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BULLETIN 162

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THE PYROXENE GRANULITES OF THE MOUNT WRIGHT MAP-AREA, QUEBEC–NEWFOUNDLAND

R. A. Roach and Stanley Duffell

Ottawa
Canada

Price, $2.50

1968

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1,450—1967—5659-2

Critical Reader
H. R. WYNNE-EDWARDS
Technical Editor
S. E. JENNESS
Editor
JACQUELINE DEMERS
Printed on No. 1 Enamel
Set in Times Roman with
20th Century captions by
TELFORD AND CRADDOCK PRINTERS
Artwork by CARTOGRAPHIC UNIT, GSC

GEOLOGICAL SURVEY
OF CANADA

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By

R. A. Roach and Stanley Duffell

DEPARTMENT OF
ENERGY, MINES AND RESOURCES
CANADA

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from Geological Survey of Canada,
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1735 Barrington Street

MONTREAL
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Price $2.50 Catalogue No. M42-162

Price subject to change without notice

ROGER DUHAMEL, F.R.S.C.
Queen's Printer and Controller of Stationery
Ottawa, Canada
1968

PREFACE

Geological investigations in the Mount Wright area of Quebec and Labrador show that the dominant rock types in that part of the region assigned to the Superior province of the Canadian Shield are hypersthene granulites. These rocks have characteristics similar to charnockitic rocks from other Shield areas of the world, and although such rocks have been described from Baffin Island which lies within the Churchill province, the Mount Wright occurrence was the first to be reported from the Superior province.

This bulletin describes these rocks in the Mount Wright area, their geological setting, distinguishing features, petrography, and modification by Grenville metamorphism; it compares them with similar rocks from Precambrian areas of other continents and presents some thoughts on their mode of origin.

Y. O. FORTIER,
Director, Geological Survey of Canada

OTTAWA, August 17, 1965

BULLETIN 162 — Die Pyroxen-Granulite des Kartenblatts Mount Wright in Quebec und Labrador

Von R. A. Roach und Stanley Duffell

Eine Erörterung der geologischen Lage, der Mineralogie, Petrographie und Petrogenese der pyroxenhaltigen Granulite in der tektonischen Provinz Superior gleich nördlich der Grenvillestirn und südwestlich der Labradormulde, nahe der Grenze zwischen Quebec und Labrador. Die Merkmale dieser Gesteine ähneln denen der Charnockitgesteine in anderen präkambrischen Gebieten.

БЮЛЛЕТЕНЬ 162 — Пироксеновые гранулиты картографированного района горы Урайт Квебека и Лабрадора

Р. А. Роч и Стэнли Дюффель

В этой работе обсуждаются вопросы геологической обстановки, минералогии, петрографии и петрогенезиса пироксеноносных гранулитов в Верхней структурной провинции, сразу же на север от гренвильской передней и юго-западной частей Лабрадорского прогиба, возле границы Квебека с Лабрадором. Отличительные черты этих пород подобны таковым в чарнокитовых породах других районов докембрия.

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THE PYROXENE GRANULITES OF THE MOUNT WRIGHT MAP-AREA, QUEBEC-NEWFOUNDLAND

Abstract

An assemblage of pyroxene-bearing granulite facies rocks occurring in the Superior province of the Canadian Shield immediately north of the Grenville front in the Mount Wright area, Quebec, has characteristics similar to those of charnockitic rocks from other Precambrian areas of the world. These rocks vary from leucocratic varieties composed essentially of alkali feldspar and quartz with more than 75 per cent silica to mafic pyroxene-rich varieties with less than 50 per cent silica. Most common varieties are quartz pyroxene–plagioclase granulites of intermediate composition and others with a granodioritic composition. The geological setting, mode of occurrence, distinguishing features, and characteristic minerals of these rocks are described as well as the petrography of the various types.

As these high-grade rocks are traced southward toward the Grenville front, they become progressively more recrystallized owing to later retrograde metamorphism related to the Grenville orogeny. Along the front the granulites have been converted to hornblende and biotite-bearing gneisses and schists similar to the almandine–amphibolite facies rocks within the Grenville province. The mineralogical changes involved in this retrograde metamorphism are described.

Petrogenesis of the granulites is dealt with and the role of the variables, temperature, water vapour pressure, and rock pressure, is discussed in relation to the nature of the feldspars, the presence of hydroxyl-bearing minerals, and the fabric of the granulites.

The status of charnockite nomenclature is considered in the light of the reinterpretation of the type area at Madras by Subramanian (1959), and the literature on the mode of origin of such rocks is reviewed. The authors propose a non-genetic classification in order to overcome previous confusion and place greater emphasis on chemical composition and the position of these rocks within the metamorphic facies concept.

Résumé

Un assemblage de roches à faciès de granulite pyroxénifère que l'on trouve dans la province Supérieure du Bouclier canadien, immédiatement au nord du front de Grenville, dans la région du mont Wright (Québec), possède des caractéristiques semblables à celles des roches charnockitiques des autres régions précambriennes du monde. Ces roches se distinguent à partir de variétés leucocrates composées essentiellement de feldspath alcalin de quartz qui contient plus de 75 p. 100 de silice jusqu'aux variétés abondant en éléments ferromagnésiens riches en pyroxène contenant moins de 50 p. 100 de silice. Les variétés les plus communes sont les granulites de plagioclases-pyroxène quartzifères de composition intermédiaire et d'autres de composition granodioritique. Le milieu géologique, le mode de gisement, les traits distinctifs et les éléments caractéristiques de ces roches sont décrits en même temps que la pétrographie de leurs différents genres.

A mesure que ces roches à haute teneur apparaissent au sud, dans la direction du front de Grenville, elles se recristallisent progressivement en raison du métamorphisme rétrograde ultérieur connexe à l'orogénie de Grenville. Le long du front, les granulites se sont transformées en hornblende et en gneiss biotitifère ainsi qu'en schistes semblables aux roches à faciès d'amphibolite–almandine, dans la province de Grenville. Les auteurs décrivent les changements minéralogiques qu'entraîne ce métamorphisme rétrograde.

La pétrogenèse des granulites est étudiée ainsi que le rôle des variables: température, pression de la vapeur d'eau et pression de la roche en fonction de la nature des feldspaths, la présence des minéraux contenant des hydroxyles ainsi que la structure des granulites.

La situation de la nomenclature charnockite est considérée à la lumière de la réinterprétation de l'aire type à Madras par Subramanian (1959), et la documentation sur la genèse de ces roches est passée en revue. Les auteurs proposent une classification non génétique dans le but de mettre fin à la confusion antérieure et insister davantage sur la composition chimique et la place de ces roches dans le concept du faciès métamorphique.

INTRODUCTION

During the study of the regional geology of Mount Wright map-area, Quebec–Newfoundland (reference 23B W/2 in the National Topographic grid of Canada), a group of pyroxene-bearing granulites was encountered that appeared to have many characteristics similar to those of the "Charnockite series" first described by Holland (1900), from Madras, India. Petrological studies have since revealed further similarities in mineralogy and chemical composition between the Mount Wright rocks and the several divisions of Holland's original series.

The evidence available in the Mount Wright map-area suggests that the granulites formed a large part of the eroded Archaean basement upon which the Kaniapiskau rocks of the Labrador Trough were deposited. During the Grenville orogeny both the granulites and the Kaniapiskau rocks were involved, in part, in the metamorphism and folding. North of the so-called Grenville front the granulites have retained their original characteristics, but south of the front they have been intensely folded, recrystallized, impregnated by granitic material, and converted to gneisses and schists of a lower grade. In some instances the effects of the Grenville metamorphism are over-shadowed by further retrograde recrystallization related to vertical movement along fault zones associated with the Grenville front.

Unfortunately the terminology for charnockites is controversial, with many authors using the terms in different senses and in reference to different rock types. Therefore, that the reader, who may not be too familiar with the charnockite controversy, will have some understanding of the terms 'charnockite', 'charnockite series', and 'charnockite suite', a short review is given of Holland's original definition of these first two terms and of their reinterpretation by Subramanian (1959). This is followed by a brief survey of the various origins postulated for rocks with charnockitic characteristics; consideration is given to the metamorphic facies concept so that a clearer picture may be presented of the relationship between charnockitic rocks, granulites, and the rocks here described.

Acknowledgments

The writers would like to express their thanks to all who helped in the various stages of this work: first, the technical staff of the Geological Survey of Canada for the preparation of thin sections and X-ray determinations; also, the staff of the geochemistry section for the work involved obtaining the four chemical analyses.

Our thanks also go to K. E. Eade and W. R. A. Baragar of the Geological

Manuscript received 6 July, 1965.

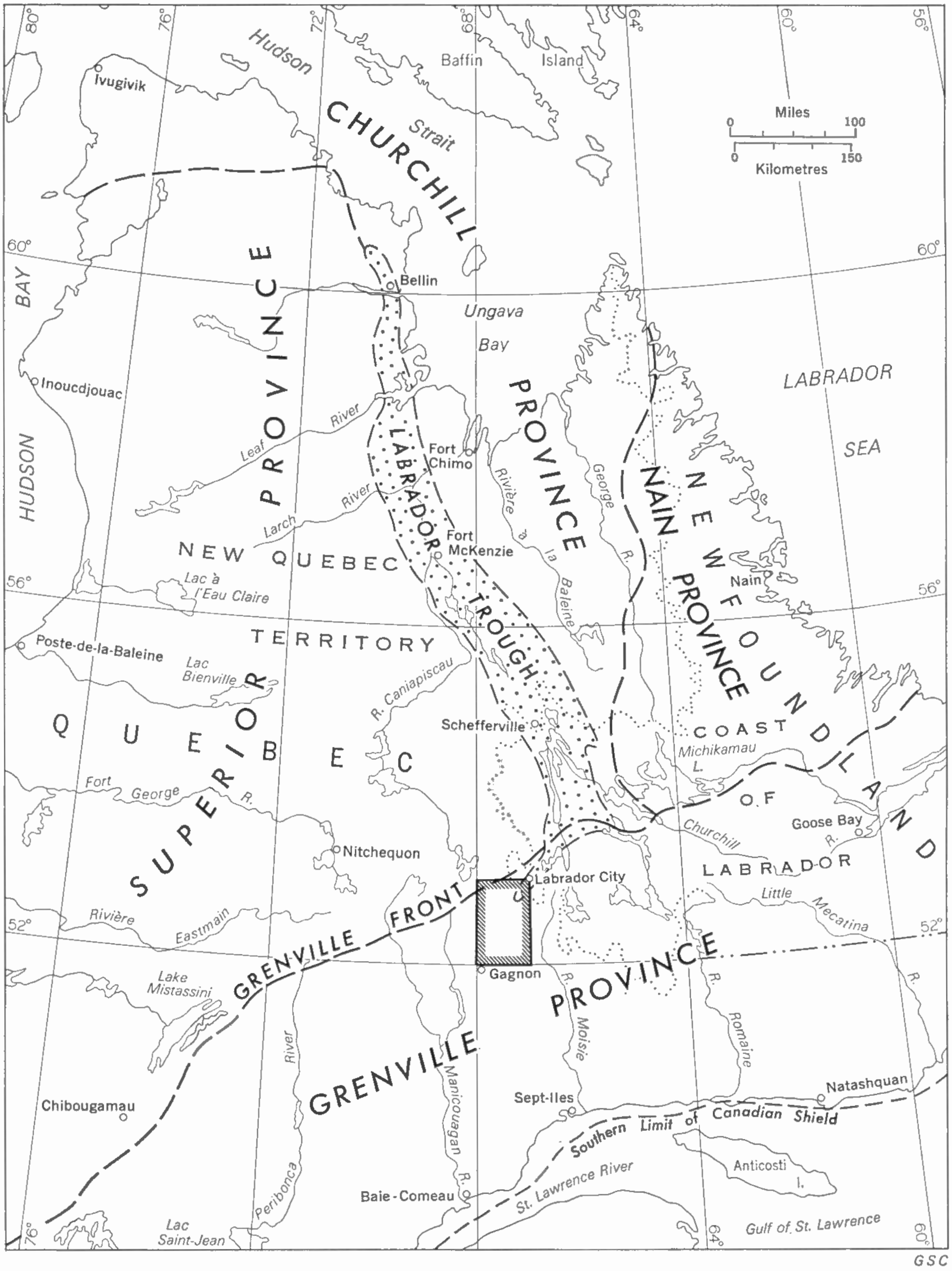


FIGURE 1. Location of Mount Wright map-area and its relation to the major tectonic units of New Quebec Territory and Coast of Labrador.

Survey of Canada, and to Graham Park and John Thomas of the University of North Staffordshire, England, for helpful discussion and information.

Nomenclature

Holland (1893) first used the term "charnockite" in reference to a hypersthene granite from Madras, India. The name was given in honour of Job Charnock, founder of Calcutta, whose tombstone was made of this rock. However, a few years later in his classic memoir on the Charnockite Series, Holland (1900, p. 130) used the term 'charnockite' as a "convenient name for a quartz–feldspar–hypersthene–iron-ore rock in the charnockite series and not as a name for any hypersthene granite occurring in other petrographical provinces." The term 'charnockite series' was applied to the whole group of rocks, including charnockite, which he believed were genetically related to one another and which varied from acid to ultrabasic in composition.

The group or series was characterized by several distinct petrographic qualities, of which perhaps the dark colour exhibited even by the acid varieties is most distinctive. This dark colour is due largely to the blue of the quartz and the dull green-grey of the feldspar. Mineral lineation, compositional banding, and general gneissose appearance along with an even-grained granulitic or panidiomorphic texture are common characteristics. Perthitic, antiperthitic, and myrmekitic relationships were observed in the intermediate and more acid rock types. A highly pleochroic hypersthene was present throughout the series, with augite, brown hornblende, and deep brown biotite occurring less consistently. Of the accessory minerals, magnetite and ilmenite were dominant, while in the gneissic varieties garnet was commonly present.

In 1959, Subramanian, after re-examining Holland's type area, redefined the terms 'charnockite' and 'charnockite series'. According to him, charnockite is a "hypersthene-quartz-feldspar rock with or without garnet, characterized by greenish-blue feldspar and greyish-blue quartz" (op. cit. pp. 345–346). He justified this redefinition on the ground that the paratype (Charnock's tombstone) is found to be garnetiferous and that this facies is prevalent in the area. He does not agree that there is a genetic relationship between the members of Holland's "charnockite series", and if the term 'series' is to be retained he would like it to be restricted to a group of related alaskites, charnockites (*in sensu stricto*), enderbites, and quartz hypersthene syenites, all of which are garnetiferous. However, for these rocks which correspond to Holland's acid division, Subramanian preferred the appellation 'charnockite suite'.

Howie (1955), on the other hand, from a geochemical and petrological study of charnockitic rocks from the type area, agreed more with Holland's views regarding the genetic relationships between members of the series. He regarded the various members as representing a plutonic igneous rock series that underwent slow recrystallization in the solid state on being subjected to plutonic metamorphism at the granulite facies level.

Holland (1900, p. 133) believed that the term 'charnockite series' should not be applied to apparently similar rocks outside Madras unless a genetic relationship could be proved. However, the striking similarity of these rocks with others since described in the Shield areas of Africa, Scandinavia, North America, Antarctica, and Australia has encouraged fairly wide use of the terms 'charnockite' and 'charnockite series'. In many cases the terms have been used indiscriminately so that there are in the literature, as Subramanian stated, numerous references to "Charnockite rocks which bear little resemblance to the type area". Also, according to Subramanian, Holland's classification of the charnockite series into acid, intermediate, basic, and ultrabasic divisions has been misunderstood and rocks have been described as acid, intermediate, and basic charnockites.

From the discussion above it can readily be seen that many differences of opinion exist on the interpretation and use of the terms 'charnockite' and 'charnockite series'. Authors such as Groves (1935) favour the adjective charnockitic in referring to rocks with strong similarities to those of the type area. The writers prefer this usage and have used it in this bulletin.

TABLE I *Nomenclature used by Holland (1900) in the Madras area of India, compared with that of Groves (1935) in Uganda, Subramanian (1959) in the Madras area, and the writers in Quebec–Newfoundland.*

1900 HOLLAND	1935 GROVES	1959 SUBRAMANIAN	1965 ROACH AND DUFFELL
'Acid' division of charnockite series, including leptynites. Several varieties described including charnockite *in sensu stricto.*	CHARNOCKITE SUITE	*Charnockite suite.* Alaskites (leucocratic granites). Charnockites (hypersthene granites or bikremites). Enderbites (hypersthene granodiorites).	*Acid granulites.* Granitic granulites (or hypersthene granite); similar to charnockite *in sensu stricto.* Granodioritic granulites (or hypersthene granodiorite); similar to enderbite. Aplogranitic granulites (or aplogranite); similar to alaskites. Can be garnetiferous.
'Intermediate' division of charnockite series, with contemporaneous veins and basic fine-grained schlieren.		*Hybrid rocks.* Homogeneous granodioritic rocks with xenoliths of basic granulite, and charnockite–pyroxene granulite migmatites composed of alternating layers of pyroxene granulite and coarse charnockite material. Coarse veins of charnockitic material occur in profusion, traversing these hybrid rocks.	*Intermediate granulites.* Biotite–pyroxene–quartz–plagioclase granulites. These occur interbanded with acid granulites. Together these rocks form a gently dipping layered complex of composite gneisses. Ptygmatic and crosscutting veins of aplogranite are common.
'Basic' division of charnockite series; equivalent in composition to norites.		*Basement rocks.* Pyroxene granulites and variants containing hornblende, garnet, biotite, etc. Appear to be reconstituted sheets of norite or gabbro	*Basic granulites* *Pyroxene–plagioclase granulites.* Biotite pyroxene–plagioclase granulites with occasional hornblende. These occur as

TABLE I (*Conc.*)

1900 HOLLAND	1935 GROVES	1959 SUBRAMANIAN	1965 ROACH AND DUFFELL
	↑ CHARNOCKITE SUITE ↓	associated with the metasedimentary basement; some of them may be reconstituted calcareous rocks. Present as lenticular bodies and as xenoliths in the hybrid and charnockitic rocks; form the mafic component in the migmatitic facies. Some granulites carry nodules of calc-silicate rock.	thin bands and lenses within the intermediate granulites. Nodules of diopside–plagioclase granulite are occasionally encountered.
'Ultrabasic' division of charnockite series.		*Syntectonic lenses of basic rock.* Norite with layers and schlieren of pyroxenite.	*Pyroxene-rich granulites.* Mafic, rich in pyroxene. Less than 20% plagioclase, occurrence similar to that of the pyroxene–plagioclase granulites.
Not recognized.		*Basement rocks.* Schistose gneisses composed of quartz, feldspar, biotite, garnet, sillimanite and frequently graphite (khondalites). Leptynite appears to be thoroughly reconstituted and recrystallized facies of the above. Thin interstratified bands of magnetite quartzite.	No other rocks encountered.

Postulated Origins of Charnockitic Rocks

As with the nomenclature, confusion about the origin of rocks with charnockitic affinities has ensued. Howie (1955, p. 726) has stated the problem well: "As many modes of occurrence have been suggested for these rocks as there have been descriptions of them". It would appear that there are charnockites and charnockites just as there are granites and granites.

The magmatist school, represented by such authors as Vogt (1893), Washington (1916), Suter (1922), Groves (1935), Tilley (1936), and Rajapolan (1946), envisages the charnockites as igneous rocks that formed through differentiation of an original magma with perhaps some contamination and hybridization. Of these authors, Suter, Tilley, and Rajapolan have stressed the relative paucity of water of the magmatic phases giving rise to such rocks. Others considered the genetic relationship between charnockites and anorthosites. Stillwell (1918) and Howie (1955a), although adhering to the magmatic concept, postulated some recrystallization under plutonic metamorphism at some stage during or after initial crystallization.

