblende-bearing granodiorite.

The oldest value found in the metamorphic envelope is 1 000 ± 25 m.yr. (2) (zircon), which gives the age of emplacement of the Egersund-Ogna body (Pasteels and J. Michot, 1975). Moreover the final phase of the crystallization of the Bjerkrem-Sogndal lopolith has been dated to 967 ± 18 m.yr. (zircon). The 'farsundite' seems to be either contemporaneous (sphene: 957 ± 43 m.yr.) or slightly older (zircon: 993 ± 18 m.yr.; Pasteels *et al.*, 1970; J. Michot and Pasteels, 1972).

Another example of synorogenic anorthosite is the Morin plutonic complex (Quebec). Martignole and Schrijver (1970*a*) favour the emplacement and consolidation of the massif during a pennine-style deformation of the surrounding terrains. This result is in contrast with previous interpretations (Wynne-Edwards, 1969) in which the complex is considered as pretectonic, with respect to the Grenville orogeny.

On the other hand, the Flakstadöy massif (Lofoten Islands, North Norway) could be considered an anorogenic anorthosite on the basis of field relationships (Romey, 1971) and geochronological data (Heier and Compston, 1969).

Examples from different parts of the world show that anorthosites may occupy anorogenic and synorogenic positions in the tectomagmatic cycle. As early as 1951, P. Michot (1951) demonstrated that the orogenic character of the 'basic' anorthositic magmatism in the catazone of southwestern Norway contradicted H. Stille's classical views on the tectomagmatic cycle, based upon the study of epizonal orogenies. This conclusion was later to be integrated by P. Michot (1956) himself into the concept of a geology of the deep zones of the earth's crust, characterized by the fact that the basic magmatism extends further than the geosynclinal stage, and is operating down to the deepest deformation level. The anorogenic character of some anorthosites (e.g. those from Labrador) would moreover extend the duration of the 'basic' anorthositic magmatism to the cratonic phase of the cycle.

Metamorphic envelope and level of intrusion

Synorogenic anorthosite massifs are emplaced in high-grade metamorphic terrains. In Rogaland metamorphism reached the mangerite facies (P. Michot, 1951) which is equivalent to the orthopyroxene-plagioclase subfacies (*sensu* de Waard, 1965*b*). The Morin complex occurs in the (hornblende)-garnet-clinopyroxene subfacies which is considered to have retrograded from the (hornblende)-orthopyroxene-plagioclase subfacies (Martignole and Schrijver, 1971).

In the anorogenic massifs the conditions of intrusion are more difficult to ascertain because there is no regional deformation in the surrounding terrains during the intrusion. In the Nain complex anorthosites were emplaced in metamorphic terrains either of the granulite facies or of the higher grade portion of the amphibolite facies (Emslie *et al.*, 1972). The level of intrusion may not have been as deep as the regional metamorphism indicates. At Michikamau the anorthosite (1 460 m.yr.; zircon) (Krogh *et al.*, 1973) cut across granulite facies rocks after the metamorphism of the Petscapiskau Group rocks in the greenschist facies

(2) An older age, 1 200 m.yr., is suggested by the study of some U-Pb and Rb-Sr systems (Pasteels and J. Michot, 1975). A premetamorphic age related to a volcanic or a plutonic activity could be involved. It should be mentioned that Versteeve (1970) obtained an age of 1 470 ± 78 m.yr. using the Rb-Sr isochron method on a very heterogeneous series of gneisses.

(1 520 m.yr.; K-Ar, Biotite) (Emslie *et al.*, 1972). Thus the level of intrusion appears relatively superficial (upper mesozone).

In the Lofoten-Versteraalen province, anorthosites occur in high-grade granulite facies rocks (gneiss and mangerite) which locally show evidence of retrogression to amphibolite-facies conditions (Green, Brunfelt and Heier, 1972; Romey, 1971). Field relationship between the Flakstadöy anorthosite and the associated mangerites (Romey, 1971) do not permit an unambiguous definition of the level of intrusion.

The latter can however be estimated (Griffin and Heier, 1969, 1973) owing to the presence of *corona structure* (resulting from retrograde reactions between e.g. olivine and plagioclase) in the igneous rocks or in the metamorphic rocks of the envelope, or in both.

