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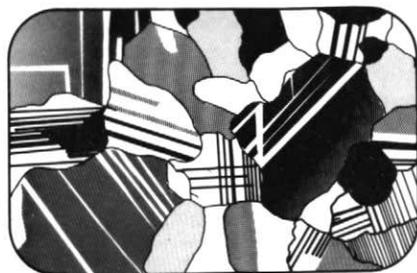
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Résumé de l'article

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Nature and Origin of Anorthositic Suites

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Summary

Anorthositic suites are spatially and temporally associated assemblages of rocks ranging from gabbro, troctolite and anorthosite through diorite to granitic compositions. The largest known concentration of these rocks in the world is in the Grenville Province and in Labrador north of the Grenville Front. New data on the rock and mineral chemistry of the suites are leading to reassessment of ideas about their origins. One of the keys to understanding the tectonic evolution of the Grenville Province lies in correct interpretation of anorthosite suites in terms of the igneous processes that formed them and their subsequent metamorphism. Renewed appraisal of the economic potential of anorthositic suites is taking place on several fronts.

Résumé

Les suites anorthositiques sont des roches associées dans le temps et l'espace de composition du gabbro, troctolite, anorthosite au granite en passant par la diorite. La plus grande concentration de ces roches connue au monde est située dans la province de Grenville et au Labrador, au nord du front de Grenville. De nouvelles données sur la chimie de la roche et des minéraux de ces suites amènent à réévaluer les théories sur leur origines. Une des clefs pour comprendre l'évolution tectonique de la province de Grenville est l'interprétation correcte des suites

d'anorthosite en fonction des processus ignés qui les ont formées et de métamorphisme subséquent. L'évaluation du potentiel économique des suites anorthositiques est à nouveau menée sur plusieurs fronts.

Introduction

The purpose of this article is to outline some of the more recent research directions and findings on anorthositic and related rocks for geologists outside the field of active investigation. Comment is directed particularly toward the widespread, voluminous masses occurring in the eastern part of the Canadian Shield (Fig. 1).

The last major conference devoted to investigations of anorthositic rocks was

entitled "Origin of Anorthosite and Related Rocks" and took place in Plattsburg, N.Y. in 1966. It became clear to the participants at the conference and to readers of the volume subsequently produced (Isachsen, 1969) that much eclectic argument for and against various hypotheses of origin was generated simply because of a lack of detailed information on the nature of anorthositic suites. Recognition of that fact by the participants was one of the more important contributions of the conference.

In 1966 a program of mapping and petrological research on anorthositic rocks was initiated at the Geological Survey of Canada. Studies have included unmetamorphosed complexes