In 1918, Vrendenburgh suggested that certain charnockites in south India resulted from the high-grade metamorphism of sedimentary and volcanic rocks. Since then an increasing number of authors, including Groves (1935), Quesnel (1951), and Buddington (1952), have postulated the contribution of both magmatic and metamorphic processes to the formation of rocks with charnockitic affinities. The relationship between various types of charnockitic rocks cannot always be explained in terms of simple isochemical metamorphism or contamination, and such authors as Schoeman (1951), Pichamuthu (1953), Subramanian (1959), and Compton (1960) have suggested the action of such processes as metasomatism through wet diffusion, migmatization, and palingenesis, in addition to metamorphic recrystallization.

Ramberg (1948) attributed the west Greenland occurrences to high-grade metamorphism and considerable metasomatism along with some reactivation of the acid members. Bugge (1945), who may be said to represent the extremist school of dry diffusionists, believed that dry diffusion and reaction in the solid state was of prime importance in the formation of migmatitic rocks with charnockitic features in the Arendal district of Norway.

The brief review above illustrates the wide range of opinions about the origin of charnockitic rocks. This, together with the different terminology used by Howie and Subramanian for the type area, accentuates the uncertainty that will exist as long as the definition of terms is based on mode of origin. Were the emphasis to be placed on petrographical characteristics, which would be contrary to Holland's original view, less confusion would ensue. The term 'charnockite series' or 'charnockite suite' could well be dropped in favour of the adjective 'charnockitic' applied to quartz–feldspar rocks that are generally dark in colour, contain orthopyroxene, are characterized by greenish blue feldspar, and greyish blue quartz and have an even-grained granulitic texture. The term 'charnockite' (*in sensu stricto*) used for a specific type of granite, need not suffer the same fate. If 'charnockitic' rocks are to be classified on the basis of their petrographical characteristics, which are in turn a product of their environment of crystallization, one may properly discuss them in the light of the metamorphic facies concept.

The Metamorphic Facies Concept Applied to Charnockitic Rocks

Parras (1958) observed that even though a considerable part of charnockite research has been devoted to probing possible modes of origin, the end products of different processes are often similar. The overall mineralogy of the varieties of charnockitic rock is governed by such factors as rock pressure, water vapour pressure, and bulk chemical composition during their crystallization. Even in the early papers dealing with charnockitic rocks, the probable high-temperature and depth environment of these assemblages was suggested and the relative scarcity of hydroxyl-bearing minerals was thought to indicate a dry environment. Stillwell (1918) related these rocks to Grubenman's katazone. Several years later Tyrrell (1926) postulated that the rocks were a product either of crystallization of a magma under high temperatures and pressures or of plutonic metamorphism in a similar environment.

Korjinsky (1936, et seq.) assigned the charnockitic rocks of the Aldan Massif to an 'Aldan facies' and was one of the first workers to relate the mineral assemblages to a specific temperature–pressure field. His estimate was based in part on the stability of calcium- and magnesium-bearing silicates under carbon dioxide pressure. Dunn (1942) suggested that variation in water content might explain some of the differences in mineral assemblages in localities where rocks with a mineral assemblage characteristic of the almandine–amphibolite facies are interdigitated with rocks with a mineral assemblage associated with the granulite facies.

The association of non-charnockitic and charnockitic minerals within the granulite facies has been considered by Ramberg (1948, et seq.), who concluded that the granulite facies metamorphism in west Greenland was far from isochemical. If these views are adopted, the final composition of a given rock will be of little use in determining the original nature of granulites and charnockites in general. It is possible that the composition of these high-grade rocks is controlled to a certain extent by the stability of the fields of the minerals formed. If this is so, then there may be certain ranges of bulk composition that would be rare or even absent at the highest metamorphic levels.

The possibility of setting up a special charnockitic facies lying between the granulite and eclogite facies was investigated by Quesnel (1951, p. 306). The presence in his Swedish charnockitic rocks of hydroxyl-bearing hornblende and biotite was thought to point to disequilibrium among the different constituent minerals. It should be pointed out, however, that though Eskola (1952, p. 140) stated that "Amphiboles and micas do not belong to the granulite facies", and did not list these as typomorphic minerals, he did indicate that they were present in certain types of granulite, possibly in equilibrium with the other minerals, although they appeared to form late in the paragenetic sequence. From a review of the literature dealing with the presence of hydroxyl-bearing phases in charnockites, it appears that in some instances both biotite and hornblende may be in equilibrium with other anhydrous mafic mineral phases over certain ranges of chemical composition (e.g., Parras, 1958, pp. 93–96 and pp. 107–109). This question is referred to again when the hydroxyl-bearing mineral phases in the present examples are discussed.

It is interesting to note what Eskola himself had to say concerning the charnockitic rocks that are present in his granulite assemblages from Finnish Lapland (Eskola, 1952, pp. 133–171). There, hypersthene-bearing granulites, in part identical with charnockitic rocks, occur as bands with more acid granulites and calcareous granulites that were thought to be the metamorphosed equivalents of arenaceous, pelitic, and calcareous sedimentary rocks. The equivalents of the basic and ultrabasic varieties of Holland's charnockite series were denoted as basic and ultrabasic granulites, respectively, and were thought to represent original volcanic or hypabyssal rocks. The equivalents of the more acid varieties of the charnockite series were called hypersthene diorites and were supposed to represent magmatically emplaced phases. Though Eskola recognized the similarities involved he was careful not to attach any charnockite terminology to his granulites.

The Pyroxene-Bearing Rocks of Mount Wright Map-Area

From the preceding examination the writers consider the pyroxene-bearing rocks of the Mount Wright area to be granulites. Though their resemblance to various members of Holland's charnockite series is close, the emphasis in this paper is placed on their position within the metamorphic classification. Regardless of the origin of these rocks, their present mineral assemblage can be compared to that of other granulites (termed charnockite or not) that have reached equilibrium or near equilibrium under similar plutonic conditions.

The granulites of the Mount Wright map-area have a wide range of composition, from leucocratic (aplogranitic) types with more than 75% SiO_2 to mafic pyroxenitic types with less than 50% SiO_2. They can be broken into three groups as acid, intermediate, and basic. In the area examined the acid and intermediate granulites formed the greater part of the observed outcrop. The more acid varieties vary from medium-grained rocks with granoblastic texture to coarse-grained or even pegmatitic. The coarser grained types have an inequigranular subidiomorphic (blastic) texture. These acid varieties, for convenience, are referred to generally as acid granulites, though in some instances, depending on their precise composition, they may be variously referred to as granitic granulites, granodioritic granulites, or aplogranitic granulites. The granulites of an intermediate or basic composition are medium to fine grained with either granoblastic or nematoblastic texture where a mineral lineation is developed.

Though variation in chemical composition produces several distinctive rock types, their mineralogy is universally the product of crystallization at high temperature and pressure and was controlled in part by water vapour pressure. The granulites of intermediate and basic composition appear to have formed through the solid state recrystallization of earlier rocks. The acid granulites on the other hand possessed some degree of mobility at the time of their formation and emplacement. These latter are thought to be partly the products of crystallization from a liquid-crystal mesh phase. Subsequent recrystallization of the acid granulites has produced their present metamorphic texture. Field and microscopic evidence suggests in addition that a certain amount of metasomatic segregation has occurred.

GEOLOGICAL SETTING OF THE PYROXENE GRANULITES

Distribution

The pyroxene-bearing granulites of this report occur in the northern third of Mount Wright map-area (Duffell and Roach, 1959), or the part underlain by rocks of the Superior structural province of the Canadian Shield (Fig. 2). The remainder of the area is underlain by gneisses and schists of the Grenville province. There is no doubt that most of the gneisses and schists in the Grenville are metamorphic equivalents of the rocks to the north. The contact between the granulites and the lower grade gneisses of the Grenville province is the Grenville front, which here takes the form of a gradational zone striking east-northeast from Lac Gensart to Lac Virot.

Figure 2 shows the main geological features of the Mount Wright area (after Duffell and Roach, 1959). The northern limit of the Grenville orogeny is marked by the Grenville front (line AA-BB on Fig. 2). Minor fringe effects, which resulted in small amounts of recrystallization of the granulite facies rocks, are still encountered several miles from the front. The pyroxene-bearing rocks of the Superior province described in this report are to the north and west of the Grenville front. To the south of the front these high-grade rocks along with the overlying Kaniapiskau Supergroup rocks have been intensely refolded, metamorphosed, and subjected to considerable migmatization. The present distribution of the iron-formation and associated quartzite and dolomite (shown in black on Fig. 2) illustrates the intensity of the orogeny and indicates two main fold directions: (1) NE-SW; (2) NW-SE (varying NNW-SSE). In the large downfolded areas to the southeast, the metamorphosed carbonaceous shales and volcanic rocks overlying the iron-formation have been preserved. In the centre and west of the area, the gneisses and schists lying some distance below the iron-formation are thought to be reconstituted granulite facies basement rocks. The gneisses and schists immediately beneath the iron-formation of sedimentary origin represent the basal beds of the Kaniapiskau Supergroup.

In Mount Wright map-area the gneisses within the Grenville province include thin bands of marble, quartzite, and iron-formation, overlain by graphitic schists and hornblende gneisses that are considered by the writers to be metamorphosed equivalents of rocks of the Kaniapiskau Supergroup (Frarey and Duffell, 1964) of the Labrador Trough. North of the Grenville front, strata of the Kaniapiskau Supergroup clearly lie unconformably on granulites and granitic rocks, but south of the front this unconformity has been erased. The Kaniapiskau Supergroup

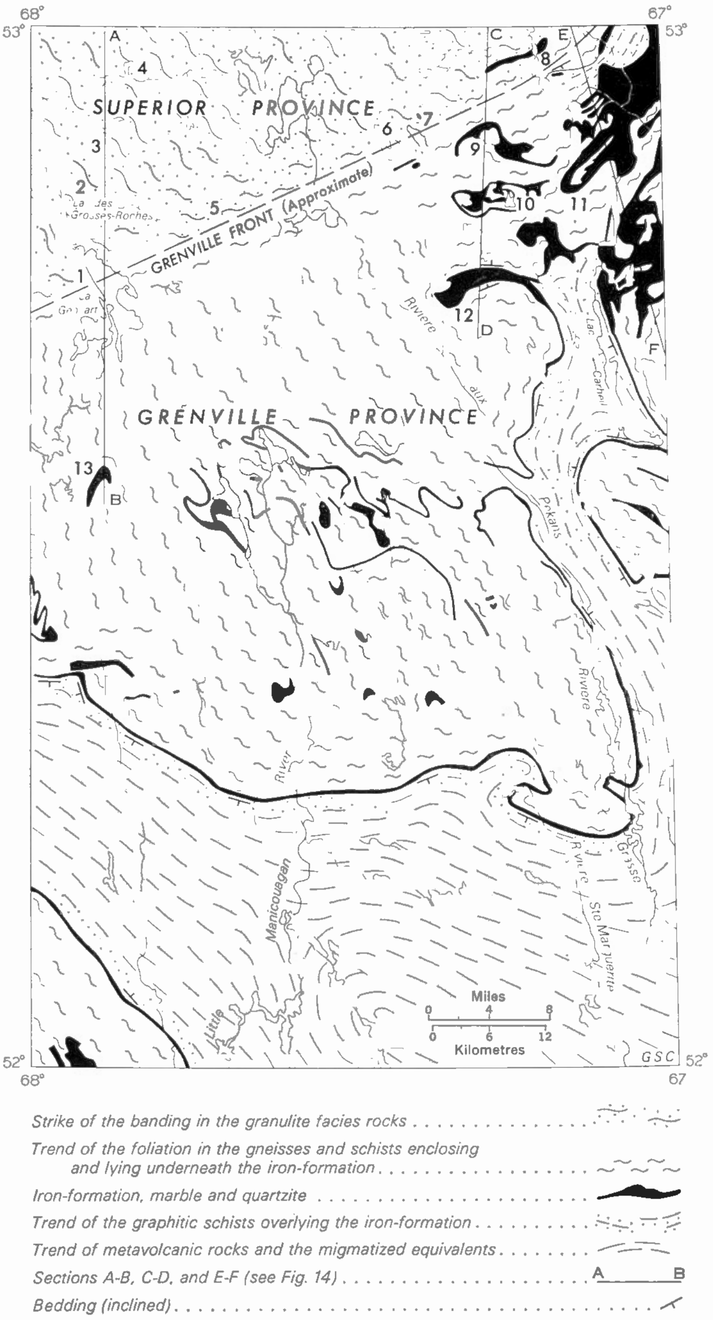


FIGURE 2.
Main geological features of the Mount Wright area (after Duffell and Roach, 1959).

LOCALITIES REFERRED TO IN TEXT

1. Lac Gensart
2. Lac des Grosses-Roches
3. Seahorse Lake
4. Lac Sheree
5. Crown Lake
6. Lac Cherney
7. Boulder Lake
8. Lac Virot
9. Sudbury Lake
10. Bloom Lake
11. Tupper Lake
12. Mount Wright
13. Olga Mountain

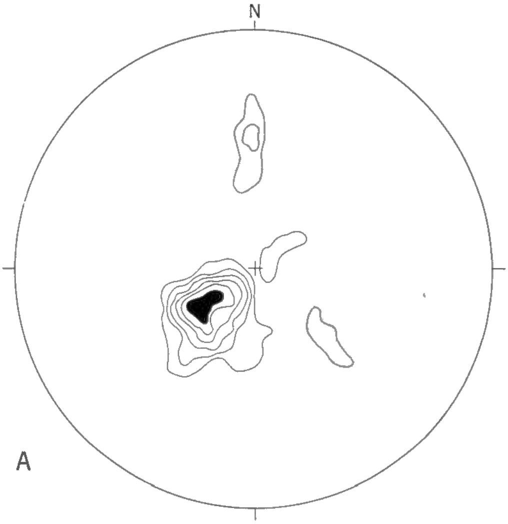
rocks north of the Grenville front (Frarey, 1961; Fahrig, 1960) are at the greenschist level of metamorphism, but south of the Grenville front they have been raised to about the kyanite–muscovite subfacies of the almandine–amphibolite facies. The underlying granulites on the other hand have been downgraded to the almandine–amphibolite facies. Because of this equalization of the grade of metamorphism on both sides of the unconformity in the Grenville province, it is difficult to distinguish basement rocks from rocks of the Kaniapiskau Supergroup. Fortunately the marble, quartzite, and iron-formation members, perhaps because of their monomineralic character, retained their identity throughout the Grenville metamorphism. These strata form an easily recognizable horizon, but unfortunately other formations are not so readily recognized in their metamorphosed state. Thus it is possible that, in the wide areas of gneisses between outcrops of recognizable Kaniapiskau rocks, occurrences of basement granulites and their metamorphosed equivalents have not been recognized.

Rocks similar to the pyroxene granulites described in this paper have been reported from various parts of the Superior province northwest of the Mount Wright area and west of the Labrador Trough. Eade, *et al.* (1959) and Stevenson (1962) both reported the presence of such rocks in their reconnaissance surveys north of 53 degrees latitude and west of the Trough. Fahrig (1960) reported similar granulites along the western margin of the Labrador geosyncline in the Shabogamo area immediately northeast of Mount Wright area. In all these areas the Kaniapiskau rocks of the Labrador geosyncline rest with major unconformity on the older gneisses. It would seem therefore that the pyroxene granulites formed a large part of the massif around which the sediments of the Labrador geosyncline were deposited. The granulites of this massif were most probably formed during the Kenoran orogeny (2,500 ± 100 m.y. ago). For K–Ar ages in this part of the Canadian Shield *see* GSC Paper 64-17.

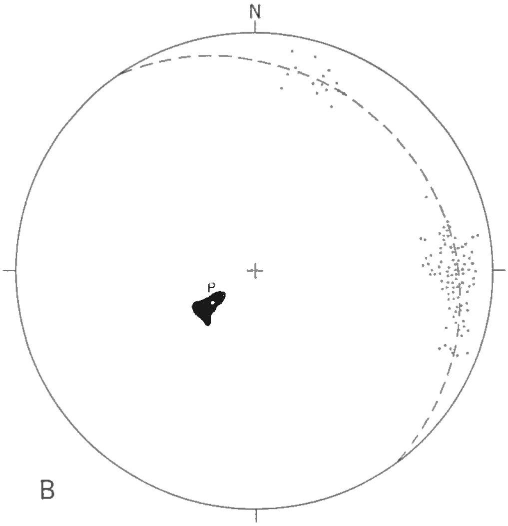
Mode of Occurrence

Granulites of acid and intermediate composition are the most common varieties. They alternate in layers and thin lenses to produce banded gneisses, which strike NW-SE or NNW-SSE with the dip at low to moderate angles (generally less than 35 degrees) to the northeast or north-northeast (Fig. 3A). The banding is a result of two distinct relationships. The first is small-scale banding, as much as several centimetres thick, within the intermediate granulites due to variation in the ratio of felsic to mafic minerals. The second relationship is an alternation of layers, lenses, and tongues, as much as several metres thick, of acid and intermediate granulite resembling a migmatite, but which is better defined as a banded gneiss (Pl. I).

Locally a more irregular distribution of the granulites may be developed. Irregular patches of acid granulite may be found within areas of intermediate granulites. Also the acid granulites may vary in grain-size from pegmatitic to medium grain and in their quartz–feldspar and plagioclase–microcline ratios. The contact between the acid and intermediate granulites may be sharp or transitional

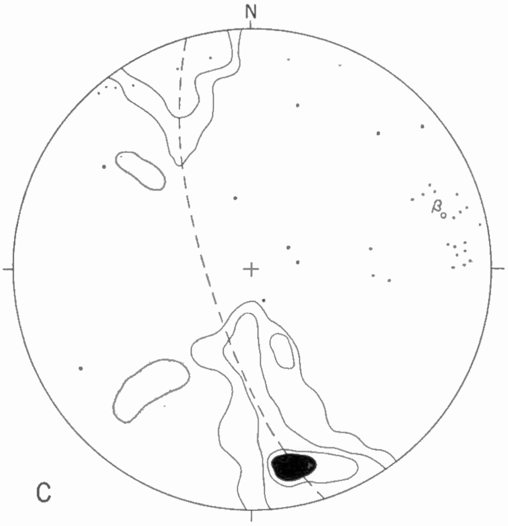


Orientation of the banding in the granulites in the northwest corner of the Mount Wright area. Plots of seventy poles to banding have been plotted and contoured. The regular attitude of the gentle northeasterly dip of the granulites is indicated by the restricted field of the contours. Contours at 1-2-3-6-10-15 per cent per one per cent area.

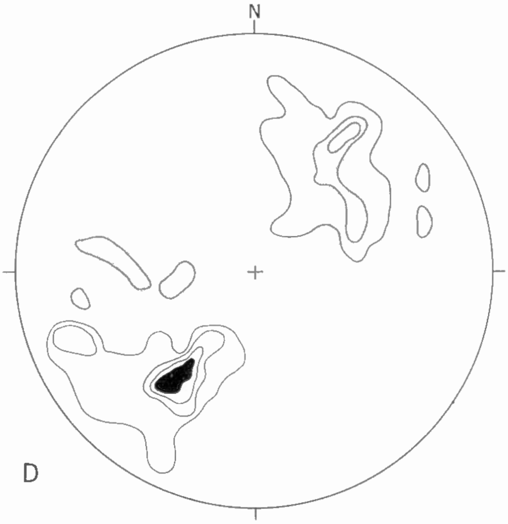


Plots of 100 lineations measured within the granulites. The main set of easterly plunging lineations are formed of minor fold axes and mineral elongation. The later generation of north-northeasterly plunging lineations are all of minor fold axes. Both generations of linear structures are seen to be spread along the plane of the granulite banding which is defined statistically by the great circle (in dashes). The 15 per cent contour of Figure 3A is shown surrounding the pole P of this great circle.