On the basis of the experimental data of Kushiro and Yoder (1966) and of Green and Hibberson (1970), Griffin and Heier suggest that pressures of at least 7 to 10 kb (25-35 km) are required to give rise to corona structures. A similar approach by Martignole and Schrijver (1971, 1973) for the Morin complex also suggests a cooling at pressures of the order of 8 kb.

Conversely the absence of corona structures allows an upper limit to be fixed for the pressure during the consolidation process and further evolution of a rock.

In Rogaland olivine and plagioclase of variable chemical compositions ($Fo_{70}+An_{67}$ in the gneissic border of the Egersund-Ogna body, from $Fo_{71}+An_{49}$ to $Fo_{6}+$mesoperthite in the Bjerkrem-Sogndal lopolith—Duchesne, 1972*b* and unpublished data) coexist without any reaction rim. The confining pressure was thus certainly lower than in Lofoten and possibly below 6-7 kb. Independent estimate of *P-T* conditions with the garnet-cordierite thermo-barometer gives 6-7 kb and 730-750 °C (Henry, 1974). The pressure values are consistent with the previous results.

No garnet corona structure is reported from the Labrador anorthosite massifs. This can be explained at Michikamau by the fact that the intrusion, as already said before, took place in the upper mesozone. For the Nain complex the absence of corona structure sets an upper limit of about 6-7 kb to the pressure prevailing during cooling. This shows that the Nain complex was more superficially emplaced than the Flakstadöy anorthosite and, according to Martignole and Schrijver (1973), than the Morin complex.

It can thus be concluded that the anorthosite massifs are emplaced not only at different times in the tectomagmatic cycle but also at various levels in the earth's crust, from mesozone down to deep catazone.

The common connection of anorthosites, either syn- or anorogenic, with granulite facies rocks is certainly one of their most striking characteristics. It is worth mentioning that this feature has been differently interpreted. Several authors (Wynne-Edwards, 1969; Laurin *et al.*, 1972) believe that in Quebec the granulites originated from 'dehydration and thermal metamorphism of the envelope by the emplacement of the anorthosite bodies'. However Martignole and Schrijver (1970*a*) found inclusions with granulite gneiss structure in the Morin complex, and consider that this hypothesis is unlikely. According to these authors (1970*a*, 1970*b*), the association with granulitic rocks results from the process of emplacement by buoyancy. The density contrast would indeed be more effective for granulite facies anhydrous rocks than for hydrous rocks of the amphibolite and greenschist facies. This would explain that the diapiric ascent of the anorthosite could only be effective in the denser rocks of the catazone. This mechanism, essentially synorogenic in the case described by Martignole and Schrijver, could also be applied to anorogenic massifs. The intruded, high-grade metamorphic rocks, which constitute the craton, would retain a sufficient density contrast with the magma or the crystal mush to allow buoyancy up to levels higher than the catazone. This could explain that e.g. in Michikamau, the magma rises to an interface (Emslie, 1970) between a basement of granulitic gneiss and upper greenschist facies rocks of the Petscapiskau Group. In Rogaland according to P. Michot (1951-1972), the association with granulite facies rocks results from the very nature of the anorthositic magmatism which is synorogenic and takes place in the deepest part of a catazonal orogen.

Shapes and structures of anorthosite massifs

Anorthosite massifs present a great variety of shapes and structures. Domes, diapirs and layered massifs are common; sheets and dykes are rarer.

The proportion of crystallized material in the magma at the time of emplacement seems related to the structure of the massifs. The layered bodies would arise from magma containing little or no crystals in suspension; diapirs from magma very rich in crystals; sheets and dykes from crystal mush lubricated by a small amount of liquid.

In layered massifs rocks present gravity-induced mesoscopic structures and microscopic textures as defined by Wager and Brown (1968) in other layered igneous complexes. In diapirs the principal phenomenon connecting the different rock types seems to be a filter-press mechanism.

It is worth mentioning that the Bjerkrem-Sogndal lopolith of Rogaland presents (fig. 8), besides its synorogenic character, a great variety of layered structures (P. Michot, 1960, 1965*b*), such as igneous lamination, small scale rhythmic unit, cryptic layering and macro-rhythmic units. The development of gravity-induced structures thus is possible within a tectonic environment.

Rock types

All the rock types reported by de Waard in the first part of this paper are also found in Rogaland massifs. It should be added that Mg-olivine bearing rocks occur only in few places and that Fe-Ti oxide ore-bodies are common (Duchesne, 1973; Krause *et al.*, 1970; Gierth *et al.*, 1973). Fe-Ti oxide ore bodies are also found associated with the anorthosites in the Grenville province (Lister, 1966), but have not been found in the Labrador anorthosites.