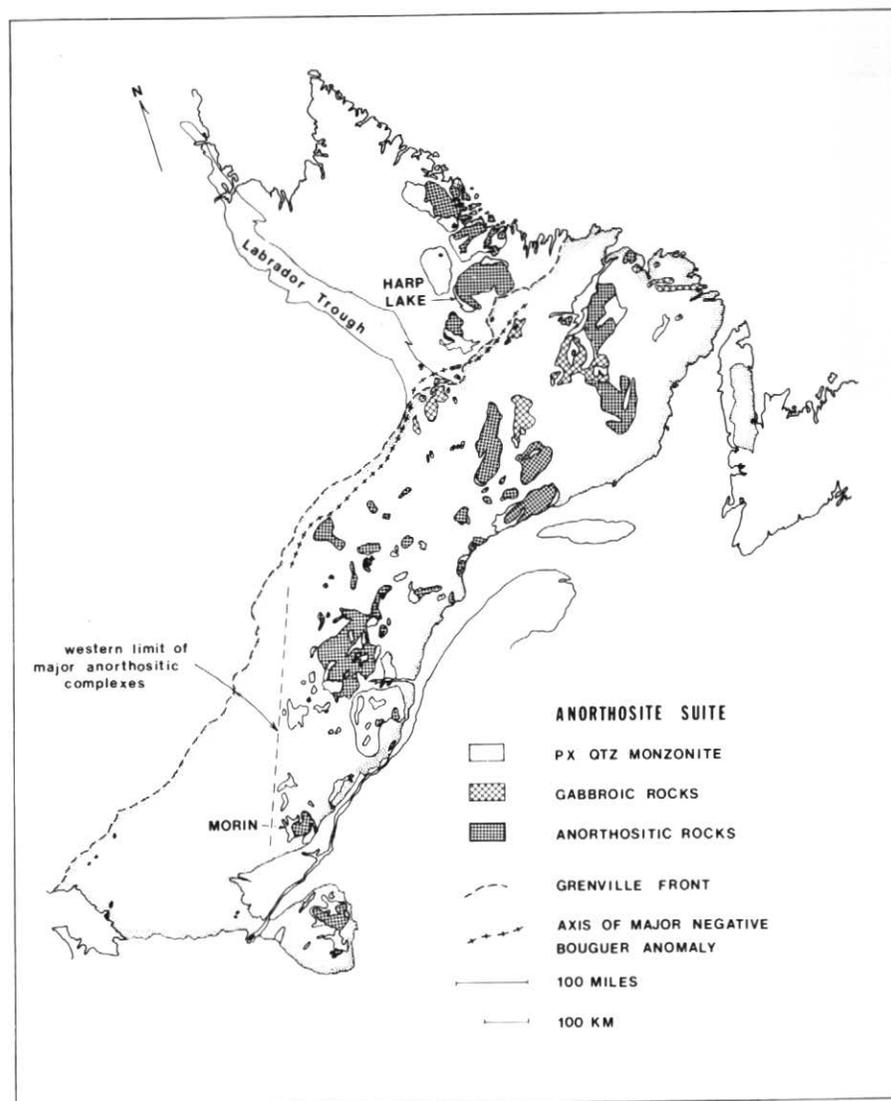


Figure 1
 Distribution of anorthositic and related rocks in the eastern Canadian Shield. The Grenville Structural Province is outlined with a stippled pattern. Locations of Harp Lake and Morin complexes indicated.

Grenville Structural Province is outlined with a stippled pattern. Locations of Harp Lake and Morin complexes indicated.

in Labrador north of the Grenville Front and meta-anorthositic complexes within the Grenville Province. The project is aimed at providing basic data on anorthositic suites in terms of structural relations, rock and mineral chemistry, associated economic mineral concentrations, ages, tectonic settings and metamorphism.

A major field program was started in 1971 in coastal Labrador based at Nain, the region of pioneering studies on anorthositic rocks by the late E. P. Wheeler 2nd. Principal investigator S. A. Morse with associates Wheeler and D. deWaard have coordinated mapping projects by students along the coast with logistic support from a 50 foot vessel equipped to do routine petrographic work. The mapping program is now well advanced and emphasis is shifting toward detailed chemical and mineralogical studies (see Morse, 1974 and previous years). The superb rock exposure of the coastal region allows insights into geological relationships not readily available elsewhere.

Apart from these two long term projects, university personnel and their students have provided and continue to provide valuable new information. A few examples include studies in southwestern Quebec by J. Martignole, K. Schrijver, J. M. Baron, and R. Doig; in the Lac St. Jean region by M. M. Kehlenbeck; and in the Parry Sound area by I. Mason and R. H. McNutt. A number of workers including Y. W. Isachsen, J. M. McLelland, and P. Whitney have made recent contributions in the Adirondack region.

Some Physical and Chemical Aspects of Anorthositic Suites

The term "anorthositic suite" is used here because anorthositic rocks are the most distinctive members but the range of rock types includes gabbro, troctolite, norite, the leucocratic equivalents of these and anorthosite, diorite, granodiorite, monzonite, quartz monzonite and granite. Rock compositions from diorite through granite are sometimes referred to by names such as opdalite, enderbite, quartz mangerite and charnockite - this simply means that the rocks are pyroxene-bearing (dominantly orthopyroxene). The rock assemblages are called suites to emphasize their association without specifying a clear comagmatic relationship as was

implied in the older usage "anorthosite-charnockite kindred".