FIGURE 3. Stereograms showing orientations



Orientation of the foliation in the recrystallized granulites along the Grenville front between Lac Virot and Lac des Grosses-Roches. Poles to 110 foliations have been plotted and contoured. Linear structures are plotted as small dots. It is apparent from the distribution of the contours that the foliation generally trends ENE-WSW and dips to the north-northwest. This trend is parallel to the line of the Grenville front. The axis of folding along the Grenville front can be defined statistically by the pole to the girdle formed by the spread of the contours. This statistically defined fold axis β is seen to lie within the field of a set of lineations which include minor fold axes. The ENE-WSW structural trend appears to be governed therefore by folding about axes that generally plunge to the east-northeast. Contours at 1-2-3-5 per cent per one per cent area.



Orientation of the foliation in the almandine amphibolite facies gneisses south of the Grenville front and north of the belt of iron-formation between Mount Wright and Mount Olga. Two hundred poles to foliation have been plotted and contoured. The structural trend to the south of this section of the Grenville front is seen to be governed by folds which trend between NW-SE and NNW-SSE. These folds are thought to postdate the WSW-ENE trending folds developed along the Grenville front. Contours at 1-2-3-5 per cent per one per cent area.

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of banding, lineation, and foliation in the granulites.

across several centimetres. Thin selvedges rich in pyroxene and biotite may separate these two rock types. The patches of acid granulite commonly occur as ribbons, seams, and lenticular patches parallel with the larger scale banding producing a rock resembling a hybrid, but which is better defined as a composite gneiss (Pls. II and III). In addition to this banding, there is in many instances marked alignment of the longer axes of the pyroxene and plagioclase grains. This lineation is best developed in the intermediate and basic granulites. In thin sections cut parallel with this lineation the texture is seen to be typically nematoblastic (Figs. 7B and 8B); perpendicular to this the texture is typically panidioblastic granular (Fig. 8A). The lineation commonly plunges in an easterly direction at 10 to 20 degrees (Fig. 3A).


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PLATE I.
Bands of coarse hypersthene granite (acid granulite) are seen alternating with bands of finer grained intermediate and basic granulite. The intermediate and basic granulites themselves are banded on a smaller scale and contain lenses and thin selvedges of granitic rock. The photograph was taken looking at a vertical rock face almost parallel with the strike of the banding.

Whereas the acid and intermediate granulites alternate to produce the larger scale banding, the basic granulites are present mainly as thin seams and lenses within the intermediate granulites, or as rounded or subangular inclusions within the acid granulites (Fig. 4 and Pl. I). The thin bands of basic granulite may vary rapidly in thickness laterally so as to show 'pinch and swell' structures, which can

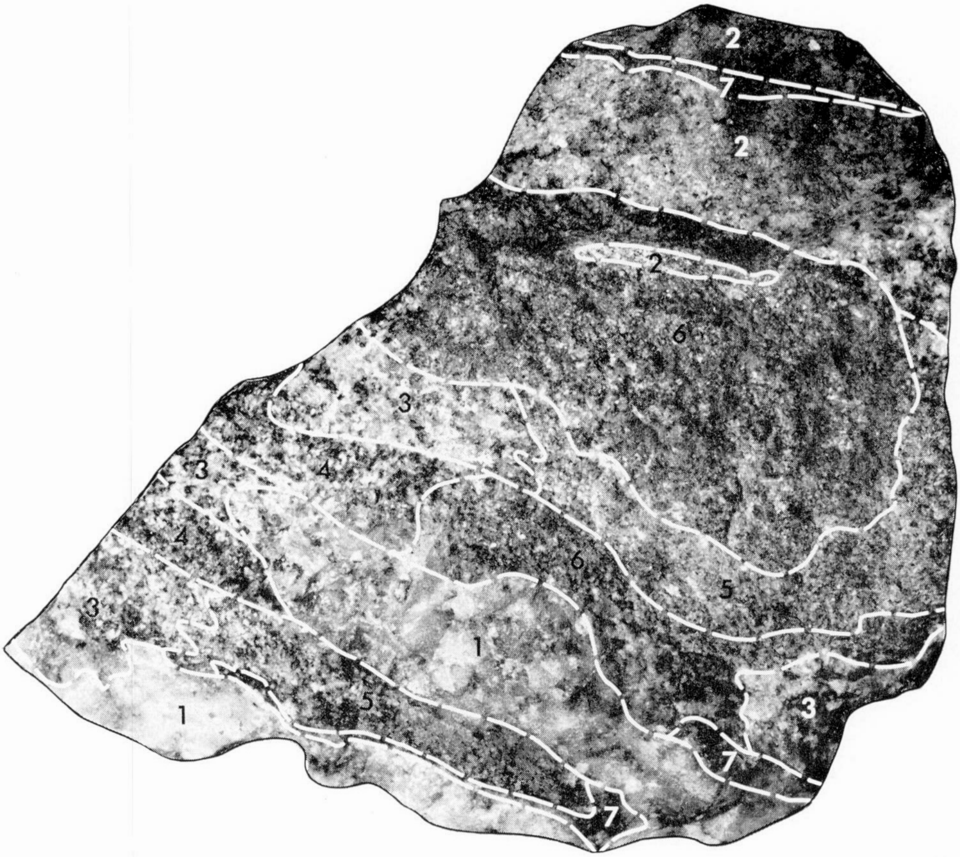

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PLATE II. Specimen of composite gneiss illustrating the intimate manner in which the various types of granulite are associated. This intimate association of several phases of contrasting composition may be partly explained by some process of metasomatic segregation, possibly accompanied by local melting so as to produce pockets of acid magma.

1. Coarse-grained quartz-rich rock with minor feldspar.
2. Medium-grained hypersthene granodiorite (acid granulite) with oligoclase, potash feldspar, and quartz.
3. Coarse-grained quartz–pyroxene–plagioclase granulite.
4. Coarse-grained pyroxene–plagioclase granulite.
5. Medium-grained quartz–pyroxene–plagioclase granulite.
6. Medium-grained pyroxene–plagioclase granulite.
7. Pyroxene-rich seams and lenses.

be traced into a series of isolated lenses separated by intermediate or acid granulite. The acid granulites have a more uneven granoblastic or granitic texture.

Figure 4 shows sketches of some of the relationships observed between the acid granulites and the intermediate and basic ones. All four sketches were drawn looking down the easterly plunge of the mineral lineation. Acid granulites are shown as blanks, intermediate granulites as short dashes (which also indicate the trend of the small-scale banding), and basic granulites in black. North is to the left in all examples.

Figure 4A shows thin offshoots leaving thicker bands of acid granulite and crossing the layers of intermediate basic granulite at a highly oblique angle. These

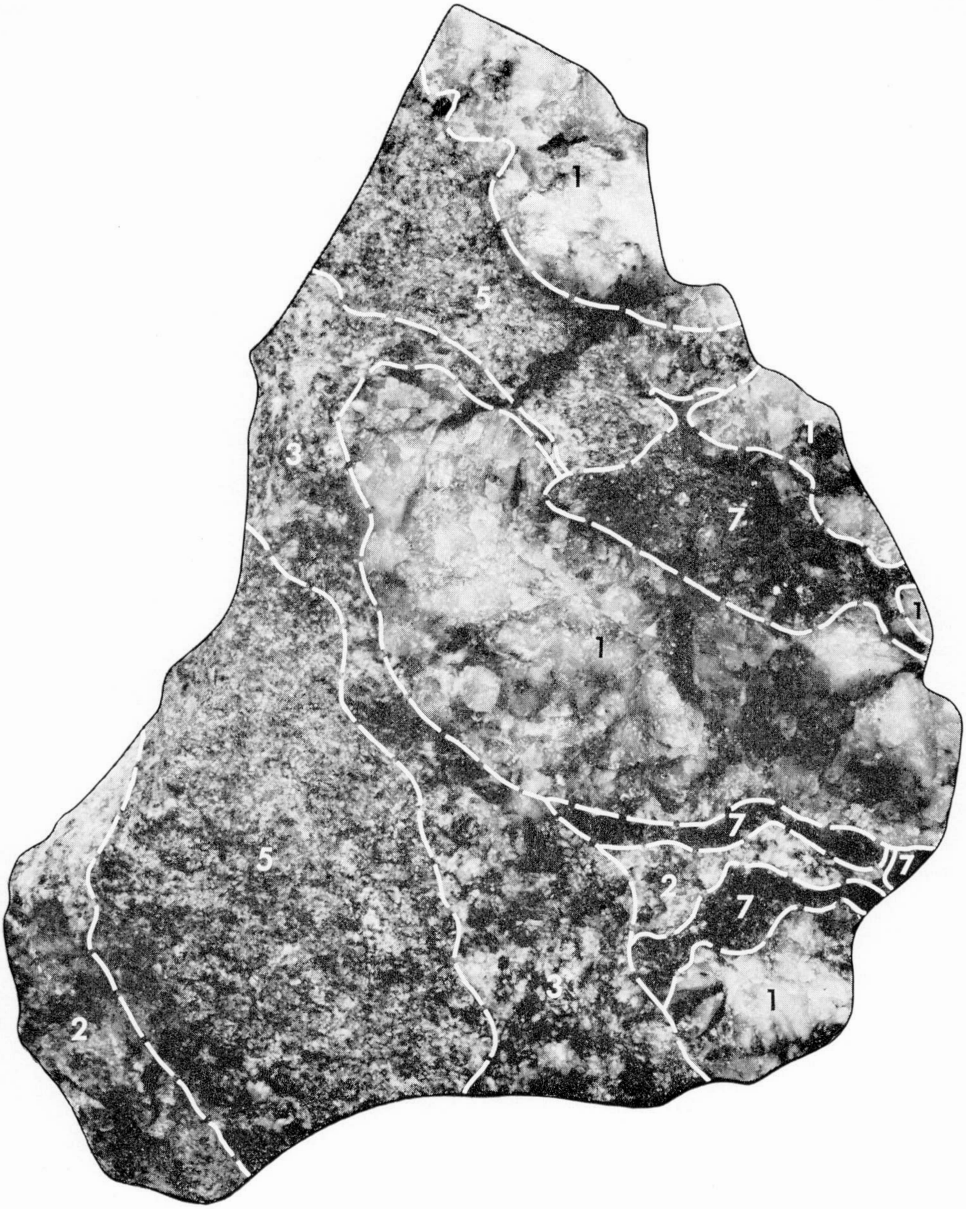

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PLATE III. Opposite side of specimen shown on Plate II. A marked feature on both plates is the rapid variation in grain-size across a small distance. The mafic patch on the right-hand side consists of biotite and pyroxene crystals as much as an inch long. Numbers represent same facies as shown on Plate II.

crosscutting veins are generally convex northwards. They may be rimmed by thin selvedges of pyroxene and biotite, and, except immediately adjacent to the veins, the smaller scale banding in the intermediate granulites is not markedly distorted. The crosscutting veins tend to be parallel sided and do not in general show small-scale plication. The veins are thought to have been emplaced at a late stage in the formation of the complex, when stretching of the more competent bands of granulite caused cross-fractures, that were filled with crystallizing granitic material. The convex form of these cross-veins, however, suggests that some type of differential movement parallel with the banding may also have been in operation.

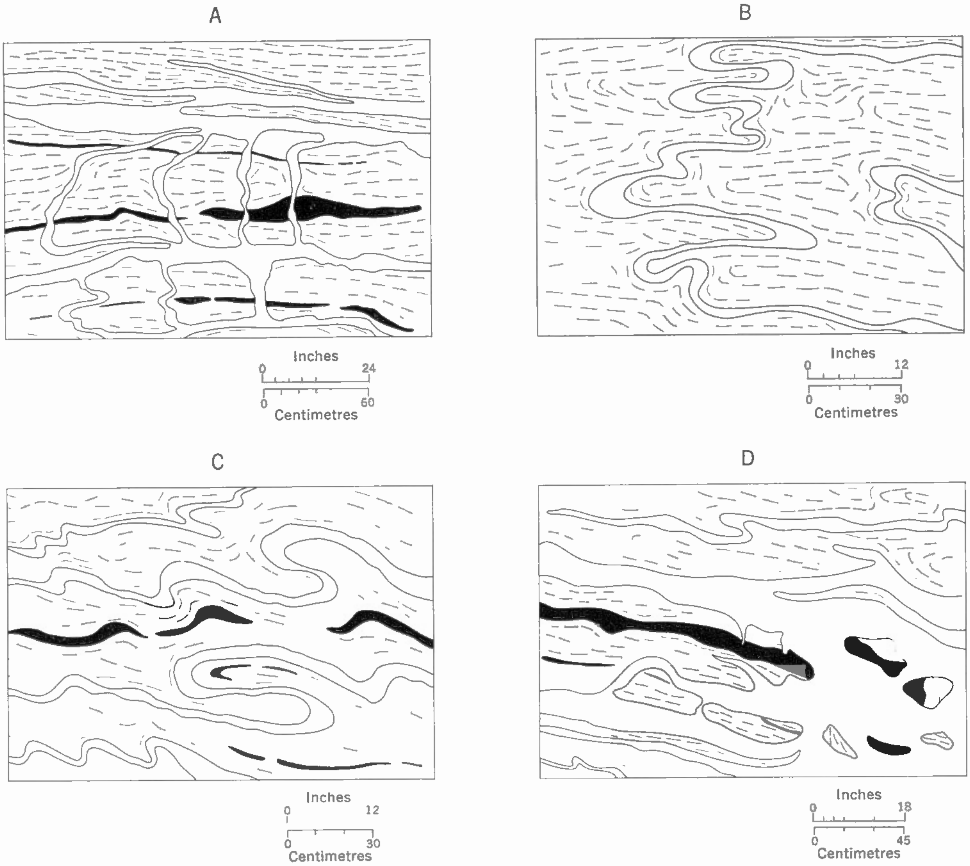

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FIGURE 4. Sketches showing some of the relationships observed between the acid granulites and the intermediate and basic granulites. See text for explanation.

Figure 4B shows complex paratectonic injections of primary origin. The axes of the ptygmatic folds are parallel with the mineral lineation. The banding in the intermediate granulites is only notably disturbed adjacent to the injection veins, while the axial planes of the folded veins are nearly horizontal and parallel with the plane of the banding.

Figure 4C shows alternating bands and lenses of acid, intermediate, and basic granulite, and small-scale folding with axial planes overturned northwards. Along such zones, there has been considerable sub-horizontal shear movement causing plastic flow of material and distortion of the banding during and after the formation and emplacement of the acid granulites.

Figure 4D shows blocks of intermediate and basic granulite suspended within acid granulite (hypersthene granite). These occur in areas where the proportion of acid granulite is high, and resemble features produced by magmatic stoping. The banding displayed in these inclusions has a random orientation. This feature along with the magmatic stoping observed to the left, indicates that the acid granulites were mobile and capable of penetrative movement at some stage during their formation.

Along the northern margin of the area examined, farthest away from the Grenville front, the dominant rock type is the intermediate granulite. It carries smaller amounts of acid granulite in the form of thin bands and lenses parallel with or occasionally crosscutting the intermediate granulite. Complex paratectonic ptygmatic veins of aplogranitic acid granulite occur, against which the small-scale banding and fine biotite foliation may or may not sweep in a concordant manner (Fig. 4A and B).

These aplogranitic veins may be present as small folds overturned to the north with their fold axes parallel with the mineral lineation in the intermediate granulites. Their variation in thickness from limb to limb and the parallelism of axes of the folds with the regional lineation indicates a form governed by tectonic movement (Fig. 4B). Less commonly, these veins occur as offshoots crossing a band of intermediate granulite and connecting two parallel layers of acid granulite. Here, even though they have a tortuous outline, the banding within the intermediate granulite (except immediately adjacent to the vein) is undisturbed. Such highly folded veins crossing comparatively undisturbed banded granulites indicate a form of ptygmatic injection, as proposed by Wilson (1952, p. 20), whereby the vein was buckled during its period of injection. Since these ptygmatic veins are similar in composition to the bands of acid granulites it would appear that the injection, movement, and crystallization of the latter took place both during and after the period of stress producing the dominant lineation in the intermediate granulites. Further evidence of this relationship is given below.

The proportion of acid granulite increases southwards until the banded gneisses contain nearly equal proportions of acid and intermediate granulites. A further stage is the nearly complete enclosure within the acid granulite of discontinuous bands and lenses of the basic and intermediate granulite (Fig. 4D). Here is further evidence of the mobility of the acid granulite at the time of its formation, as the banding and lineation in these inclusions is randomly oriented. As the continuity of the bands of intermediate and basic granulite is destroyed, the acid granulite develops a more definite foliation, which is oriented east-northeast, approximately parallel with the contact zone with lower grade rocks to the south of the Grenville front (Fig. 2).

Within the granulite, the gneissic banding is locally deformed into small folds that are best observed on an outcrop surface of several feet. The axes of these folds are approximately parallel with the mineral lineation and plunge in an easterly direction at a low angle (Fig. 3C). The folds vary in cross-section from gentle undulations to tight flexures that may be overturned to the north in a recumbent manner. The ptygmatic folds mentioned above commonly have their axes parallel with this easterly plunging fold-direction with a nearly horizontal axial plane. Where folding about these easterly plunging axes is intense, the banding in the granulites becomes vague and mineral lineation becomes more pronounced. Locally there is evidence of folding about axes plunging at a low angle in a north or north-northeast direction (Fig. 3A). Such folds are generally open and gentle, but where they are intense the easterly plunging folds were not observed. North-easterly plunging folds do not appear to be accompanied by new mineral lineation and are therefore considered to represent a late phase of cross-folding.

The nature of the structures previously described gives some idea of the conditions existing during their formation. At the high temperatures and pressures under which granulites form a plastic style of deformation is possible. Paratectonic ptygmatic folds, 'pinch and swell' structures, and boudinage phenomena are products of such a plastic style of tectonism. Some of the structures so produced compare with the flow folds of Wynne-Edwards (1963).

Even in those localities farthest away from the Grenville front, all varieties of granulite show some degree of alteration to a mineral assemblage more typical of a lower metamorphic grade. It is not always easy to distinguish, however, whether the later amphibole replacing the pyroxene is the result of subsequent metamorphism, or of normal retrograde changes, which many high-grade metamorphic rocks of the pyroxene granulite facies experience when uplifted to higher levels in the earth's crust.

There is stronger evidence, however, of effects of the later Grenville metamorphism as one approaches the lower grade rocks to the south. It is evident that an almandine–amphibolite facies level of metamorphism has been superimposed on the earlier granulites. Concomitant with the mineralogical changes, there has been some remobilization and refolding of the acid granulites, as can be seen from the manner in which they develop a foliation, the trend of which changes as the contact zone is approached (Fig. 3B and C).