Models for the origin of anorthosite

P. Michot (1956) explains the formation of anorthosite by crystallization of a plagioclasic magma resulting from the assimilation of large quantities of pelitic rocks by basaltic magma. A quartz-monzonoritic composition of the parental magma has been postulated (P. Michot, 1965*b*, p. 971). Assimilation would take place in the deepest part of a fundamental orogen, i.e. an orogen resulting from the evolution of a geosynclinal sedimentary piles lying directly on the oceanic crust (P. Michot, 1963, 1969). Gravity differentiation of the plagioclasic magma resulted in the gradation between rocks of the anorthosite-mangerite suite. The same differentiation mechanism is suggested by Philpotts (1966, 1969) to explain some south Quebec anorthosite-mangerite associations. He considers that the parental magma results from assimilation of sedimentary rocks and anatectic melts by basaltic magma. This assimilation process is thus not essentially different from that proposed by Michot. P. Michot (1955) and later on J. Michot (1960, 1961) also consider that anorthosites can be produced by anatexis of leuconoritic material: a leuconoritic melt is produced and a refractory residuum is left which constitutes the paraanatectic anorthosite. Partial anatexis is also considered a possibility by de Waard (1967*b*) and Anderson and Morin (1969).

According to Martignole (1974), the Morin plutonic complex resulted from the crystallization of a plagioclasic magma. Crystallization would begin below the level of intrusion. The diapiric ascent of a plagioclase mush lubricated by a gabbronoritic liquid yielded anorthosite and jotunite. Later, at a slightly higher level a recurrent intrusion of a magma impoverished in plagioclase yielded troctolite. The mangerites which border on the massif would result from contact anatexis of the surrounding gneisses. However Martignole (1974) does not completely preclude the possibility that the mangerites resulted from the hybridization of residual liquids with products of anatexis of the envelope.

In Flakstadöy, Romey (1969) suggests a model in which anorthosite is derived from a basaltic magma by floatation of plagioclase crystals above a troctolitic liquid. Mangerites are considered to be formed either by contact anatexis of the envelope, by crystallization of a mangeritic intrusion, or by regional anatexis.

Association of rock types in Rogaland

The plagioclasic magma concept developed from the study of the Bjerkrem-Sogndal lopolith (P. Michot, 1956-1969) where spatial relationships between anorthosites, acidic rocks, and the relatively scarce Mg-olivine bearing rocks are clearly exhibited (fig. 8). In its major structure the lopolith is divided into three units (or phases) which are from bottom to top (P. Michot, 1965*b*) the anorthosito-noritic phase, the monzonoritic (jotunitic) phase, and the mangeritic phase, which contains both mangerites and quartz-mangerites. The monzonoritic phase, by far the less voluminous with respect of the other two, constitutes the transition in perfect geometrical, lithological and mineralogical conformity between the noritic upper part of the first phase and the mangeritic part of the last one. The massif resulted from gravity differentiation. As it is frequently the case in layered intrusions, the filling of the magmatic chamber was not accomplished in a single event. Several influxes of fresh magma have taken place during the consolidation of the anorthosito-noritic phase, giving rise to macro-rhytmic units which are recurrences in the chemical evolution of the differentiation (Duchesne, 1970, 1972*a*). Taking into account the recurrences in the evolution, it is possible to reconstitute the lithological sequence of differentiation: anorthosites and leuconorites (in which locally a Mg-olivine rock occurs) are followed by norites which grade into monzonorites (jotunites), mangerites and quartz-mangerites. The principal rock-forming minerals display a smooth chemical evolution in the series (Duchesne, 1971, 1972*a*, 1972*b*).

Besides the monzonorites belonging to the second (transitional) phase of the Bjerkrem-Sogndal lopolith, another lithological unit of quartz-monzonoritic composition—the Eia-Rekefjord intrusion (fig. 8) (P. Michot, 1960)—was emplaced in a stage of brittle deformation of the lopolith. An extensive network of dykes is related to this intrusion. They cut across the anorthosito-noritic phase of the lopolith, its basement (the Egersund-Ogna body) and also across the Haaland-Helleren and Aana-Sira massifs. Another occurrence of monzonorite is also found in the Hidra (Demaiffe *et al.*, 1973) and Garsaknatt (Demaiffe, oral communication) bodies (fig. 8). A fine grained monzonorite, locally containing plagioclase phenocrysts, constitutes the border facies of the bodies. A smooth transition between the border rock and the coarse grained leuconorite forming the central part of the Hidra body is achieved by a progressive enrichment of plagioclase phenocrysts and a simultaneous decrease in the matrix proportion. The genetic relation between the border monzonoritic facies and the central leuconoritic (and anorthositic) rocks is therefore obvious.