Anorthositic rocks that concern us here formed by the accumulation of plagioclase crystals precipitated from magma (Fig. 2a and 2b). This is one of the keys to their understanding that was recognized by astute observers

many years ago but still appears not to be fully appreciated by some writers. Support for this interpretation is primarily from studies of fresh, non-tectonized rocks in which textures are identical in all respects to analogous cumulate textures developed in many mafic intrusions such as Skaergaard,

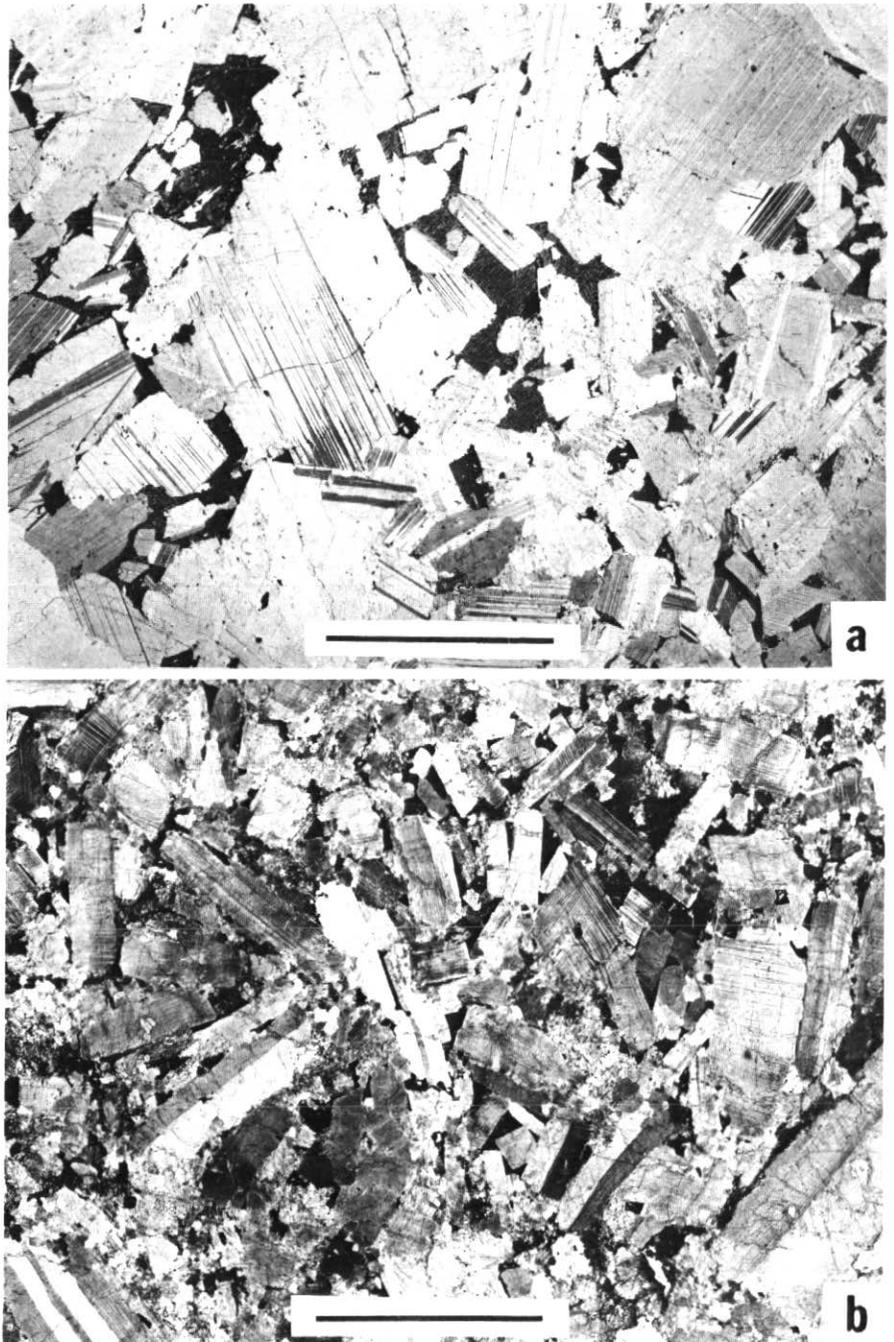


Figure 2
Cumulate textures in anorthositic rocks. These are plagioclase cumulates with interstitial pyroxenes and minor opaque

oxide (dark grey and black). (a) Harp Lake complex. (b) Morin meta-igneous complex. Bars are one cm long. Cross-polarized light.