Superimposed on the textures and fabric related to the granulite facies metamorphism are such cataclastic phenomena as shearing, microfracturing, and granulation related in part to the marginal effects of the later Grenville orogeny. These structural adjustments were accompanied by alteration of the earlier minerals and crystallization of new ones stable under these later conditions. These relationships were observed for the granulites marginal to the Grenville front. Along the Grenville front, however, nearer the orogenic belt, the higher temperature and pressure conditions resulted in the formation of a completely new fabric and mineral assemblage. The overall picture is, therefore, of a relatively rigid foreland to the north, during the Grenville orogeny, that became structurally less rigid (more mobile) southwards, and was incorporated within the Grenville orogenic belt south of the Grenville front. The Grenville front represents, therefore, the transition from the rigid foreland to mobile root zone of the Grenville orogenic belt. This root zone was originally overlain by the Proterozoic Labrador geosynclinal deposits, which are now recrystallized and complexly folded along with the recrystallized granulite basement.

DISTINGUISHING FEATURES AND CHARACTERISTIC MINERALS

Distinguishing Features

Many of the distinguishing features of the granulites of the Mount Wright region are similar to the ones attributed to charnockitic rocks described from other countries (e.g., Holland, 1900; Groves, 1935; Quesnel, 1951). In general, the intermediate and basic granulites are dark grey rocks that weather to a dull rusty or buff colour. Members of the acid variety and in particular the aplogranitic types may be leucocratic in character. This is particularly the case near the Grenville front where such rocks have experienced some recrystallization and remobilization. Away from the front the acid granulites become grey, rarely dark grey, with dull grey, brownish grey, or dull greenish feldspars, and dark grey or bluish grey quartz. It is possible that the partial recrystallization and remobilization of the acid granulites, during the Grenville metamorphism, has been responsible for the formation of a light-coloured rock, an anomalous feature when compared to the normal dark colour of charnockitic rocks.

Microscopically, the intermediate and basic granulites have a constant even-grained granoblastic or panidioblastic texture normal to the lineation, and a nematoblastic texture parallel with the mineral lineation when it is present. The biotite when present in sufficient quantity forms a rude microscopic foliation. The acid granulites, however, vary in grain-size from medium to pegmatitic, and in texture from granulitic to panidiomorphic-(blastic) and may be gneissose. In these gneisses where there is an intimate and irregular distribution of the acid and intermediate granulites, sharp variations in composition, grain-size, and texture on both a microscopic and megascopic scale (Pls. II and III) result.

Throughout the groups of rocks considered here, many of the minerals are remarkably constant in their microscopic characters. The same mineral assemblage occurs in all types and not infrequently all the units of the assemblage are together in one hand-specimen. The presence of hypersthene accompanied by clinopyroxene in variable amounts (except for the latter's absence in the acid granulites), is one of the distinctive features of the whole group. Biotite, hornblende, garnet, and iron ore constitute the remaining mafic minerals, the felsic components being quartz, potash feldspar, plagioclase, and mixed feldspars. Accessory minerals include zircon, apatite, and, in one instance, spinel.

All the minerals above have been identified as belonging to the main period of metamorphic recrystallization and magmatic crystallization. Other minerals present in varying amounts, such as actinolite, green hornblende, epidote, talc, chlorite, sphene, calcite, serpentine and anthophyllite, are the result of later recrystallization, mainly that produced by the Grenville metamorphism.

Characteristic Minerals

Quartz

The quartz is either blue, grey, or greenish grey. Under the microscope it is seen to be equigranular in the intermediate granulites, but markedly uneven in shape and size in the acid granulites. In most of the specimens examined the quartz

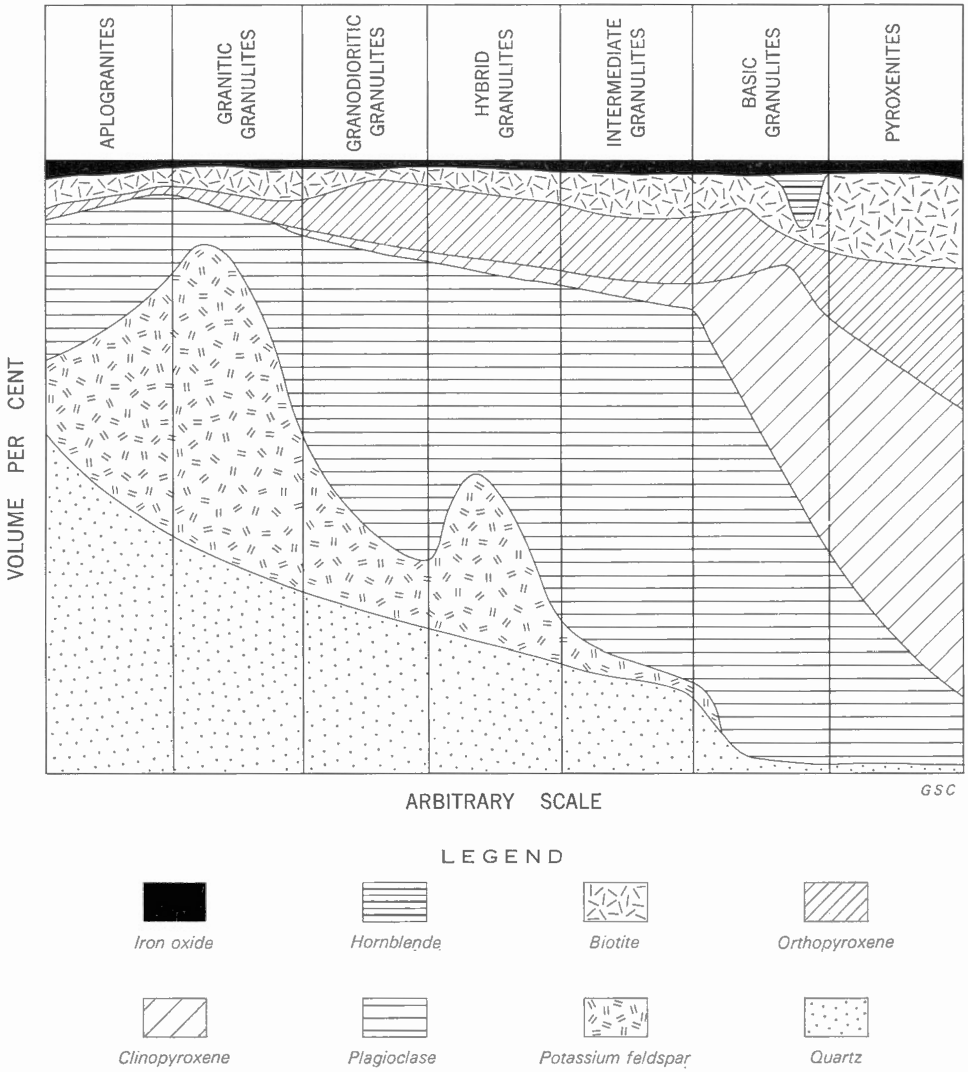


FIGURE 5. Mineral variation in the pyroxene granulite facies rocks. Cumulative diagram based on volumetric analyses.

corrodes and indents the mafic minerals and plagioclase, sometimes to such an extent that these minerals are dissected into a number of smaller components. This relationship may be attributed in part to the late formation of quartz in the paragenetic sequence, and in part to the effects of the later superimposed Grenville metamorphism, during which the quartz would have been one of the first minerals to be reactivated in the course of deformation and recrystallization.

The development of myrmekite in the acid granulites indicates that some quartz was set free during reaction between the potash feldspar and plagioclase and during the later conversion of calcic plagioclase into a more sodic variety with the change of metamorphic grade. Quartz also appears to have been formed when green biotite has replaced garnet and when pyroxene has been involved in a reaction with red-brown biotite. The green biotite is related to the youngest metamorphism, while the red-brown biotite is a late primary mineral of the granulite assemblage.

Most quartz grains exhibit a variable degree of undulose extinction varying from a slight twist to one of as much as 30 degrees. A more advanced stage of the effects of strain is observed where an individual grain is broken into nearly parallel aligned planes and sheaves. Intercrystal granulation, along with mineral alteration, becomes more important southwards towards the Grenville front.

Plagioclase Feldspar

This is the dominant type of feldspar, present in nearly all varieties of the granulite assemblage, often to the exclusion of a free potash-rich feldspar phase. It is only in certain acid granulites (equivalent in composition to alaskite and charnockite *in sensu stricto*) that the potash feldspar occurs in amounts equal to the plagioclase or greater than it. Within the acid granulites, the plagioclase is commonly oligoclase (An_{24-28}). In the intermediate granulites, plagioclase ranges from calcic oligoclase (An_{26}) to sodic andesine (An_{36}). The more basic varieties of the group (i.e., the basic granulites) carry calcic andesine (An_{46-50}), while the pyroxene-rich granulites carry calcic labradorite and even sodic bytownite. These mafic rocks also carry a sodic plagioclase, which formed at a later stage. Occasionally a slight variation in composition was observed between the centre and margins of a particular grain. Zoning within the plagioclase was not observed.

The plagioclase generally possesses antiperthitic intergrowths of potash feldspar, commonly developed on such a fine scale as to be almost undetectable except under high magnification. This antiperthitic development of the feldspars has been emphasized in recent years as a feature characteristic of most rocks with charnockitic affinities.

Antiperthitic plagioclase may occur in all the varieties of granulite, being especially characteristic of the intermediate and basic granulites where it is the main type of feldspar present. Owing to the fine nature of the intergrowth, it is difficult to deduce by microscopic methods the ratio of potash feldspar intergrowth to the host plagioclase. In the more acid varieties of granulite the antiperthitic intergrowth is of a different nature. Whereas in the more basic rocks the intergrowths occur as thin spindles commonly showing alignment parallel with the (010) plane, in the acid varieties they become coarser and are spread over the host feldspar in either a regular or irregular system of tongues of patchy distribution. When this intergrowth is developed on a coarse scale the potash feldspar may be seen to possess microcline-type grid twinning.

The proportion of potash feldspar to plagioclase becomes approximately equal in some intergrowths, to form mesoperthite, a name suggested by Michot (1951, p. 270), who considered that they are formed under a high-temperature environment. Similarly, Eskola (1957, p. 107), considered hair mesoperthite, a form found in these New Quebec charnockites, as indicative of high temperatures. Previously, Eskola (1952, p. 148) had described this hair type of perthite as occurring in the pyroxene granulites from Lapland. Sometimes the potash feldspar plates forming the antiperthite in the acid granulites may be in optical continuity with a potash feldspar crystal adjacent to their plagioclase host. Cheng (1944, p. 141) described similar antiperthite in migmatites from Scotland, and considered that they had been formed by potash feldspar replacing the oligoclase.

Kohler (1948) considered that antiperthite occurs typically in feldspathized schists, hybrid granulites, and feldspathized amphibolites, where Drescher-Kaden (1948, p. 77) concluded from a study of antiperthite in injection gneiss, similar to that described here, that it is a result of replacement of plagioclase by potash feldspar. Tilley (1936, p. 315), on the other hand, considered that the development of antiperthite in enderbite indicates a high temperature of consolidation of magmas accompanied by a low water content. Also, Tuttle (1952, p. 116), following the magmatist school, stated that ". . . perthite when composed of nearly equal amounts of albite and microcline is evidence of high temperatures", and suggested a magmatic environment for these.

From the discussion above, it appears that there may be more than one environment and process to account for the formation of antiperthite; high temperature, however, always seems to be a constant feature in its formation. The nature and origin of these mixed feldspars is discussed again on a later page (p. 54).

Potash Feldspar

The potash feldspar varies from microperthite without visible microcline-type quadrille twinning to microcline–perthite and microcline. The potash feldspar in the acid granulites generally carries plagioclase intergrowths in some form. Hair or film microperthites are common. Patch-perthites are developed locally and also some vein perthites. Some of these forms have been described by Eskola (1952) and Subramanian (1959) from similar pyroxene-bearing rocks. The film microperthites are developed on such a small scale in places that the intergrowth appears to grade into a cryptoperthitic form. This is especially so when the potash feldspar does not show any microcline-type grid twinning.

The potash feldspar, however, generally exhibits a microcline grid twinning, which although well developed in places is commonly vague and indefinite and may be visible only over parts of an individual phenocryst. In some instances only a shadow effect similar to strain extinction is visible. Potash feldspar grains with or without this cross-twinning may occur together in the same micro-section. Untwinned crystals extinguish homogeneously as individuals, but well-twinned crystals may show an uneven extinction owing to the fact that each crystal is composed of several components differing slightly in their orientation. Some of these features are related to the later stresses affecting these rocks.

Orthopyroxene

This mineral, the most distinctive in the present study, is present in all varieties of the granulites except possibly within some of the aplogranites. While optical properties indicate compositions within the hypersthene–bronzite range, the pleochroic character of the orthopyroxenes is weak compared with the more strongly coloured orthopyroxenes from some charnockite areas. Although the most strongly pleochroic orthopyroxenes are in the intermediate and acid granulites, there does not appear to be any direct relationship between the iron and magnesium content of the orthopyroxene and its pleochroic intensity; however, the ferrous iron present may govern the pleochroic tints as suggested by Howie (1955, p. 753). Optical data for the orthopyroxenes in the several varieties of granulite and their approximate composition expressed in terms of atomic percentages are shown in Table II. The approximate compositions of the orthopyroxenes were obtained by using the curves suggested by Hess (1952, Fig. 2).

TABLE II | *Optical Properties of the Pyroxenes*

Specimen Number	Rock Type	Orthopyroxene					Approximate composition	Clinopyroxene			
		Pleochroism	2V	Nz	Nx	Nz-Nx		2V	$Z \wedge c$	Nx	Composition En. Fs. Wo.
58.130	Acid granulite; granodioritic	X=p pinkish red Z=p bluish grey	74	1.694	1.683	.011	En_{80}				
58.138	Acid granulite; granitic	X=m pinkish red Z=m bluish grey	78	1.690	1.678	.012	En_{83}				
58.90	Hybrid granulite	X=p reddish pink Z=p bluish grey	60	1.710	1.697	.013	En_{69}	58	41	1.723	38: 12: 50
58.133	Intermediate granulite	X=orange yellow Z=greenish blue	74	1.693	1.681	.012	En_{80}	59	42		32: 18: 50
58.155	Intermediate granulite	X=p orange red Z=p greenish blue	63	1.705	1.693	.012	En_{71}	57	40	1.720	40: 10: 50
57.17	Intermediate granulite	X=p yellow Z=p bluish grey	69	1.696	1.684	.012	En_{76}	58	41	1.721	38: 12: 50
58.154	Basic granulite	very weak	72	1.695	1.684	.011	En_{78}	59	40	1.720	40: 10: 50
58.137	Basic granulite	very weak	70	1.696	1.685	.011	En_{74}	59	39	1.718	42: 8: 50
58.136	Basic granulite							57	40	1.718	41: 9: 48
58.89	Basic granulite	X=v p yellow red Z=v p blue	62	1.718	1.706	.012	En_{72}	58	39	1.715	47: 5: 48
58.134	Pyroxenite granulite	very weak	67	1.694	1.683	.011	En_{74}	59	42	1.725	35: 15: 48
58.153	Pyroxenite granulite	very weak	75	1.690	1.680	.010	En_{81}	57	44	1.733	27: 25: 50
58.152	Pyroxenite granulite	very weak	73	1.691	1.680	.011	En_{79}	58	41	1.721	38: 12: 50
58.154	Pyroxenite granulite	very weak	74				En_{80}	58	41	1.722	38: 12: 50

p = pale, v p = very pale.

An anomalous inclined extinction of as much as 10 degrees with the cleavage was observed in some places. A similar feature has been recorded by Quesnel (1951, p. 241) from charnockitic rocks in Sweden, by Rama-Rao (1945) from similar rocks in Mysore, and by Washington (1916) from the type locality in Madras.

Depending on the fabric and composition of the granulites the following grain shapes have been distinguished: (1) in the acid granulites the orthopyroxenes are highly irregular in outline, in places skeletal and sponge-like, and appear to have been intensely corroded and replaced; (2) in the finer grained intermediate and basic granulites the orthopyroxenes are more regular in outline. When a lineation is present the orthopyroxenes are elongated parallel with their *c* axes; the orthopyroxenes are generally subidioblastic, xenoblastic, or nematoblastic in outline; (3) in the mafic granulites where the grain-size is variable, the orthopyroxenes have outlines similar to those described in (1) and (2), and in addition may become large and poikiloblastic in respect to clinopyroxene, biotite, and plagioclase.

Clinopyroxene

Clinopyroxene, the second important dark mineral, has optical properties characteristic of diopsidic augite. Table II shows the optical properties of clinopyroxene from the several varieties of granulite. The position of these properties in the tables of Hess (1948) and Winchell (1951, p. 413) indicates that the clinopyroxenes belong to the diopside–hedenbergite series.

In contrast with pyroxenes described from other areas of charnockitic rocks, no form of reaction relationship between the two forms was observed. They occur as separate components except in some of the mafic rocks where large poikiloblastic plates of one type of pyroxene may enclose several smaller pyroxenes of the other type. The only replacement textures noted were the coronas of green amphibole and biotite around the pyroxene, resulting from the younger Grenville metamorphism to the south. Both the clinopyroxene and orthopyroxene contain scattered schiller plates of iron ore. Clinopyroxene is present in all the granulites, but is more abundant than orthopyroxene only in the basic varieties.

Amphibole

A greenish brown hornblende is present in some basic granulites, where it appears to be restricted to bands. This hornblende tends to assume a subidioblastic crystal outline and is better formed than the pyroxenes, although it may also occur with biotite as small inclusions within the pyroxene, which suggests some replacement by the latter.

Amphiboles within the pyroxene-rich granulites form a small percentage of the mode and appear to be later in the paragenetic sequence. Here they occur as irregular and skeletal grains filling the interstices between the pyroxenes. They are pleochroic in faint shades of yellow and brown. The greenish brown and brown varieties of amphibole developed during the initial formation of the granulites and can be distinguished from those formed during the later Grenville and retrograde metamorphism. These later amphiboles are considered on a later page.

Biotite

This mineral occurs in variable quantities in all varieties of the series, forming as much as 6% of the acid granulites, and in the pyroxene-rich varieties as much as 25% of the mode (Tables III, IV, and V).

The pleochroism is distinct in light to dark shades of red, brown, orange-brown, and greyish brown. Refractive index and birefringence measurements give fairly constant values for biotite flakes from the several varieties of granulite. With Ny 1.635 to 1.644 and Nz - Nx about 0.05, a composition with approximately equal amounts of iron and magnesium is suggested according to Winchell's tables (1951, p. 374).

Another feature characteristic of the biotite in addition to its pleochroism, is the presence of large amounts of iron-ore grains as minute inclusions. They appear as possible exsolution stringers, which may be parallel with a cleavage plane, crossing the biotite flakes in an irregular manner, or occurring as a diffuse rim of small grains around the margin of the biotite flakes. Very thin, almost colourless needles of what appears to be rutile are also present along directions parallel with what would be, if developed, (010) and (111) partings in the biotite. That these are not actual cleavage traces as first appears to be the case, is deduced from the fact that the distribution of these very thin needles is patchy and not continuous right across a basal section of the biotite.

The observed replacement of the red-brown biotite by a greenish biotite is possibly related to the borderline effects of the Grenville metamorphism.

Garnet

Garnet was observed only in the acid granulites, where it is a relatively minor constituent. The mineral is generally irregular in shape, with numerous inclusions and vermicules of quartz and feldspar. In hand specimen the garnet is brownish red, whereas in thin section it is seen to be pale pink or colourless. X-ray and refractive index measurements suggest a garnet containing nearly equal amounts of pyrope and almandine.

Although garnet was not included as an essential mineral in Holland's definition of charnockite, Subramanian (1959) included it in his redefinition of charnockite *in sensu stricto.* Subramanian suggested that it has been formed in part from orthopyroxene during partial recrystallization of the original charnockite.