Moreover the association between anorthosite and acidic rocks is also found on a regional scale. The various anorthositic, leuconoritic and noritic rocks which constitute the anorthosite units of the igneous complex have their acidic counterpart in the late orogenic Lyngdal Hb-granodiorite (fig. 8) which extends southeast of the complex (Pasteels *et al.*, 1970; J. Michot and Pasteels, 1972).

Parental magma : hybridization or not ?

Studies on the initial $^{87}Sr/^{86}Sr$ ratio provide arguments which do not favour the hybridization of basaltic magma with crustal material prior to its intrusion, but clearly indicate that the contamination takes place during the magmatic differentiation after or during the intrusion. Indeed, in the regional trend of magmatic evolution, the successive igneous bodies of the Rogaland complex are characterized by a progressive increase in the initial ratio (J. Michot and Pasteels, 1969; Pasteels *et al.*, 1970; Demaiffe *et al.*, 1974). Table 1 summarizes the data.

TABLE 1

Egersund-Ogna body :	
Central anorthosite	0.703 5 ± 0.000 2
Gneissic leuconoritic border	0.704 5 ± 0.000 2
Bjerkrem-Sogndal lopolith :	
Anorthosito-noritic phase	0.705 – 0.706
Mangeritic phase	0.712 0 ([a])
South-eastern satellitic bodies :	
Farsund Charnockite	0.712 0 ± 0.000 3 ([a])
Lyngdal Hb-Granodiorite	0.705 4 ± 0.000 2

([a]) Values obtained from Rb-Sr isochrons (Demaiffe *et al.*, 1974; Pedersen *et al.*, unpublished) which give slightly younger ages than the zircon and sphene ages.

The initial ratio found for the central anorthosite of the Egersund-Ogna body (0.703 5) is relatively low and falls in the range of the oceanic and continental basaltic and andesitic rocks. It cannot be taken as an indicator of large assimilation of pelitic material unless the incorporated crustal rocks were of very low initial $^{87}Sr/^{86}Sr$ ratio, as e.g. the Lewisian grey gneiss (Evans, 1965). On the other hand the higher value (0.704 5) of the gneissic leuconoritic border (3) indicates some crustal contamination possibly during the slow diapiric uprise of the massif. The anorthosito-noritic phase of the Bjerkrem-Sogndal lopolith is characterized by a somewhat higher ratio (0.705-0.706) and the mangeritic phase by still higher values (0.712). Crustal contamination before intrusion and during the differentiation process in the lopolith is thus apparent. The Farsund charnockite also gives 0.712. These high initial ratios imply a large scale hybridization of the residual magma with anatectic melts, or even, in the case of the Farsund charnockite (Pasteels *et al.*, 1970), a direct production of anatectic melts. The intruded gneiss of the envelope, whose initial ratios range from 0.705 9 to 0.731 9 (J. Michot and Pasteels, 1969 ; Franssen and Deutsch, 1973), seem to have been affected by contact anatexis during the magmatic evolution. Successive residual magmatic liquids would have been hybridized to yield a series of rocks displaying a continuous variation in chemical composition. The relatively lower value in the Lyngdal Hb-granodiorite (0.705 4) permits to consider this rock as an acidic product of the differentiation of the large anorthositic massifs, such as e.g. the Egersund-Ogna body. Variants of the same hybridization mechanism have already been proposed by Hargraves (1962) for the Allard Lake massif and by Martignole (1974) for the Morin complex.

At both the regional scale and the scale of the Bjerkrem-Sogndal massif, the net result of the hybridization process is, that it increases in a proportion yet to be determined, the quantity of acidic rocks which would have been produced by fractionation of the parental magma in a closed system.