Bushveld and Stillwater. There is evidence from several complexes that the mechanism of accumulation of plagioclase to form anorthositic rocks was settling of crystals. Other mechanisms such as floating and filter pressing have been suggested but not proven. Layered structures are also present in many complexes. Figure 3 shows cross-bedding of anorthosite layers in leucogabbro at Harp Lake. This structure is evidence for magma movement during crystallization and may have resulted from new injections of magma into the complex.

Although the term "suite" has been used purposely to avoid sweeping generalizations about genetic relationships among members of the suites, the question inevitably remains - How are the members related?. The close spatial and temporal relationships are certainly general arguments favouring cogenetic (not necessarily comagmatic) origins but the matter has remained disputable.

Arguments based on continuity of variations in different chemical parameters of bulk rocks have been used to support a comagmatic origin for members of some complexes (e.g., Philpotts, 1966). Such evidence is open to the usual criticism that other processes such as mixing of magmas or progressive contamination of a magma by wallrock assimilation may also lead to trends on variation diagrams. Conversely, gaps or discontinuities in chemical trends in some suites have been used as ammunition to argue against comagmatic origins. There is great diversity in the proportions of various rock types in different complexes and, not uncommonly, some members are absent. These features suggest that a complex is not formed by simple in situ fractional crystallization of a single magma parent. In addition, it is typical of most suites to show progressively younger intrusive relations from the basic to the silicic members. Nevertheless, examination of the bulk rock chemistry of a number of anorthositic suites (Emslie, 1973) suggests that several chemical characteristics are common to many, e.g., high $A1^{2O3}$, high total Fe relative to Mg and alkalies, and high K^2O/SiO_2 . Rapakivi texture is known to occur in silicic rocks of a number of anorthositic suites and the chemistry of



Figure 3
Cross-bedded igneous layering in the Harp Lake complex. Lighter layers are

anorthositic, darker layers are leucogabbro. Height of outcrop face about 10 m.

Fennoscandian rapakivi granitic rocks is similar.

Because anorthositic complexes are commonly (but not invariably) intruded into upper amphibolite - to granulite - facies terranes the tacit assumption has sometimes been made that emplacement and crystallization took place under such conditions. There is little good evidence to defend this interpretation. In Labrador, north of the Grenville Front, contact metamorphism of wallrocks of several large complexes is consistent with pressures less than five kb, lower than those usually considered appropriate for granulite facies. The high-grade terranes may have been partly or completely exhumed and cooled before the anorthositic complexes were emplaced.

Ages

Isotopic age determinations on anorthositic rock suites are still sparse. Zircon is characteristically very abundant in the silicic members and has been dated in several complexes. The whole rock Rb-Sr isochron method has been applied but Rb is typically very low in many suites tested.

North of the Grenville Front in Labrador quartz monzonitic rocks of the Michikamau and Harp Lake complexes gave closely-agreeing,

nearly concordant U-Pb zircon ages of about 1450 m.y. (Krogh and Davis, 1974). In both complexes these rocks are the younger intrusive members and it could be argued that they provide only a minimum age for the anorthositic rocks they intrude. However, ages of biotite (1400 ± 50 m.y., K-Ar) and hornblende (1479 ± 101 m.y., K-Ar) from anorthositic and gabbroic rocks at Michikamau suggest that the time interval of crystallization of the whole complex was not large.

Within the Grenville Province dating of anorthosite-suite rocks by Rb-Sr whole rock and U-Pb zircon methods has given ages in the range 1125-1200 m.y. interpreted by the authors as igneous crystallization ages. Ages in the 1400-1500 m.y. old range have not been discovered by direct determination on anorthositic suites although indirect evidence has been used to argue for the existence of suites of this age.