Although other authors have noted the formation of garnet by a breakdown of pyroxene with the formation of replacement coronas, etc., no similar relationship has been observed in the granulites of the Mount Wright region. It is felt, however, that further investigation is needed on this point. As the acid granulites are traced southwards towards the Grenville front, aggregates of quartz and green biotite replace the garnet.

PETROGRAPHY

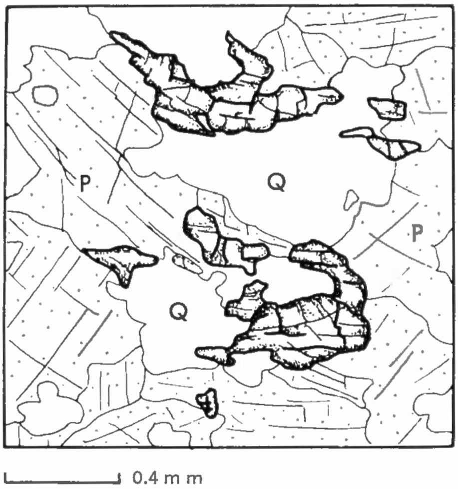
The Acid Granulites

Apart from the presence of hypersthene and garnet, the rudely foliated and lineated acid granulites are like normal granitic rocks found in areas of lower grade metamorphism in the eroded portions of orogenic mountain belts. The main constituent minerals present are quartz, potash-rich feldspar, sodic plagioclase, and biotite, and it is largely on the basis of variation in the proportion of these minerals that several varieties are distinguished (Fig. 6A–C).

Acid granulites rich in oligoclase are the most common and have been termed granodioritic granulites. As they are relatively poor in potash feldspar they are somewhat similar to enderbite, a variety of charnockitic rock described by Tilley (1936, p. 312), in which plagioclase occurs to the near or complete exclusion of potash feldspar. Less common are the acid granulites in which potash feldspar is more abundant than oligoclase. These are termed granitic granulites and are similar to the 'charnockite *in sensu stricto*' of Holland. Rocks carrying potash feldspar to the near or complete exclusion of oligoclase, and therefore equivalent to Holland's quartz–hypersthene–syenite, were not observed except in the highly leucocratic rocks, which are better defined as aplogranitic granulites. The aplogranitic granulites have variable proportions of sodic plagioclase, potash feldspar, and quartz. Either potash feldspar or sodic plagioclase may be the dominant feldspar. Orthopyroxene and biotite occur in small amounts, while garnet is slightly more abundant than in the granodioritic or granitic granulites (Table III, columns 1–7).

The distribution of the various types of acid granulite appears irregular. The granodioritic granulites grade into the granitic granulites without any form of boundary or contact separating them. The aplogranitic granulites appear to have been relatively mobile at a late stage as they may vein and transgress the foliation of the other acid granulites, the small-scale banding in the intermediate granulites, and the general layering in the complex. In other instances, the aplogranitic granulites grade into the other varieties of acid granulite. The ptygmatic veins are generally aplogranitic in composition, and where these can be traced laterally to their point of origin they are seen to grade into bands of granitic or granodioritic granulite (Fig. 4A).

The acid granulites are medium to coarse in grain-size, in places becoming pegmatitic. Quartz, feldspars, and orthopyroxene range in diameter from 3 mm to 20 mm, biotite from 2 mm to 10 mm, and garnets are as much as 20 mm. Tex-



A. Hypersthene granodiorite (acid granulite) (58.132). Irregular-shaped grains of hypersthene and plagioclase (P) are highly corroded by quartz (Q). The margins of adjacent grains generally tend to be interlobate. Mag. X30.

B. Hypersthene granodiorite (acid granulite) (57.45). Hypersthene (H) has been involved in reaction with biotite (B) for several apparently separated but optically continuous biotite flakes are embedded in pools of quartz just above the hypersthene. Mesoperthite (M), with the plagioclase intergrowth enclosed by the stippled lenses) is seen to be replacing the larger plagioclase (P) grains. The numbered plagioclases indicates those that are optically continuous ie. all grains numbered 2 once formed part of the same grain. Some myrmekite is seen at bottom right centre. Mag. X30.

C. Garnetiferous aplogranite (acid granulite) (58.130). Rounded and partly indented garnets (G) are partly enclosed amongst plagioclase grains (P). Quartz (Q) is corrosive towards the plagioclase and less commonly the garnet. Chlorite (C) has formed partly at the expense of the garnet, while sericite (S) has formed from the plagioclase. The overall texture is granoblastic. Mag. X30.

GSC

FIGURE 6. Hypersthene granodiorite and garnetiferous aplogranite as seen in thin section.

turally these rocks are either xenomorphic or xenoblastic, inequigranular in aspect. The tendency towards an elongation of individual grains and grain aggregates in a constant direction produces a rude lineation, accentuated by biotite, which when present may be aggregated into discontinuous foliae.

The modes of several specimens of acid granulite are shown in Table III. Quartz forms 20 to 35 per cent of the mode in the granitic and granodioritic types, whereas in each of these, the dominant feldspar forms at least 50 per cent of the rock. There does not appear to be any definite relationship between the type and amount of feldspar present and the quartz content in any given acid granulite. While the potash feldspar-rich granulitic types generally have a higher quartz percentage than the granodiorites, the highest quartz content was measured in an aplogranitic rock with sodic plagioclase as the dominant feldspar. The overall picture, however, is complicated by the mixed nature of the feldspars.

Plagioclase with a composition of oligoclase $An_{24\text{-}28}$ is generally without well-defined twinning. When present, twinning appears to be of the polysynthetic albite and pericline type. A common feature in some sections is the bending and disappearance of these twin lamellae as they are traced across a plagioclase grain. Uneven extinction and occasional microfracturing of the grains was also noted.

Antiperthitic intergrowths of potash feldspar within the plagioclase are not as common as in the intermediate and basic granulites. In the acid granulites, the potash feldspar intergrowths are rectangular, sub-rectangular, or more rarely rounded patches within the plagioclase. The intergrowths tend to be elongated approximately parallel with the trace of (010) cleavage and twin plane and have their shorter ends parallel with the (001) cleavage. They do not form more than 5 per cent of the total feldspar and appear to be exsolution antiperthites of the type described by Sen (1959, p. 493), who ascribes them to unmixing as a result of slow cooling or to the effects of shearing stresses. Both processes are able to supply the energy necessary for the change in Si–Al ratio in the molecular structure. In some instances the potash feldspar intergrowths within the oligoclase show quadrille microcline twinning, whereas in others they may be untwinned and extinguish evenly.

In addition to potash feldspar intergrowths within the oligoclase, there are numerous minute colourless inclusions with a thin prismatic or lenticular form and a random orientation. The nature of these has not been established, but it is assumed that they are some form of liquid or gaseous inclusion, the presence of which may explain the common greenish grey hue of the feldspars. The potash feldspar occurs as microcline, and microcline-microperthite. The grains are more irregular in shape than the plagioclase and can be interstitial to the latter. The perthitic intergrowths are largely of the exsolution film and hair types, so fine in places as to be almost cryptoperthitic. The sodic plagioclase intergrowths occur either as thin films or as thin lenses, or less commonly assume an interconnecting, thin flame-like appearance. Because of the small size of these intergrowths, it is difficult to determine how much of the feldspar they form, but estimates range from 5 to 25 per cent.

TABLE III *Chemical Analyses, C.I.P.W. Norms, and Modes of Granulite Facies Rocks Acid and Pyroxene-bearing in Composition*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
											Analyses									
SiO_2	73.4							73.74	69.73	77.47	75.50	69.57	77.32	79.53	65.95	66.90	70.32	70.52	72.94	66.96
Al_2O_3	13.7							12.70	14.39	11.0	13.92	15.08	9.81	12.49	15.27	14.02	16.32	17.45	13.41	14.32
Fe_2O_3	0.9							0.88	1.02	1.04	0.48	0.26	0.41	0.53	0.12	1.46	0.58	0.13	0.67	1.78
FeO	2.06							2.07	4.18	2.02	1.17	3.29	3.33	0.61	4.86	3.50	1.37	0.71	2.03	3.85
CaO	1.5							1.59	1.44	1.02	3.54	2.62	1.14	2.38	2.95	2.44	2.64	3.08	2.02	2.06
MgO	1.5							0.68	0.12	0.43	0.52	2.00	1.21	0.26	2.70	2.71	0.49	0.35	0.50	1.12
Na_2O	2.8							2.64	3.12	2.86	3.64	2.87	1.94	3.78	3.74	4.00	4.05	5.38	2.38	2.73
K_2O	3.1							4.76	2.10	4.14	0.74	3.99	3.27	1.33	2.06	3.59	3.62	1.80	4.94	5.14
H_2O+	0.37							0.53	0.51	0.20	0.15	0.53	0.25	0.04	0.25	0.59	0.56	0.27	0.32	0.04
H_2O-										0.05	0.30		0.07	0.05	0.20	0.05	0.08	0.10	0.06	1.18
TiO_2	0.07							0.39	0.75	0.26	0.08	0.02	0.56	0.09	0.99	0.59	0.28	0.18	0.36	0.97
P_2O_5	0.0							0.09	0.06			0.04		0.03		0.13		0.24	0.05	0.33
MnO	0.1							0.04	0.12			0.02	0.03	0.01	0.22	0.01	0.03	0.02	0.08	0.23
Total	99.95							100.11	97.54	100.49	100.04	100.29	99.94	101.13	100.31	99.99	100.34	100.23	99.76	100.71
										Norms										
Qtz	38.1							34.9	28.22	41.22	42.3	25.26	45.06	45.78	22.92	19.32			34.04	24.12
Or	18.25							28.12	12.54	24.46	4.5	23.91	22.90	7.78	12.23	21.13			28.91	30.02
Ab	23.58							22.25	31.71	24.10	30.9	24.63	16.40	31.96	31.44	34.06			20.44	23.06
An	8.06							7.51	13.27	5.0	17.5	13.07	4.92	11.95	14.73	9.45			9.65	8.90
Cor	2.75							0.45	1.18		0.6	1.12	0.55	0.41	1.53				0.54	1.02
Di									1.73							1.63				
Hy	6.2							4.08	8.34	3.34	2.9	10.81	7.90	1.13	13.53	10.32			3.96	7.29
Mt	1.4							1.49	1.47	1.62	0.7	0.41	0.46	0.70	1.62	2.09			0.93	2.55
ilm								0.75	1.57	0.61	0.2		1.06	0.15	1.98	1.22			0.68	1.82
Ap								0.16	0.15				0.27	0.07		0.34			0.13	0.67
										Modes										
Qtz	42.0	33.8	25.57	20.7	23.2	60.0	31.0	35.0	30.6	40.0	42.5	20.3	41.8	48.6	23.8		25	26	35	26
Or	31.0	10.3	12.26	13.6	60.3	0.6	36.2	37.9	19.6	48.0	4.5	58.0	28.5	3.5	16.3		28	4.5	29.3	38
Plag.	16.0	51.2	56.17	51.0	10.9	30.3	31.0	20.2	32.2	6.0	48.5		19.5	41.2	32.2		41	64.8	31.4	23
O.Py	3.8	3.7	2.47	9.0	0.8	1.2	0.4	4.9	9.0	3.0	3.0	12.3	7.9	4.7	12.3		0.8	1.3	1.8	2
C.Py				P	P										P					3
Amph.																				3
Bi	3.6	0.75	2.7	4.7	0.4	1.0	0.4	0.2	0.7	1.0		9.4		0.9	1.0		5.0	3.0	0.2	P
Ir.Ox.	0.5	0.2	0.5	1.0	0.1	0.5	0.3	1.5	1.4	2.0	1.0	P	2.2	1.0	1.7		0.2	0.4	1.7	4
Gar	3.0				0.3	6.2	0.4	P	5.7			P			12.6					
Ap+Zr	0.2	0.1	0.3	0.1	0.1	0.2	0.3	0.2	0.6			P	0.1	0.1	0.3				0.3	0.8

P = present in minor amount.

In several specimens of acid granulite in which oligoclase is the main feldspar, a mixed feldspar composed of nearly equal amounts of plagioclase and potash feldspar is present, the latter being slightly more dominant. This mixed perthite is the mesoperthite mentioned on page 23. The plagioclase of the intergrowth, which appears to be more sodic than the adjacent oligoclase grains, occurs in elongated blobs. At their boundaries the potash feldspar grains have replaced the major plagioclase phase as inclusions of the latter are seen within the mesoperthite. The plagioclase intergrowth, however, appears to be unrelated to the adjacent plagioclase grains as the latter are more calcic and altered. It appears that exsolution took place after cessation of plagioclase replacement while temperatures were falling (Fig. 6B).

Myrmekite is developed to a greater extent in the aplogranitic than in the granitic and granodioritic rocks. It occurs as lobes and irregular areas based on oligoclase grains with which it may be optically continuous, and projects into potash

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Key to Table III

1. Garnetiferous orthopyroxene granite (acid granulite). Analysis made from several similar specimens collected in the Seahorse Lake area, Mount Wright region. Analyst, K. Hoops, GSC.
2. Orthopyroxene granodiorite (acid granulite) 58/138. Mode only. Northeast of Seahorse Lake, Mount Wright region.
3. Orthopyroxene granodiorite (acid granulite) 57/48. Mode only. Northeast end of Lake Cherny, Mount Wright region.
4. Orthopyroxene granodiorite (acid granulite) 57/8. Mode only. Northeast end of Lake Cherny, Mount Wright region.
5. Orthopyroxene-bearing aplogranite (acid granulite) 58/131. Mode only. Seahorse Lake, Mount Wright region.
6. Garnetiferous aplogranodiorite (acid granulite) 58/130. Mode only. Seahorse Lake, Mount Wright region.
7. Orthopyroxene-bearing aploadamellite (acid granulite) 57/20. Lac Sheree, Mount Wright region.
8. Charnockite *in sensu stricto*. Average of five analyses from the type area, Madras. Calculated from tables by Subramanian (1959, p. 348).
9. Enderbite. Average of six analyses from the type area, Madras. Calculated from tables by Subramanian (1959, p. 348).
10. Charnockite. St. Thomas Mount, Madras. Analyst, H. S. W. Washington (1916, p. 325).
11. Enderbite. Proclamation Island, Enderly Land, Antarctica. Tilley (1936, p. 134).
12. Charnockite G. 80. Between Waki Camp and Bukumi Camp, Bunyoro district, Uganda. A. W. Groves (1936, p. 163).
13. Charnockite 4639. Pallavaram, Madras. Analyst, R. Howie (1955, p. 97).
14. Enderbite 36218. Pallavaram, Madras. Analyst, R. Howie (1955, p. 97).
15. Garnetiferous enderbite. West of Hasanapuram quarry, south of Pallavaram, Madras. Analyst, T. Katsuna. Howie (1957, p. 572).
16. Granite (gneiss) adjacent Wapassakatoo Series. Six miles west of Wabush Lake. Gill, Bannerman, and Tolman. *Bull. Geol. Soc. Amer.* 1937, vol. 48, pp. 567–587 (this is thought to represent partly recrystallized charnockite).
17. Fine-grained hypersthene granite (acid charnockite). Kotkaniemi Vihti, Finland. Parras (1958, p. 124).
18. Hypersthene granite (acid charnockite). Valkinmaa, Nummi, Finland. Parras (1958, p. 124).
19. Hypersthenic acid granulite, No. 30. 829. Near Mount Carruthers, Musgrave Ranges, Australia. Wilson (1954, vol. 11, p. 335, Table V. 3).
20. Ferrohypersthene adamellite. Spinifex Hill, Musgrave Ranges, Australia. Wilson (1954, vol. 11, p. 385, Table IV.)

feldspar. Plagioclase grains of normal outline may be myrmekitic against potash feldspar without penetrating the latter. Myrmekite is also present completely surrounded by potash feldspar grains. The quartz tubules can be up to five times as long as they are thick, and are arranged normal to the myrmekite–potash feldspar boundary. Generally the rocks richest in microcline contain the largest amount of myrmekite. In these, the myrmekite may penetrate potash feldspars that contain numerous diversely orientated plagioclase inclusions with myrmekitic borders.

Quartz commonly has an undulose strain extinction and is locally sheared into aggregates of grains in near optical continuity. A further stage of cataclasis is reached by the granulation of quartz grains into a series of stringers of still smaller grains. A marked feature of the quartz, as mentioned earlier, is the extent to which it may corrode or indent the feldspars and to a lesser extent the biotite, pyroxene, and garnet. This indicates either the relatively late crystallization of quartz during the formation of these rocks, or a period of reactivation and recrystallization during the Grenville metamorphism.

Pyroxene, mainly in the orthorhombic form, constitutes as much as 10 per cent of the granitic and granodioritic granulites, although the average mode is nearer 5 per cent. The aplogranites carry less than 2 per cent pyroxene. In hand specimen the orthopyroxene occurs as a subhedral to highly irregular, rarely skeletal form. The orthopyroxene was difficult to study, however, because of subsequent alteration. Results of optical measurements from two specimens shown in Table II indicate a compositional range En_{80} to En_{83}. Their pleochroic character varies from pale to strong shades of X=pinkish red to Z=bluish grey. Although clinopyroxene was observed in a few instances, the optics could not be determined because of partial alteration of the mineral.

Biotite, with $Ny = 1.644$ forms an average of 3.5 per cent of the granodioritic and granitic granulites, but only 0.6 per cent of the aplogranites. It is strongly pleochroic with X = pale green-yellow, Y = reddish brown, Z = dark reddish brown, or X = pale greenish brown, Y = greenish brown, Z = greenish brown. It occurs as irregular or subhedral plates, which may have ragged terminations and a tendency to mould themselves onto other minerals. Reference has already been made to the inclusions of rutile needles and iron-ore grains that follow potential (111) and (010) directions.

The biotite appears to have been formed at a relatively late date in the formation of the granulites since a close inspection of its irregular form shows that it fills interstices between adjacent plagioclase and pyroxene grains. Thin fingers of biotite may extend out from the main biotite flake as wedges and seams between the adjacent pyroxene and plagioclase grains. The relationship of biotite to quartz and potash feldspar is more uncertain, however. The biotite is indented by the quartz, which may also occupy fracture lines crossing the biotite.

There is an interesting relationship between biotite and potash feldspar. Where the latter is present in notable amounts, biotite may occur as somewhat skeletal grains, partly or wholly surrounded by quartz. In such instances a reaction seems to have taken place among orthopyroxene, potash feldspar, and water to produce large skeletal biotites and quartz. Where potash feldspar is of minor importance, these large skeletal biotites appear to be for the most part in equilibrium with the pyroxenes.

Garnet is present as irregular grains with quartz inclusions. The outline of the mineral may also be markedly indented by quartz, which in addition partly fills crossfractures in the garnet. One specimen has the following properties: $N = 1.787$; unit cell edge $Å = 11.496$. These values indicate a representative of the pyralspite series with about 47 per cent pyrope molecule and 53 per cent almandite molecule. This is substantiated by spectrographic analysis indicating iron and magnesium as major constituents with calcium and manganese as minor constituents. Whereas this specimen was from a granodioritic granulite, a second specimen of garnet from an aplogranitic type gave properties indicating 40 per cent pyrope and 60 per cent almandite.

Magnetite, hematite, or rarely pyrrhotite occurs as separate grains or as small aggregates in the groundmass, or in stringers made up of numerous fine grains within the biotite, forming along the cleavage, occurring marginally, or along irregular fracture planes. In addition to the opaque minerals, rounded zircons and apatites are also present as constant accessory minerals. As in other charnockite localities, sphene was absent except in those specimens showing considerable alteration due to the Grenville metamorphism.