The composition of the parental magma

Following the method used by Heier and his coworkers (Green *et al.*, 1969, 1972) in the Lofoten-Vesteraalen province, rare-earth elements are being studied in Rogaland. In the Hidra monzonoritic rocks the rare-earth distribution shows a very weak Europium anomaly, which limits to a maximum of 10 % the quantity of plagioclase that fractionated before consolidation of the rock (Duchesne *et al.*, 1975). Within that approximation the monzonorite can thus be considered as the best representative of the parental magma of the Hidra body. Preliminary investigations on quartz-monzonorites of the Eia-Rekefjord intrusion (fig. 8) also indicate a lack of an Europium anomaly in the rare-earth distribution, thus supporting the idea that the parental magma of the anorthosite suite was monzonoritic to quartz-monzonoritic in composition.

In its major element geochemistry the parental magma is characterized by high contents in Ti and P, a low Si content and high Fe/Mg and K/Si ratios. It can grossly be defined as an ilmenite-rich, low-Si andesite. Emslie (1973) also gives evidence of high Fe/Mg ratios in liquids in equilibrium with plagioclase in the anorthosite suite. The high Ti and P contents are particularly interesting. Recent experimental investigations of Kushiro (1974) show indeed that Ti and P play in the genesis of magmas in the upper mantle a role antagonistic to that of alkalies and water. The presence of Ti and P shows that the formation of Si and alkali-poor

(3) A very low value of $0.702\,6 \pm 0.000\,1$ has been found in a leucotroctolitic gneiss of the border (Demaiffe *et al.*, 1974). Its meaning has yet to be ascertained.

magmas can take place in pressure conditions (15-20 kb) similar to those required for the formation of Si and alkali-rich liquids (i.e. andesite) in the absence of Ti and P. This constitutes evidence for an upper-mantle origin of the parental magma. Trace element geochemistry indicates, moreover, that amphibole might have played a significant role in the genesis of this magma (Duchesne *et al.*, 1974).

To what extent such a magma can give rise to the suite of troctolite-anorthosite-acidic rocks remains a problem not yet solved in Rogaland. Any generalization to other provinces is thus premature, though similar chemical trends of pyroxenes in several anorthositic massifs—such as Bjerkrem-Sogndal, Michikamau and St-Regis, Adirondacks—seem to indicate a unique composition of the parental magma (Duchesne, 1972*b*).

Future researches should take into account the following considerations. The Hidra body displays a clear preponderance of anorthosites and leuconorites over troctolites and acidic products (Demaiffe, pers. comm.). The latter are only present either as small dykes cutting across anorthositic rocks, or as products of crystallization of intercumulus liquid in some coarse-grained leuconoritic orthocumulates. In the Bjerkrem-Sogndal lopolith the apparent proportion of acidic rocks (mangerite and quartz-mangerite) is far more important than in Hidra, but their complete consanguinity with anorthosito-noritic rocks is being questioned on the basis of isotopic data.

Trace elements and isotopic data, in addition to field relationships and petrological data, thus show that it is necessary at least to verify the degree of consanguinity between acidic rocks and anorthosites before attempting to reconstitute the parental magma on a volumetric basis.

Conclusions

(1) Intrusion of anorthosite massifs takes places at different stages of the tectomagmatic cycle. They can be syn- or anorogenic.

(2) Anorthosite massifs occur in terrains of regional high grade metamorphism, usually in close association with granulite facies rocks, irrespective of their syn- or anorogenic character.

(3) The level of intrusion is variable. Anorogenic intrusions do not take place at any particular level within the crust, e.g. Flakstadöy (Lofoten) is very deep-seated; Michikamau (Labrador) is more shallow. On the other hand, synorogenic anorthosites were emplaced in medium (Egersund) to high (Morin) pressure granulite facies environments.

(4) In the Rogaland igneous complex, gravity differentiation initiated by crystallization and sinking of plagioclase is the principal mechanism which yields the anorthosite-mangerite suite. A unique composition for the parental magma, as it was initially proposed by P. Michot, is still favoured. REE evidence shows that a monzonoritic to quartz-monzonoritic magma, enriched in Fe, Ti and P, is a possible parental magma of upper-mantle origin. A process of hybridization during differentiation, that is mixing of successive residual magmatic liquids with anatectic melts, produced in the envelope by contact anatexis, is suggested to explain the increase of the $^{87}Sr/^{86}Sr$ initial ratio with differentiation. The quartz-mangerite and the Farsund charnockite have both high initial ratios. They represent the more

contaminated products of the igneous sequence, the latter possibly the anatectic melt itself. From a more general point of view, direct derivation of acidic rocks solely by crystal fractionation from a single parental magma is questioned.

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