In Wisconsin, the Wolf Lake rapakivi granite-anorthosite batholith has yielded Rb-Sr ages of about 1500 m.y. Further west, the Laramie, Wyoming anorthositic complex has yielded some Rb-Sr ages of around 1400 m.y. It would seem surprising that 1400-1500 m.y. old anorthositic suites occur near the northeastern and southwestern extremities of the exposed Grenville Province but are absent within it.

Evidence for Cogenetic Suites in Two Complexes

The Harp Lake complex in central Labrador (Fig. 1) underlies about 10,000 km² and comprises a complete range of rock types from gabbro through granite with rocks of intermediate composition present in relatively small amounts. Compositions of coexisting pyroxenes and Fe-rich olivines from members of the complex are shown in Figure 4. They show continuous trends culminating in extreme Fe-rich compositions. Plagioclase and alkali feldspar compositions show similar regular variations (Emslie, 1975a).

The Morin meta-igneous complex, Quebec (Fig. 1) underlies roughly 5,000 km² dominated by anorthosite and leucogabbro with sub-equal amounts of pyroxene quartz monzonite and relatively smaller amounts of intermediate rocks (Martignole and Schrijver, 1970; Emslie, 1975b). Compositions of coexisting pyroxenes from the main rock units are shown in Figure 4. Plagioclase and alkali feldspars display corresponding regular changes in composition.

The continuous variations in pyroxene and feldspar mineral chemistry in the Harp Lake and Morin complexes are those that would be predicted to result from a fractional crystallization process. In both complexes the succession of rock types from basic to silicic compositions shows a corresponding progression of decreasing intrusive ages. It seems necessary to conclude that the main fractional crystallization process took place at some depth beneath the level of emplacement of the complexes.

Morin pyroxenes do not extend to the extreme Fe-rich compositions present at Harp Lake. Numerous concentrations of Fe-Ti minerals are associated with the Morin complex (Rose, 1969) whereas such deposits are rare at Harp Lake. It is likely that different conditions of magmatic crystallization in the two complexes led to iron concentration in silicates in one and oxide minerals in the other. The mineral chemistry of anorthositic suites may thus prove to be a valuable prospecting guide to such deposits.