A chemical analysis was made from several specimens of granitic granulite having a similar mineralogy, which were collected from the Seahorse Lake area. In Table III (column 1) it is compared to other analyses of acid hypersthene granulites and rocks that come under Subramanian's term 'charnockite suite'. The average of five analyses of charnockite *in sensu stricto* from the type area at Madras (Subramanian, 1959, p. 348) was calculated and is shown in column 8. Comparison of the average granulite from Mount Wright with the average charnockite from the type area (columns 1 and 8, Table III) shows striking similarities except for MgO, K_2O, and TiO_2. The higher MgO content of the Canadian rocks is explained by the presence of garnet and biotite, in addition to orthopyroxene; the lower K_2O is reflected in the modal alkali feldspar and the lower TiO_2 in the content of iron oxide. In all other respects the rocks can be considered identical.

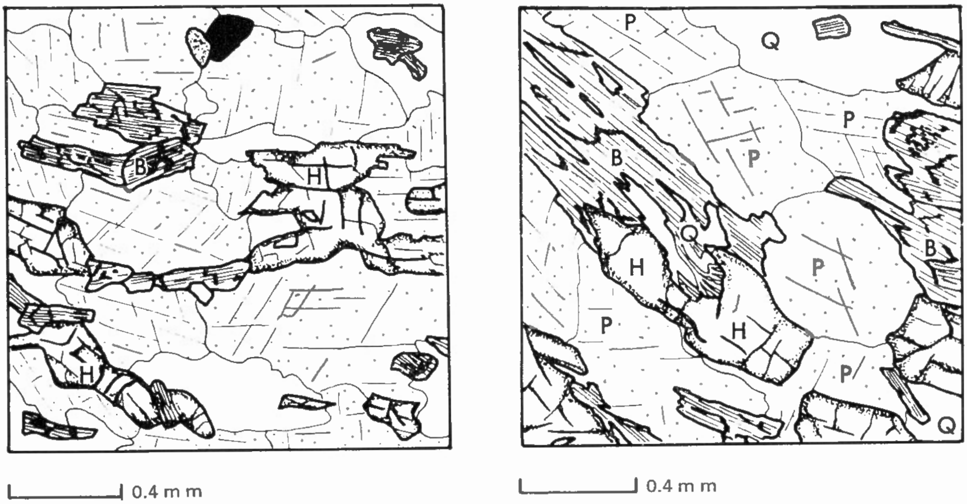
The Intermediate Granulites

This group, with the acid granulites, constitutes the greater part of the granulite assemblage. There is a distinct break in composition between the intermediate granulites with an average modal composition of 15 per cent quartz, 55 per cent plagioclase, 25 per cent mafic minerals, and those of basic composition with an average mode of 2 per cent quartz, 43 per cent plagioclase, and 55 per cent mafic minerals. This compositional break is visible in the field where the basic granulites are seen as sharply defined lenses and thin bands within the enclosing intermediate granulites. A certain amount of feldspathization of the basic granulites takes place, however, where the bands, lenses, and inclusions of these rocks are intimately veined and enclosed by acid granulite.

The relationship between the intermediate and acid granulites is, as mentioned earlier, a more intimate one. Where well-defined bands, lenses, and seams of the acid and intermediate granulite alternate in a regular manner, a banded gneiss is formed. Where, however, the acid granulite is present as numerous intimate bands, tongues, lenses, and irregularly distributed patches within intermediate granulite, the resultant rock has the appearance of a composite gneiss.

Thin pyroxene- and biotite-rich selvedges separate the two varieties of granulite, and even with the acid and intermediate granulite related on such a small scale, their different grain-size is distinct. Here the acid granulites are either in sharp contact with the intermediate granulites or they grade into each other across a short distance (Pls. II and III).

The intermediate granulites are medium or medium-fine grained, 0.5 mm to 1.0 mm in grain-size, grey when fresh, but with a brownish grey tinge when weathered. A slight variation in the proportion of felsic to mafic constituents may produce small-scale banding. A lineation, produced by the approximate parallel alignment of the longer axes of the feldspar and pyroxene grains, is generally present, and the biotite flakes usually lie with their (001) faces parallel with the banding (Fig. 7A and 7B).



A. Intermediate granulite (58.133.) showing the flattening of grains parallel to the general banding in the rocks. The elongated nature of the main constituent grains, especially that of the biotites (B) and hypersthenes (H), produces a rude form of nematoblastic texture. Mag. x 30.

B. Intermediate granulite (58.90) composed of quartz (Q), plagioclase (P), biotite (B), and hypersthene (H). A synantetic intergrowth of quartz and biotite (left centre) occupies an indentation with the hypersthene. All the quartz in this area (left centre) is in optical continuity. Mag. X100.

GSC

FIGURE 7. Intermediate granulite as seen in thin section.

These granulites show a xenoblastic or subidioblastic equigranular texture in thin sections cut perpendicular to the mineral lineation. Sections cut parallel with this lineation show an elongation of constituent grains that produce a nematoblastic texture. Modal values are given in Table IV, columns 1 to 4. Plagioclase forming between 50 and 60 per cent of these rocks has a composition ranging from calcic oligoclase An_{26} to sodic andesine An_{36}. There is a slight variation in composition from core to rim in some instances, but the main variation in plagioclase composition is in grains from different specimens and does not come from within the individual. Albite and pericline-type twinning, although moderately or poorly developed, is rarely absent. Antiperthites are more common than in the acid granulites. The potash feldspar intergrowths take the form of minute films or spindles commonly aligned in the (010) plane. More rarely, the intergrowths are larger and rectangular or oblong with a variable development of microcline quadrille-type twinning. Potash feldspar, in minor interstitial quantities of about 3 or 4 per cent of the mode, may exhibit microcline cross-twinning. The microcline may carry fine hair-type microperthitic intergrowths of sodic plagioclase. Myrmekite is not common.

A marked feature of the quartz, which constitutes 15 per cent of the intermediate granulites, is the manner in which it indents and replaces or corrodes the other minerals present. This indentation reaches its maximum development where individual plagioclase grains are dissected into smaller components still retaining their optical continuity. A similar development takes place in the acid granulites. As in the latter, undulose extinction in the quartz and plagioclase along with some microfracturing and intercrystal granulation indicates a late period of stress related in part to the Grenville metamorphism.

Pyroxenes forming 10 to 25 per cent of the intermediate granulites are mainly of the orthorhombic type, within the bronzite–hypersthene compositional range. The orthopyroxene is more strongly pleochroic than its representatives in the acid and basic granulites. Typical pleochroic formulae are X = pale orange-red, Y = pale straw-yellow, Z = pale blue; or X = pale orange-pink, Y = greenish grey, Z = pale yellowish green; or X = pinkish yellow, Y = yellowish green, Z = pale green. Some of the grains are rather skeletal, but are identified by their optical continuity. Some optical properties of the orthopyroxene in these rocks are given in Table II, from which it appears that they lie within the hypersthene–bronzite compositional range $En_{69}Fe_{31}$ to $En_{76}Fs_{24}$. An anomalous inclined extinction of as much as 12 degrees was noted in several orthopyroxenes. The nature of this inclined extinction has been discussed earlier.

Clinopyroxene has a form and size similar to those of the hypersthene. It forms less than 10 per cent of the total pyroxene content and always occurs separately from the hypersthene. The optical properties (Table II) indicated diopsidic augite within the compositional range $Wo_{50}En_{40}Fs_{10}$ to $Wo_{50}En_{32}Fs_{18}$. The clinopyroxene is commonly colourless, rarely pleochroic from palest green to colourless.

Biotite with Ny averaging 1.635 is variable in amount, forming from 3 to 15 per cent of the rock, with an average of 10 per cent. As in the other members of the granulite assemblage, it is strongly pleochroic from pale straw-yellow to dark brown or orange-brown. The biotite forms anhedral flakes singly or in aggregates. As in the other varieties, stringers of iron-ore grains are abundant within the biotite either along its cleavage, marginally, or filling irregular crossfractures. Iron ore is also present as larger anhedral grains between the other minerals. Apatite and zircon are other minor constituents, rather small and rounded in outline. Garnet appears to be absent.

A chemical analysis (Table IV, column 1) was made from several similar specimens of intermediate granulite, which were collected across the region. The modes of three of these specimens are given (Table IV, columns 2 to 4) as well as the approximate calculated chemical composition. The chemical composition of these three rocks was calculated from the mode and a knowledge of the approximate chemical composition of the individual minerals calculated from their optical properties.

When the chemical analysis is compared with the calculated analyses the similar values obtained for the various elements is the most notable feature. The similarity of the chemical compositions adds further support to the field observation and modal analyses, which points to granulites of an intermediate nature being well distributed as a distinct rock type across the whole region. Silica and alumina values appear remarkably constant while lime magnesia and iron-oxide values total 13.4, 14.00, 13.74, 14.27 in each instance. Slight differences are apparent when comparing the individual amounts of MgO, FeO, Fe_2O_3, and Na_2O. This is reflected partly in the ratio of biotite to orthopyroxene. The analyzed FeO value is high compared to the one in the calculated analyses, whereas the MgO value is low. This may reflect an error in the optically calculated iron:magnesium ratios in the biotite or orthopyroxenes.

The remaining columns in Table IV represent the chemical and modal analyses of rocks broadly intermediate in composition, which have been described from other terrains where high-grade pyroxene-bearing rocks are charnockitic in character. In several of these other analyses amphibole has been observed, generally in lieu of biotite. Garnet appears to be even less common in these intermediate rocks. Comparison of the Mount Wright intermediate granulites with those from other regions (Table IV, columns 1 to 4 and 9 to 16), reveals that the former are generally richer in magnesia and poorer in lime; a similar relationship is even more strongly displayed when the Mount Wright intermediate granulites are compared with average figures for plutonic quartz diorite and effusive quartz latite (Table IV, columns 5 and 6).

The Basic Granulites

Basic granulites occur either as thin lenses or rare discontinuous bands within the intermediate granulites (Fig. 4). Like the intermediate granulites they may also be present as randomly oriented inclusions within the acid granulites, where they may be cut by veins of the latter. Two distinct types of basic granulite are represented, one a medium- to fine-grained pyroxene–plagioclase rock, the other a coarser grained more mafic rock, rich in pyroxene, approaching a pyroxenite in composition but invariably containing 10 to 20 per cent modal plagioclase.

The longer axes of the lenses of these basic granulites lie parallel with the easterly plunging minor fold axes and mineral lineations observed in the intermediate granulites, where the basic granulites lie within the latter. These lenses may themselves possess a lineation of mineral grains parallel with the lineation in the enclosing intermediate granulites. Where enclosed within the acid granulites, these inclusions may lie at random orientation to the foliation of the enclosing rock, thus demonstrating the original mobility of the acid granulites.

The two types of basic granulite are considered separately.

Pyroxene–Plagioclase Granulites

These are dark medium- to fine-grained rocks with an average grain-size of 0.4 mm. Their texture is similar to that observed in the intermediate granulites. Plagioclase and pyroxene are present in approximately equal amounts except where amphibole is present (Table V, columns 1–4). A fine banded structure is produced in places where the ratio of felsic to mafic components is variable.

Albite and pericline-type lamellar twinning may be well developed in plagioclase, which forms 35 to 45 per cent of these rocks. A slight compositional zoning is present in some of the plagioclase, to the extent that there is a variation of several per cent in the anorthite component, giving a marginal composition of mid-andesine and an inner composition of sodic labradorite. Potash feldspar occurs only in very small amounts in interstices between plagioclase and pyroxene, while antiperthite is not common.

Pyroxene forming 40 to 45 per cent of the rock occurs both as orthopyroxene and clinopyroxene, the two forms varying considerably in their relative proportions; either form may dominate, or they may be nearly equal in quantity. The orthopyroxene is weakly pleochroic with X = pale pink-red, Y = pale grey, Z = pale bluish green. Optical properties (Table II) indicate the compositional range, $En_{72}Fs_{28}$ to $En_{78}Fs_{12}$, established for bronzite. The presence of an additional 010 parting results in many cleavage lines that cross the partings on 110 and 010. Anomalous extinction angles on $Z_{\wedge}c$ of as much as 15 degrees were observed, as in the other varieties of granulite.

Clinopyroxene appears to be diopsidic augite with a compositional range of about $En_{40}Fs_{10}Wo_{50}$ to $En_{47}Fs_{5}Wo_{48}$. It is pleochroic from pale green to neutral. Twinning may take place on 100, which when lamellar gives a distinct 100 parting. Some of the clinopyroxene with this development can be described as diallage. Schlieren of iron ore may be in the clinopyroxene. Intergrowth or replacement relationships between the orthopyroxene and clinopyroxene were not observed.

Amphibole is generally absent although it may form as much as 20 per cent of the mode in some basic granulites. It tends to develop good crystal faces against plagioclase and to a lesser extent against pyroxene. The pleochroism is strong with X = light green, Y = yellowish green, Z = brownish olive-green, $Z_{\wedge}c = 21°$. The optic angle is about $2V = 66° \pm 3°$, $Nz = 1.683$, Nz-Nx-0.025. These

TABLE IV *Chemical Analyses, C.I.P.W. Norms, and Modes of Granulite Facies Rocks Intermediate in Composition*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
								Analyses								
SiO_2	62.8	62.93	63.71	62.08	61.59	62.43	63.85	61.8	60.45	60.12	58.85	65.06	59.77	59.17	64.0	62.14
Al_2O_3	16.1	16.39	16.33	16.35	16.21	16.15	14.87	16.26	17.56	16.63	13.37	15.25	14.83	15.53	13.97	16.41
Fe_2O_3	1.0	2.21	1.47	1.06	2.54	4.04	2.32	1.75	0.62	2.19	4.58	3.06	2.20	2.03	0.96	1.08
FeO	5.22	3.82	3.85	4.96	3.87	1.20	5.07	6.04	5.77	4.79	7.78	3.40	7.01	5.40	5.69	3.49
CaO	3.7	3.68	3.76	3.42	5.38	4.24	4.48	4.30	4.72	3.75	7.15	2.88	4.24	5.68	6.10	5.84
MgO	3.5	4.31	4 66	4.85	2.80	1.74	3.29	3.56	1.62	0.82	2.96	1.16	4.31	2.94	1.30	3.02
Na_2O	3.5	4.79	4.84	3.83	3.37	3.34	3.72	3.40	3.75	4.73	2.83	4.01	3.88	4.22	4.14	3.93
K_2O	1.9	1.46	1.11	2.76	2.10	3.75	1.09	1.16	2.45	4.25	0.22	3.96	1.39	3.19	2.01	1.94
H_2O+	0.76	0.11	0.14	0.23	1.22	1.90	0.11	0.26	0.75	0.25	0.72	0.04	0.09	0.11	0.96	0.84
H_2O-								0.65	0.53		0.10	0.20	0.24	0.14	0.16	0.26
TiO_2	0.6	*	*	*	0.66	0.85	0.82	0.32	0.50	0.95	1.06	0.89	0.96	0.99	0.10	0.62
P_2O_5	0.1	*	*	*	0.26	0.27	0.08	0.08	0.31	0.77	0.19	0.19	0.23	0.47	0.15	0.06
MnO	0.1				0.10	0.09	0.05	0.07	0.10	0.10	0.18	0.09	0.13	0.06	0.12	0.08
Total	99.28	99.70	99.87	99.54	100.10	100.00	99.75	99.65	99.13	99.35	99.99	100.19	S 0.54 CO_2 0.3 100.12	99.93	100.66	99.71
								Norms								
Qtz	19.62						20.95	18.28	13.88	7.26	20.94	18.24		6.60		
K-Fels	11.12						6.67	7.78	15.01	25.02	1.11	23.35	8.15	18.90		
Ab	29.7						31.44	28.82	31.44	39.8	23.58	34.06	32.80	35.63		
An	18.34						20.57	21.33	21.78	11.68	23.35	11.68	17.66	13.90		
Cor	1.53							1.36	0.64				0.49			
Di							1.36			1.89	9.25	1.60		9.40		
Hy	16.52						13.74	18.14	11.16	6.68	11.77	4.46	19.45	9.26		
Mt	1.39						3.25	2.55	0.93	3.25	6.73	4.41	3.20	3.02		
ilte	1 21						1.52	0.61	2.89	1.82	2.13	1.67	1.82	1.98		
Ap								0.34	0.67	1.68	0.43	0.34	0.54	1.11		
py													0.68			
cc													2.00			
								Modes								
Qtz	14.7	15.1	16.0	14.5			15.5	22.6	11.0	14.7	17.2	27.4	8.7	5.0	10.0	12.7
K-Fels	3.5	4.1	1.0	8.0						23.4	1.5	29.5	7.4	26.2		
							55.5	59.1	49.0							
Plag.	55.6	61.3	61.4	50.2						41.0	43.5	26.5	61.2	49.7	63.0	67.2
O. Py	14.6	9.2	10.0	9.6			23.6	6.7	12.0	6.8	18.0	4.4	17.6	8.3	7.2	
C. Py	0.8	0.6	0.9	0.9					1.6	3.2	10.4	2.2		6.2	7.0	8.0
Amph.									14.3	3.0	0.9	1.1	0.1			
Bi	8.6	7.3	9.6	15.7				3.1					0.1		9.5	12.7
Ir. Ox.	1.8	2.1	1.0	0.8			5.4		6.9	4.2	8.0	7.9	4.6	4.4	3.3	0.7
Gar									5.1	2.8						
Ap+Zr	0.4	0.1	0.1	0.3						0.9	0.5	1.0	0.2	1.1		

py=pyrite; cc=calcium carbonate.

properties indicate a variety of hornblende. The hornblende may develop lamellar twinning and like the clinopyroxene may contain schlieren of iron ore. The presence of rare small rounded inclusions of hornblende within the pyroxene suggests that some of the former has been replaced by the latter.

Biotite with Ny averaging 1.635 ± .004 occurs as poorly formed flakes, sometimes very irregular in outline, and may form more than 10 per cent of the rock, although the average mode is slightly less than 5 per cent. The biotite is strongly pleochroic from pale straw to dark orange-brown and carries stringers of minute iron-ore grains in the manner previously described. It appears to have formed slightly later than the pyroxenes in the paragenetic sequence of these granulites, as its reaction with the pyroxene has produced thin ribbons of quartz that tend to separate the two mafic minerals.

Quartz is present in minor quantities as small interstitial grains in addition to its more common occurrence as a reaction product between the biotite and pyroxene. It forms an average of less than 2 per cent of the rock. No garnets were observed. In one thin section, small grains of spinel are seen to possess a good octagonal form and are grouped marginally around the pyroxenes. Apatite and zircon are minor accessory minerals.

The chemical compositions of two of the specimens used in the chemical analysis are shown in Table V, columns 2 and 4. (The chemical composition of the hornblende-bearing granulite in column 3 was not calculated because of the complex composition of the amphibole.). The calculated chemical compositions

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Key to Table IV

1. Intermediate granulite (quartz–pyroxene–plagioclase granulite). Analyses made from specimens collected in Seahorse Lake area, Mount Wright region. Analyst, K. Hoops.
2. Intermediate granulite, 58/133. Chemical composition calculated from mode. Southeast of Seahorse Lake, Mount Wright region.
3. Intermediate granulite, 56/17. Chemical composition calculated from mode. Northwest of Lac Sheree, Mount Wright region.
4. Intermediate granulite, 58/90. Chemical composition calculated from mode. West of Crown Lake, Mount Wright region.
5. Average quartz diorite. "Igneous rocks and the depths of the earth." Daly, 1933, New York.
6. Average effusive quartz latite. Op. cit. Daly, 1933.
7. Quartz–hypersthene diorite. Yercaud, Shevaroy Hills, Madras. H. S. Washington, analyst (1916, p. 328).
8. Quartz–hypersthene diorite. Three miles southwest of Kigorobya, Bunyoro district, Uganda (s. 19). A. W. Groves, analyst (1936, p. 166).
9. Quartz–hypersthene diorite. Mt. Wati, West Nile district, Uganda (s. 347). A. W. Groves, analyst (1935, p. 166).
10. Intermediate charnockite. Varberg, Sweden (S. G. U. Ser. Ba. No. 6, 1910, p. 20).
11. Hypersthene–quartz diorite from hillock, three-quarters mile south-southwest of Tivunivmalai, Madras. Analyst, T. Katsura. A. P. Subramanian (1959, p. 352).
12. Intermediate charnockite. Miladampari, Palni Town, Madras. Analyst, R. A. Howie (1955, p. 732).
13. Intermediate rock. Shevaroy Hills, Madras. Analyst, J. H. Scoon (Howie, 1955, p. 732).
14. Intermediate rock. Valegan, Pothai, Nr. Tonkar, Tinnevelly district. Analyst, R. A. Howie (1955, p. 732).
15: Pyroxene–quartz diorite (intermediate charnockite). S. W. Finland. Parras (1958, p. 116).
16. Diopside–quartz diorite (intermediate charnockite). S. W. Finland. Parras (1958, p. 116).

TABLE V *Chemical Analyses, C.I.P.W. Norms, and Modes of Granulite Facies Rocks Basic and Mafic in Composition*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Analyses																				
SiO_2	50.7	53.68		52.57	50.5	51.67	50.80	50.85	54.0	51.55	50.73	46.30	47.71	50.04	47.44	47.0	45.0	45.01	49.04	48.20
Al_2O_3	14.1	12.45		13.38	9.3	6.41	6.31	12.32	15.52	13.86	13.33	16.24	15.57	11.56	5.36	15.59	16.62	8.82	15.74	10.36
Fe_2O_3	1.3	3.63		2.1	0.9	1.62	2.14	3.34	3.97	1.51	4.99	2.54	2.31	2.63	3.13	1.29	6.05	4.36	2.50	1.96
FeO	7.83	5.30		6.0	8.32	10.48	10.43	7.34	5.95	11.63	11.80	9.42	10.85	15.76	12.42	10.28	8.97	12.38	12.13	9.09
CaO	13.2	10.90		10.67	10.5	13.11	12.46	10.83	7.11	10.28	8.79	12.24	11.52	7.89	7.60	13.75	9.50	7.28	9.27	10.32
MgO	7.6	10.93		11.1	14.5	14.66	15.30	12.27	4.37	5.8	4.5	7.83	7.24	5.58	19.96	8.8	7.24	19.90	6.52	16.91
Na_2O	1.7	2.35		2.27	0.7	0.5	0.39	1.23	4.36	3.08	2.94	2.50	2.07	3.08	0.48	1.7	2.76	0.17	1.56	0.88
K_2O	0.5	0.3		1.1	1.1	1.25	1.69	1.52	1.53	0.54	0.51	0.15	0.42	0.89	0.10	0.07	0.96	0.02	0.57	0.39
H_2O+	0.78	0.5		0.16	1.55	0.20	0.26	0.19	0.37	0.25	0.72	1.26	1.11	0.19	0.08	0.4	0.16	0.02	0.14	0.26
H_2O-									0.20	0.12	0.15	0.07	0.07			0.14	0.06	0.21	0.00	0.25
TiO_2	0.5	*		*	0.7	*	*	*	1.61	1.12	1.93	0.83	0.93	1.93	1.29	0.69	2.40	1.32	1.92	0.97
P_2O_5	0.1	*		*	0.3	*	*	*	0.45	0.23	0.17	0.10	0.12	0.20	0.27	0.07	0.00	0.13	0.52	0.04
MnO	0.2				0.1				0.15	0.23	0.44	0.33	0.38		0.15	0.15	0.31	0.22	0.36	0.37
Total	98.51	100.04		99.35	98.47	99.90	99.78	99.89	99.59	99.2	101.00	99.81	100.30	99.75	98.28	99.93	100.03	99.82	100.27	100.00
Norms																				
Qtz	1.68								2.99		4.14								3.60	
K-Fels	2.78				6.67				9.05	3.02	2.78	0.56	2.22	5.00	0.56	0.56	5.59	1.16	3.34	2.22
Ab	14.67				5.10				36.90	26.0	24.63	19.39	17.82	26.2	4.19	14.5	22.25	1.42	13.10	7.34
An	29.2				18.9				18.16	22.41	21.68	33.08	31.97	15.29	12.23	34.75	30.07	22.64	34.19	23.25
Ne												0.85					0.70			
Di	28.0				26.94				11.36	22.72	17.45	21.80	21.0	19.43	18.97	25.04	13.67	10.04	6.68	22.11
Hy	18.4				33.04				10.70	17.94	18.52		8.89	20.27	42.35	5.22		37.51	30.54	24.28
Ol					3.38					2.92		17.13	12.89	5.63	13.01	15.68	14.20	17.79		15.49
Mt	1.86								5.75	2.09	7.19	3.71	3.25	3.71	4.41	1.86	8.77	6.30	3.71	2.78
ilm	0.9				1.37				3.04	2.16	2.74	1.52	1.98	3.65	2.43	1.37	4.56	2.49	3.65	1.82
Ap					0.29				1.01	0.54	0.40	0.34	0.29	0.34	0.67	0.34		0.30	1.34	0.10
Modes																				
Qtz	1.75	4.1	1.07	0.9	0.5	Tr	Tr	1.2	6.1		5.0			1.3					0.1	
K-Fels	0.4	Tr	Tr	0.3	0.7			2.3	3.8		9.2			6.9					2.1	
																30.0				
Plag.	43.9	46.3	37.1	44.4	24.5	14.9	11.6	34.9	52.9	45.0	46.3	46.0	37.5	44.5			34.8		52.1	17.1
O.Py	13.6	20.0	1.1	16.2	24.2	26.4	25.4	20.9	5.5	25.2	10.4	15.3	6.4	6.2	46.0	9.3	9.1	56.4	24.6	
																				40.5
C.Py	30.3	22.7	43.1	25.1	32.03	42.1	42.0	24.0	13.7	24.8	19.2	12.4	24.8	17.6	5.0	16.3	25.5	25.4	14.4	
Amph.	2.2		10.3	0.4				Tr	1.4	0.9	0.6	24.1	20.0	18.9	40.7	27.6	7.5	8.7		41.0
Bi	6.0	3.4	3.4	11.1	14.6	14.4	20.0	13.5	7.9								4.6			
Ir. Ox.	2.8	3.1	3.9	1.6	1.8	1.2	1.6	2.7	4.6	3.7	8.8	2.1	2.7	4.6	8.3	2.7	5.2	5.1	5.6	1.3
																		Spinel		
Gar													8.6			11.7	13.2	4.2		
Ap+Zr	0.1	0.6	0.2	0.2	0.7	0.8	1.0	0.4	1.1		0.5	0.5		0.2			0.1	0.2	1.0	0.1

are seen to compare closely to the other chemical analysis in column 1. The three sets of silica and alumina values are similar and lime, magnesia, and iron oxides total 29.9, 30.7, and 29.8 in each column. Whereas biotite occurs as the major hydroxyl-bearing mineral in the rocks here described, an examination of the columns giving the modes of other basic pyroxene-bearing rocks from other regions indicates in these latter instances that amphibole is the main hydroxyl phase, while biotite is typically absent altogether. The low K_2O content is reflected in the mode, with minor interstitial potash feldspar, lack of antiperthite, and low biotite percentages compared to the mafic and intermediate varieties. The norm indicates the low TiO_2 content.

The analysis lies within the range of values given for other pyroxene–plagioclase granulites and basic varieties of charnockite series from other localities; the

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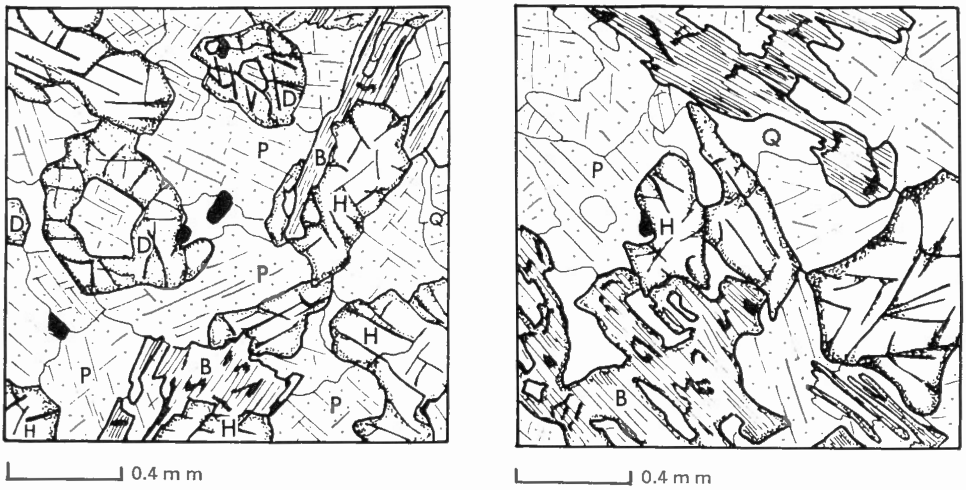
Key to Table V

1. Basic granulite (pyroxene–plagioclase granulite). Analysis made from specimens collected in the Crown Lake area, Mount Wright region. Analyst, K. Hoops.
2. Basic granulite 58/154. East of Seahorse Lake, Mount Wright region. Chemical composition calculated from mode.
3. Basic granulite 58/137. Southeast of Seahorse Lake, Mount Wright region.
4. Basic granulite 58/89B. East of Crown Lake, Mount Wright region. Chemical composition calculated from mode.
5. Pyroxene-rich granulite. Analysis made from specimens collected in the Seahorse Lake area. Analyst, K. Hoops, Mount Wright.
6. Pyroxene-rich granulite 58/153. Southeast of Seahorse Lake, Mount Wright region. Chemical composition calculated from mode.
7. Pyroxene-rich granulite 58/134. Southeast of Seahorse Lake, Mount Wright region. Chemical composition calculated from mode.
8. Pyroxene-rich granulite 58/152. East of Crown Lake, Mount Wright region. Chemical composition calculated from mode.
9. Intermediate rock (sub basic?) (G. S. I. 13.364) Salem, Madras. Analyst, J. Scoon. Howie (1955, p. 732).
10. Hypersthene diorite of the charnockite series. Pallavaram, Madras. Analyst, J. Scoon. Howie (1955, p. 732). Redefined as a 'Hybrid' by Subramanian (1959, p. 352).
11. Hypersthene diorite (hybrid rock). Near Tirusulam Village, Pallavaram, Madras. Analyst, T. Katsura, Tokyo. Subramanian (1951, p. 352).
12. Norite. Southeast side of Pammal Hill, Pammal Village, Madras. Analyst, Subramanian (1959, p. 352). Subramanian includes this in his group of syntectonic lenses.
13. Basic granulite (norite?). Summit of Paravatta Hill, Pallavaram, Madras. Analyst, T. Katsura. Howie and Subramanian (1957, p. 572).
14. Hornblende norite. St. Thomas's Mount, Madras. H. S. Washington (1916, p. 328). Groves (1936) includes it in his basic division, while Subramanian redefines it as a 'hybrid' of pyroxene hornblende granulite veined by charnockite (1959, p. 325).
15. Hornblende hypersthenite (bahiaite), Pammal Hill, Pallavaran, Madras. H. S. Washington (1916, p. 328). Subramanian redefines it as belonging to the syntectonic pyroxenite and norite lenses in the type area.
16. Basic charnockite. Hogahalla, Träslovsläge, S. W. Sweden. Analyst, N. Sahlbon. Quesnel (1950, p. 245).
17. Basic garnetiferous norite. Nipea Hill, West Nile District, Uganda. Analyst, A. W. Groves (1936, p. 170).
18. Pyroxenite. Pammal Hill, Pallavasa, Madras. Analyst, J. Scoon. Howie (1955, p. 732).
19. Pyroxene–plagioclase granulite, East Frazer Range, Western Australia. Wilson (1954, vol. ii, p. 341).
20. Augite–anorthite–bronzite–hornblende rock. Near Sentinel Hill, Musgrave Ranges, Central Australia. Wilson (1954, vol. ii, p. 341).

latter have been variously called hornblende norite, hornblende hypersthenite, basic garnetiferous norite, basic charnockite, basic granulite, hypersthene diorite, and hypersthene gabbro by different authors.

Pyroxene-Rich Granulites

These rocks may contain as much as 20 per cent plagioclase and thus are not strictly ultrabasic in composition. However, they contain such a large amount of pyroxene and have so much greater a variation in grain-size than the pyroxene–plagioclase granulites that they are distinct from them. They are dark greenish grey to black and possess a lustre related to the presence of large biotite and pyroxene plates.



A. Basic granulite (58.89). Section cut approximately perpendicular to the mineral lineation to show a granoblastic texture, with the biotites still showing a parallelism (parallel to the banding). Both hypersthene (H) and diopside (D) occur with plagioclase (P) and quartz (Q). Biotite (B) appears moulded around and grown into the pyroxene. The apparent inclusions of plagioclase within pyroxene are thought to be the result of the interlobate marginal relationships between the two minerals and are not true inclusions in the paragenetic sense. Mag. X100.

B. Basic granulite (58.135) showing hypersthene (H), plagioclase (P), biotite (B), and quartz (Q). In the lower half the quartz occurs as regularly orientated intergrowths within the biotite. All these areas of quartz are in optical continuity, the occurrences in the bottom right showing a synantetic intergrowth. Mag. X100.

GSC

FIGURE 8. Basic granulite as seen in thin section.

Pyroxenes constituting an average of 60 to 65 per cent of the mode may reach a maximum abundance of more than 70 per cent. Both clinopyroxene and orthopyroxene are present (Fig. 9). Of these, the former is about twice as abundant as the latter (Table V, columns 5–8). The orthopyroxene is weakly pleochroic in shades of pale pink and pale blue. Optical properties (Table II) indicate a compositional range $En_{38}Fs_{12}Wo_{50}$ to $En_{27}Fs_{25}Wo_{50}$. The pleochroism is pale green to colourless. The pyroxenes are relatively free from inclusions except in larger poikiloblastic plates, which may enclose smaller pyroxenes, biotite flakes, and plagioclase grains. These are the large rusty porphyroblasts visible in hand specimen.

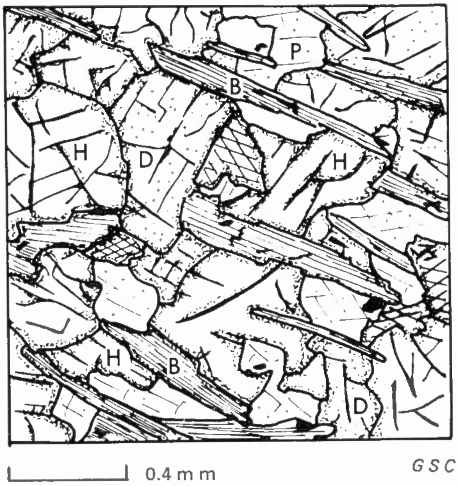


FIGURE 9.
Pyroxene-rich granulite (58.134) as seen in thin section. Mafic rock composed of hypersthene (H), diopside (D), plagioclase (P), and biotite (B). The biotite plates exhibit a strong preferred orientation. Mag. X100.

Plagioclase averaging 15 per cent of the rock has a calcic composition An_{60-70}, bringing it into the calcic labradorite to sodic bytownite compositional range. A few specimens contained calcic andesine as the main plagioclase type. Albite and pericline-type lamellar twinning are commonly well developed, while antiperthite appears to be absent. Saussuritization of the plagioclase produces a fine dark grey granular assemblage with a patchy distribution, while later recrystallization of some of the plagioclase has produced a more sodic variety free from alteration products.

Biotite with $Ny = 1.642$ to 1.636, and a strong pleochroism from light reddish yellow to deep reddish brown, is present in flakes generally possessing a marked parallel alignment. The flakes contain thin stringers of minute iron-ore grains in the manner previously described. The biotite forms 15 to 25 per cent of the rocks, while garnet again appears to be absent. Apatite is a common minor accessory mineral forming as much as 1 per cent of the mode. Iron ore both as inclusions within the biotite and as separate grains with the groundmass constitutes as much as 2 per cent of the mode.

The chemical compositions of three of the specimens used in the chemical analysis of the pyroxene-rich granulite shown in Table V, column 5, are inserted in columns 6, 7, and 8. The most mafic of these rocks shown in columns 6 and 7 carry slightly more than 6 per cent alumina, reflected by the low modal 11 to 14 per cent plagioclase content. Even here, however, the calculated SiO_2 is still about 50 per cent, indicating that the rock is not ultrabasic. As with the pyroxene–

plagioclase granulites, FeO and Fe_2O_3 values are low, giving a low iron-ore modal content and a magnesium-rich orthopyroxene. Magnesia is more abundant than lime and orthopyroxene is greater than diopside in the norm (33 per cent orthopyroxene against 26 per cent diopside). This is not the case in the mode, however, where diopside is twice as abundant as orthopyroxene (cf. diopside:orthopyroxene ratio of 3:1 in the pyroxene–plagioclase granulites). The reason for the higher diopside modal value compared to the value of the norm is that some magnesium is taken up in biotite. The latter is a subsilicic mineral and, since it constitutes about 20 per cent of the mode, accounts for the presence of olivine in the norm even though the SiO_2 is nearly 50 per cent. The low Na_2O content is reflected by the lack of albite in the norm and the calcic nature of the plagioclase in the mode. The relatively high orthoclase content of the norm as against its absence in the mode is due to the presence of biotite, which includes most of the potassium, with the result that potash feldspar does not occur even in an antiperthitic form.

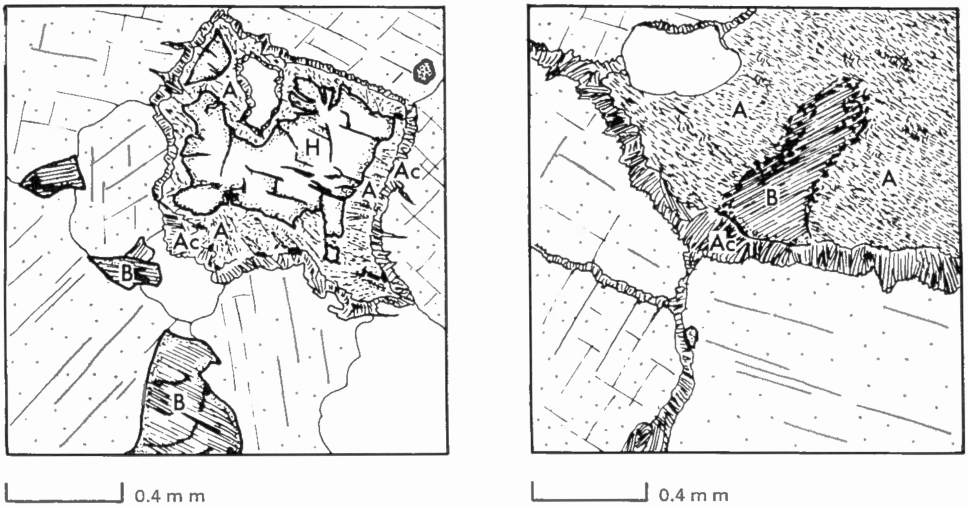
MODIFICATIONS RELATED TO THE GRENVILLE OROGENY

Many of the minerals of the granulite assemblage show variable degrees of alteration and recrystallization to other minerals more stable under a lower temperature–pressure environment. If one sets aside certain alterations, which according to Turner and Verhoogen (1951, p. 476) are frequently noted in high-grade metamorphic rocks now exposed at the earth's surface, the granulites of the Mount Wright area appear to have been affected to a variable degree by the later Grenville metamorphism. The effect of this later metamorphism is one of increasing alteration and recrystallization of the granulites as they are traced southwards towards the Grenville front. The retrogressive alteration of hypersthene, for example, is initially to serpentine and talc, which gives way southwards to coronas of fibrous actinolite and anthophyllite and finally, at the Grenville front itself, to a mosaic of greenish brown biotite and hornblende compatible with the grade of metamorphism in the Grenville province. The overall picture is complicated to a certain extent along the Grenville front by the presence of several later and narrow fault zones, the rocks within them having a distinctive texture and mineralogy, which can be related to crystallization under strong shearing stress. These cataclastites have a steeply plunging lineation, the nature of which suggests vertical movement.