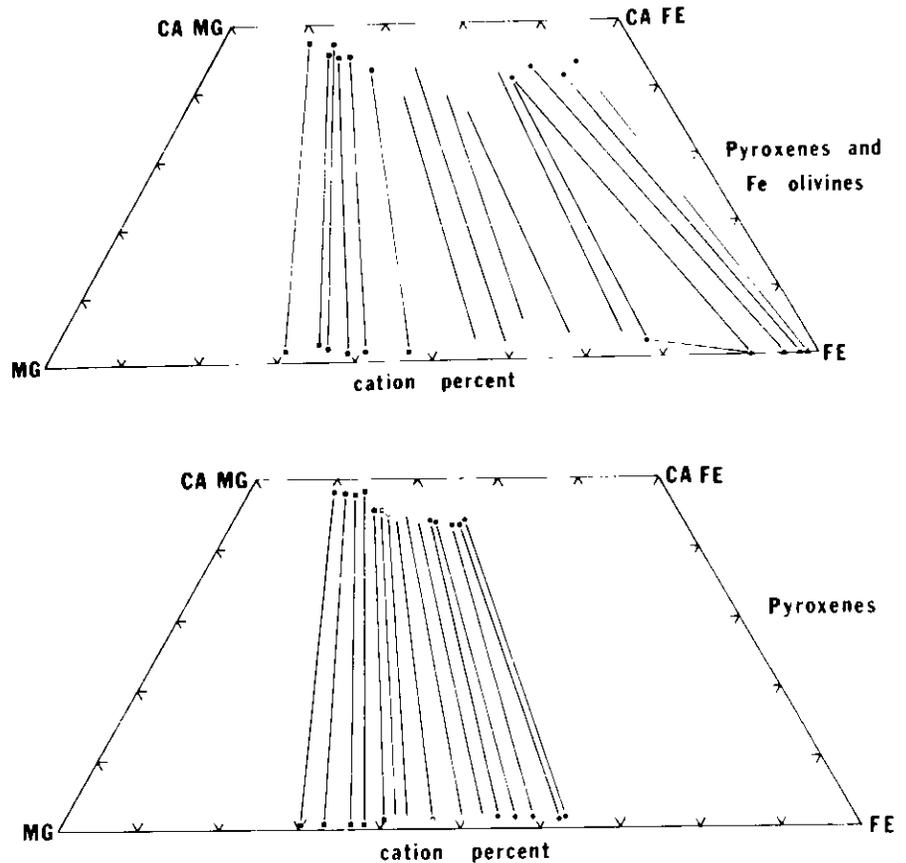


Figure 4

Analyzed pyroxenes and olivines from the Harp Lake complex (above) and the Morin complex (below). FE is total iron. Tie lines join coexisting minerals. Open squares

indicate minerals from anorthositic rocks, open circles from intermediate rocks, solid circles from silicic rocks, solid triangles are olivines.

Parent Magmas

A problem that has received increasing attention is definition of the compositions of magmas parental to anorthositic suites. Judging from the plagioclase and pyroxene compositions in most anorthositic massifs, magmas in the range from basaltic to andesitic were capable of precipitating anorthositic rocks. Whether these are related by fractionation to a "primitive" basaltic parent or are products of different degrees of partial melting in the source region is not known. It is clear, however, that subdivision of anorthositic rocks into andesine-type and laboradorite-type, although useful for certain classification purposes, does not reflect characteristics of fundamental significance to genesis. Large complexes such as Nain, Harp Lake, and Lac St. Jean are comprised of sub-units of both types.

Attempts are being made to use rare earth elements (REE) and other trace element distributions to apply some useful constraints to defining parental magmas of anorthositic rocks. These are potentially powerful tools but data are still too sparse to permit generalizations. Plagioclase is strongly enriched in europium so that parent magmas should not be depleted in that element and, conversely, residual liquids after crystallization of anorthositic rocks should show negative europium anomalies.

It is not certain whether production of anorthositic rocks is due to crystallization of large amounts of plagioclase from a single magma or if relatively smaller amounts of plagioclase are concentrated from a succession of magma batches.

Magma Sources and Depths of Crystallization

Low Sr^{87}/Sr^{86} ratios in anorthositic rocks have been used as evidence for their crystallization from mantle-derived magmas. The silicic rocks of some suites are also consistent with low initial Sr^{87}/Sr^{86} ratios but others suggest some degree of contamination by crustal strontium.

Recent work on pyroxene megacrysts with exsolved calcic plagioclase lamellae (Fig. 5a and 5b) from large anorthositic complexes provides strong support for a mantle origin of magmas (Emslie, 1975c). Although widespread, these pyroxenes are relatively rare within anorthositic complexes and their occurrences and physical characteristics suggest they are cognate megacrysts crystallized at depth and brought up in ascending magmas. Some of the original orthopyroxene solid solutions contained more than eight weight per cent Al^{2O_3} . By analogy with experimental data these aluminous pyroxenes are inferred to have crystallized at pressures up to 15 kb. Host rocks containing pyroxene megacrysts have subophitic orthopyroxenes that lack plagioclase lamellae and have Al^{2O_3} contents near two per cent. This implies that the host rocks crystallized at substantially lower pressures (< 5 kb) and is inconsistent with crystallization under granulite facies conditions. Complexes such as the Morin and Adirondack massifs which have a granulite-facies regional metamorphic overprint evidently were depressed and metamorphosed under high-grade conditions sometime after earlier igneous crystallization at upper crustal levels.

Smith (1974) reported on Fe-rich pyroxenes from the Nain complex that have compositions similar to those from Harp Lake. Using arguments based on experimental data, Smith concluded that some of the Fe-rich pigeonites required pressures not less than five kb for stable crystallization. The original pigeonitic pyroxenes have commonly broken down to olivine + orthopyroxene + quartz. The breakdown is interpreted by Smith as indicating that the original pyroxenes became unstable due to decompression accompanying uplift sometime after consolidation of the rocks. It seems equally palusible,

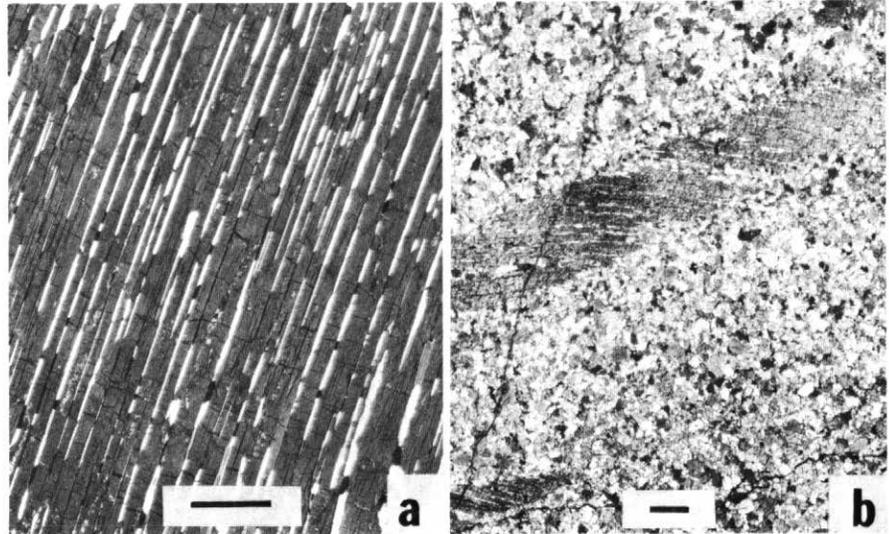


Figure 5
Pyroxene megacrysts with exsolved calcic plagioclase lamellae from anorthositic rocks. (a) From Lac St. Jean anorthosite. Note regular distribution of plagioclase lamellae (light) in orthopyroxene host. Black lamellae and grains are opaque oxide. (b)

From Morin complex. Relict deformed clinopyroxene augen with plagioclase lamellae. Matrix as recrystallized low Al clinopyroxene and anorthitic plagioclase. Bars are one mm long. Cross-polarized light.

however, that the pigeonites, after initially crystallizing at depth, became unstable after being brought into the complex by ascending magma.

Accumulating evidence seems to point to a process of deep fractional crystallization of a magma source that was tapped at intervals, but perhaps irregularly, to bring successively more fractionated magmas to upper levels of the crust.

Concluding Remarks

One of the keys to working out the history of tectonic development of the Grenville Province lies in understanding the nature of the igneous processes that produced anorthositic suites and the metamorphic processes that affected them in varying degrees. The large volumes of unmetamorphosed anorthositic suite rocks in central Labrador have provided and will continue to provide some of the more reliable information on the primary igneous rock assemblages and their mineralogy. Such information is indispensable to the correct interpretation of the commonly deformed and metamorphosed complexes of the Grenville Province.

Preservation of high pressure pyroxenes in Precambrian igneous and meta-igneous rocks has implications beyond those of direct relevance to the petrogenesis of anorthositic rocks. If the search for other high temperature, high pressure minerals and xenoliths in Precambrian igneous rocks proves fruitful these would be of great value as direct evidence bearing on paleogeothermal gradients, crustal thicknesses, and crustal and mantle evolution in the Precambrian.

The characteristic association of Fe-Ti oxide mineral concentrations with anorthositic rocks has been recognized for many years. Only a very few of the largest such deposits of the total number known in the world are currently being exploited. It seems inevitable that as natural resources of all kinds are gradually being exhausted, a time will come when many more of the deposits will be developed.

Disseminations of Cu-Ni sulphides occur in many places in the eastern half of the Harp Lake complex. These are clearly syngenetic in origin and although significant concentrations have not been proven, the fact that sulphide occurrences are found in this association is of economic interest.

At the present time the feasibility of recovering alumina from anorthosites is actively being investigated. If the technical and cost problems can be solved, Canada's supply of the raw material seems assured.

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