Alteration of the Acid Granulites

The acid granulites appear to have been most susceptible to later alteration and recrystallization. Near the Grenville front acid granulites in an advanced state of alteration were observed to carry inclusions of more basic granulites in a less altered state. Even in those localities examined some distance from the Grenville front, the acid granulites showed signs of later recrystallization, especially of the pyroxenes. In the early stages of alteration of the acid granulites, corona structures begin to develop in the orthopyroxenes. Two corona bands adjacent to one another are usually present. The mineral phase forming the inner corona is colourless, has a straight extinction and low to moderate birefringence with refractive indices from 1.60 to 1.65. These properties suggest anthophyllite. The outer corona is composed either of green biotite or pale green actinolite. These later minerals have a thin fibrous or prismatic form with the fibres or prisms developed perpendicular to the corona bands (Fig. 10A).

Where this form of alteration is more advanced, the entire grain may be replaced by anthophyllite bordered by a thin outer corona of biotite or actinolite.



A. Hypersthene granodiorite (acid granulite) (56.48) showing the early stages of recrystallization. Hypersthene (H) is being replaced by anthophyllite (A) with an outer corona of actinolite (Ac). The red-brown biotite (B) is still relatively fresh (no recrystallization). Mag. X100.

B. Altered intermediate granulite (57.40) showing anthophyllite (A) replacing hypersthene with a thin corona of actinolite (Ac). The partly enclosed biotite (B) flake is rimmed by a reaction product of iron-ore grains. Mag. X300.

GSC

FIGURE 10. Hypersthene granodiorite and intermediate granulite, as seen in thin section.

At the same time the material forming the outer corona may be seen to spread out in the form of thin irregular bands and veins along the boundaries of the feldspar and quartz grains surrounding the altered pyroxene (Fig. 10B). The outer corona is seen to be composed of green biotite when the adjacent mineral is potash feldspar. The formation of this outer biotite corona has entailed replacement of the potash feldspar to a certain extent; evidence of this is seen in the manner in which the biotite flakes grow into the potash feldspar. When plagioclase lies adjacent to the altered pyroxene, the outer corona consists of actinolite interleaved with rare biotite. Rarely cummingtonite appears in the inner corona in place of anthophyllite. According to Hietanen (1947), who has recorded similar alterations in pyroxene-bearing metamorphic rocks in southwest Finland, these reactions may be expressed as:

$$\text{7 orthopyroxene} + \text{water} \longrightarrow \text{anthophyllite (cummingtonite)}$$

$$7\,(\mathrm{Mg\ Fe})\,\mathrm{SiO_3} + \mathrm{H_2O} \longrightarrow (\mathrm{Mg\ Fe})_7(\mathrm{OH})_2(\mathrm{Si_4O_{11}})_2$$

$$\text{and 6 orthopyroxene} = \text{2 microcline} + \text{2 water} \longrightarrow \text{biotite} + \text{6 quartz}$$

$$6(\mathrm{Mg\ Fe})\ \mathrm{SiO_3} + 2\mathrm{KAl\ Si_3O_8} + 2\mathrm{H_2O} \longrightarrow$$
$$\mathrm{K_2(Fe\ Mg)_6(OH)_4(Si_6Al_2O_{28})} + 6\mathrm{SiO_2}$$

Where the degree of alteration of the pyroxene is small, a pale green serpentine-like mineral is observed along the planes of weakness in the pyroxene. This mineral, which consists of fine fibres, has the characteristics of antigorite.

The alteration may be expressed as:

$$\text{3 orthopyroxene} + \text{4 water} \longrightarrow \text{antigorite} + \text{5 quartz} + \text{magnetite}$$

$$3(\mathrm{FeO.2MgO.3SiO_2}) + 4\mathrm{H_2O} + \mathrm{O} \longrightarrow$$

$$2(\mathrm{2H_2O.3MgO.2SiO_2}) + 5\mathrm{SiO_2} + \mathrm{FeO.Fe_2O_3}$$

The antigorite appears to antedate the development of anthophyllite and biotite coronas, as seams of the latter may enclose or cross the former. In all these alterations iron ore may have been formed as small grains, often in aggregates between the other alteration products.

The breakdown of diopsidic augite was observed in only a few instances, as the mineral is of minor importance in these acid rocks. The diopside shows replacement by actinolite, with the latter often bounded by a thin green biotite corona. The actinolite itself may form an inner corona of radiating fibrous prisms, or may appear as better defined prisms replacing the bulk of the clinopyroxene. Where the acid granulite is very rich in potash feldspar the clinopyroxene appears to be altered instead to an aggregate of biotite, quartz, and calcite grains (Fig. 11A).

Thin coronas of greenish brown biotite also surround some of the original red-brown biotite in the early stages of recrystallization. The latter biotite develops as thin flakes perpendicular to the margins of the older biotite. Where the red-brown biotite lies adjacent to pyroxene the same greenish brown biotite is seen replacing both minerals. The formation of this later biotite was accompanied by the formation of a small amount of iron ore. In addition, the iron-ore stringers characteristic of the earlier biotite are now distributed in a more haphazard manner and are accompanied by small amounts of sphene. Very thin coronas of greenish brown biotite may also develop around the larger iron-ore grains.

Along with recrystallization of the mafic minerals, the feldspars have undergone adjustment to later conditions. The development of small sericite flakes with variable amounts of fine granular calc-silicate mineral of the clinozoisite type is characteristic within the oligoclase. These alteration products may be so common that the mineral has a dark cloudy appearance. The potash feldspar, however, remains comparatively fresh in this early stage, except for the presence of later minerals along well-developed cleavage and fracture planes. These later minerals may be of several types and all are characterized by a small grain-size. Where the potash feldspar lies adjacent to mafic minerals, the minerals replacing the latter (green biotite and actinolite) may partly occupy the zones of weakness in the potash feldspar. Elsewhere these zones of weakness are occupied by sericite, granular iron ore, or calcite. The sericite can be accounted for by alteration of the feldspar along these zones, but the presence of iron ore could be due either to a certain amount of iron having been originally incorporated in the feldspar and later exsolved, or to its having been precipitated by iron-bearing solutions. The presence of iron ore has the effect of producing a series of black and reddish brown spots across the potash feldspar under plane-polarized light.

The degree of alteration increases rapidly as the Grenville front is approached from the north. This is particularly true where the banding in the granulite becomes more discontinuous; the acid component becomes more common and at the same time develops a foliation that has an east-northeast trend. From the cross-sections (Fig. 14), it is seen that the Grenville front in the Lake Gensart area is about 4 miles wide at its maximum. Elsewhere it is considerably narrower.

Thin sections of acid granulites from along the northern margins of the front show an increase in the amount of the greenish brown biotite at the expense of the earlier mafic minerals and, to a certain extent, of the feldspar. This increase in the percentage of biotite is responsible for the development of a coarse foliation in these rocks. The plagioclase now shows various stages of recrystallization to a clearer sodic oligoclase form. This process begins marginally, the picture at this stage being one of cloudy plagioclase with a marginal halo free from sericite and clinozoisite. At the same time the colourless mica associated with the plagioclase and potash feldspar becomes larger, forming well-developed flakes of muscovite.

Along with the formation of muscovite the potash feldspar gradually develops a microcline cross-hatch twinning, which at first is patchy and vague. The cross-hatch twinning may develop marginally at first, sometimes around the whole rim of a grain. It also shows preferential development adjacent to inclusions and fracture lines crossing the feldspar. With the development of a microcline triclinity the perthitic intergrowths in the potash feldspar become slightly coarser and lenticular.

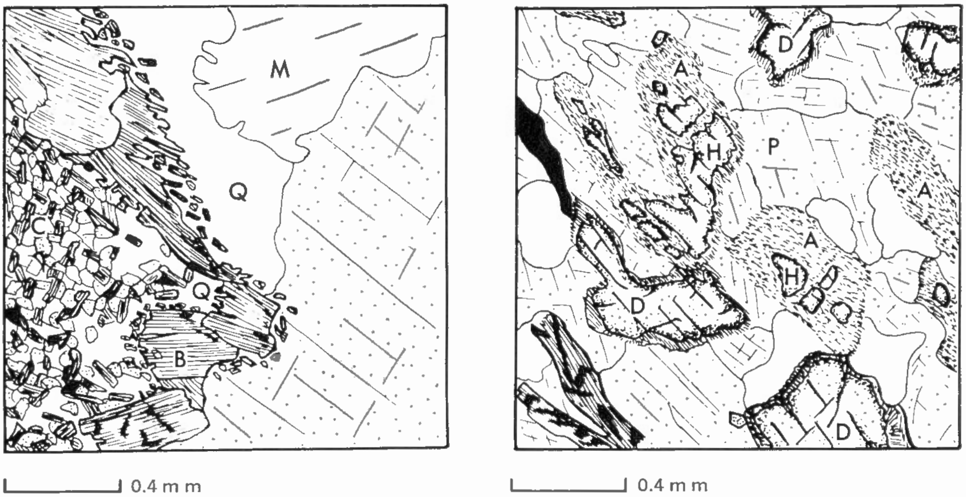
In some instances a greenish brown hornblende has developed from actinolite when the latter replaces clinopyroxene. Generally, however, the only calcium-bearing dark minerals are epidote and sphene, both of which may occur in close association with the greenish brown biotite.

The developments above take place in the zone where the original acid granulites appear to have been partly mobilized by the Grenville metamorphism. Evidence of this is seen in the formation of a new foliation with an east-northeast trend, the recrystallization of many of the minerals, the loss of the dark colour typical of the acid charnockitic granulites, and the formation of quartz veins and pink aplitic bands. Evidence of intercrystal granulation with concomitant recrystallization is seen in the development of randomly orientated small subhedral or rounded grains of microcline, quartz, and fresh sodic plagioclase along the boundaries between larger feldspar grains, and across fracture zones within the larger potash feldspars.

Along the southern margins of the Grenville front, the acid granulites have been converted into biotite granitic or granodioritic gneisses carrying variable amounts of muscovite, hornblende, and epidote (Table VI, columns 1–4). Aplogranitic bands and veins are also present. Rarely, stringers of iron ore within greenish brown biotite still retain a form characteristic of that in the biotites of the granulites, but these rocks are now more characteristic of the almandine-amphibolite or albite-epidote amphibolite facies. They are in fact more typical of certain biotite-bearing granitic gneisses underlying the iron-formation well to the south of the Grenville front.

Alteration of the Intermediate Granulites

The early stages of alteration of the pyroxenes and plagioclase of the intermediate granulites are similar to those described for the acid granulites. Anthophyllite forms an inner reaction corona in the case of orthopyroxene, whereas with the diopsidic augite this position is taken up by green actinolite (Fig. 11B). Both of these later minerals replace the pyroxenes from the margin inwards, generally along fracture and cleavage planes. The outer corona may be formed either of biotite or actinolite. Where actinolite or anthophyllite replace the pyroxene completely their thin prismatic form lies parallel with the *c* axis of elongation of the original pyroxene. Alteration of the plagioclase appears variable and patchy with sericite and granular clinozoisites as the alteration products. Thin coronas of green-brown biotite develop at the same time around the original red-brown biotite and iron-ore grains (Fig. 10B).



A. Granodiorite. Partly recrystallized (58.147) with diopside completely replaced by aggregate of calcite (C) grains, green-brown biotite (B) flakes with interstitial quartz (Q). The large red-brown biotite flakes are altering to a more greenish biotite along their margins. The microline (M) is highly corroded by the quartz. Mag. X100.

B. Altered basic granulite (58.155) showing an advanced stage of replacement of hypersthene (H) by anthophyllite (A), while the diopside (D) at this stage has only a thin corona of actinolite (Ac). Mag. X100.

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FIGURE 11. Granodiorite and basic granulite, as seen in thin section.

These alteration products appear to be somewhat later in formation than a golden yellowish mineral which characteristically appears as thin films and veins that traverse along intercrystal boundaries in the feldspars, and along cleavage and fracture planes in the pyroxenes. This yellow mineral is slightly pleochroic, has a refractive index between that of the andesine and pyroxene, and possesses a low to moderate birefringence. It appears to be fibrous in structure, but the veins are so thin that identification is difficult. These characteristics, however, suggest chrysotile. This yellow mineral is also common and has a similar habit in the acid and basic granulites. It is thought to antedate the anthophyllite, actinolite, and green biotite since coronas of these latter minerals may enclose and transgress the yellowish chrysotile.

With the breaking up of the granulite banding along the Grenville front, the intermediate granulites become inclusions and discontinuous bands within the now highly altered and foliated acid granulite. Thin sections of these inclusions show the complete or almost complete alteration of the pyroxenes. The amphibole replacing the pyroxene appears to be recrystallizing from the orthorhombic anthophyllite variety and pale greenish actinolite into a more massive greenish variety of hornblende, forming aggregates of grains in near optical continuity. This hornblende has a pleochroic formula X = pale yellow-green, Y = light green, Z = pale bluish green, with $Z_{\wedge}c = 21°$. These optically aligned aggregates merge in turn into still more massive slightly poikiloblastic grains, which are a deeper brownish green.

Along with the changes above the plagioclase, sodic oligoclase in composition, becomes less cloudy. This is due to the disappearance of sericite and the growth of small grains of calc-silicate into larger better-defined prisms of clinozoisite within the oligoclase. At the same time the original red-brown biotite has been completely altered to a medium greenish brown variety. Grains of iron ore tend to be rimmed in some instances by thin coronas of sphene. Epidote occurs marginally to the biotite and hornblende where these lie adjacent to plagioclase, which suggests some form of reaction relationship.

Just south of Crown Lake along the Grenville front, inclusions of a rock type best described as a biotite–hornblende–plagioclase schist are present within acid gneisses carrying biotite and muscovite. The latter are thought to be completely recrystallized acid granulites while the former inclusions have a mineralogy similar to those just previously described. Here, however, recrystallization is still more advanced. The amphibole is massive, irregular in outline and typically poikiloblastic with unbroken outer margins and centres riddled with irregular or rounded inclusions of quartz, plagioclase, and less commonly biotite. The pleochroic formula is again X = pale green, Y = medium olive-green, Z = dark bluish green, $Z_{\wedge}c = 21°$. The plagioclase carries clinozoisite inclusions, and the biotite, which is light to medium greenish brown, carries inclusions of iron ore rimmed by sphene. The latter mineral along with epidote now forms larger grains (Table VI, column 6).

Alteration of the Basic Granulites

The alterations that the pyroxene–plagioclase basic granulites experience are similar to those that affect the intermediate granulites. The main difference is reflected in the development of a higher proportion of amphibole in the pyroxene–plagioclase rocks, which are converted to biotite-bearing amphibolites or hornblende schists (Table VI, column 5). For a given locality away from the Grenville front, or along it, the degree of alteration appears to be greater when the pyroxene–plagioclase granulites occur as inclusions within the acid granulites rather than as lenses or thick bands within a thicker mass of intermediate granulite. Modal analyses from three biotite amphibolite specimens indicate 35 to 45 per cent plagioclase, 4 to 5 per cent quartz, 25 to 35 per cent hornblende, and 10 to 15 per cent biotite. The breakdown of pyroxene and iron-rich biotite to form amphibole could account for the higher proportion of quartz compared to the less altered pyroxene–plagioclase granulites. Replacement of some of the plagioclase to provide alumina for the amphibole is suggested from the lower plagioclase content compared to the less altered pyroxene–plagioclase granulites.

TABLE VI | *Modal Analyses of Gneisses and Related Inclusions along the Grenville Front*

	1	2	3	4	5	6	7
Quartz	29.0	29.0	17.6	20.0	6.0	13.6	21.0
K Feldspar	46.0	14.0	19.0	7.0	P	P	P
Plagioclase	13.0	40.0	52.0	52.0	49.0	43.4	45.0
Or. Pyroxene		4.0[1]		6.0[1]			
Cl. Pyroxene							
Amphibole		P		P	27.0	17.0	
Biotite	11.0	12.0	10.5	14.0	14.0	25.0	33.0
Iron Ore	0.5	0.6	0.4	0.5	0.8	0.8	P
Zircon	P	P	P	P	P	P	P
Apatite	P	0.3	0.4	P	0.8	0.4	0.4
Sphene	P	P	P	P	1.0	P	0.6
Garnet		P	P				
Muscovite	P	P	P	P			
Epidote	P	P	P	P	P	P	P

[1] Altering to amphibole and biotite.

Key to Table VI

1. Biotite granite gneiss. South side, Crown Lake.
2. Biotite granodiorite. South side, Crown Lake.
3. Biotite granodiorite gneiss. West side, Crown Lake.
4. Biotite granodiorite gneiss. Lac des Grosses-Roches.
5. Biotite–hornblende–plagioclase schist. South side, Crown Lake.
6. Quartz–hornblende–biotite–plagioclase schist. South end of Lac des Grosses-Roches.
7. Quartz–biotite–plagioclase schist. South end of Lac des Grosses-Roches.

In the advanced stages of recrystallization, the pyroxene-rich varieties of basic granulites are affected in a similar manner to the pyroxene–plagioclase types, with their characteristic development of brownish green poikiloblastic and massive hornblende at the expense of the orthopyroxenes, clinopyroxenes, and some of the calcic plagioclase. When completely recrystallized they are difficult to distinguish from the pyroxene–plagioclase granulites.

In the early stages of alteration the clinopyroxene is altered marginally and along fracture and cleavage planes to a very pale green amphibole with a thin prismatic or fibrous form. This amphibole with $Z \wedge c$ about 15° appears to be a variety of actinolite. The orthopyroxene, however, appears to be altered anthophyllite. In some specimens the formation of fibrous amphibole appears to postdate an earlier phase of alteration whereby the pyroxenes were partly altered to talc. The talc occurs as aggregates of small fibrous or platy grains that form thin zones of alteration across the pyroxenes. These talc zones cross each other in such a manner that the pyroxene is separated into smaller units, which still retain their original optical continuity. The amphiboles appear to be growing into these zones of talc and are therefore thought to postdate the latter.

The pale green actinolite may be a marginal zone around an amphibole that varies in pleochroic colour from medium orange to pale orange or colourless. This inner coloured amphibole with $Z_{\wedge}c = 19°$ may be a form of hornblende with a higher iron content than the actinolite. Along with the alteration of the pyroxenes, the plagioclase takes on a cloudy aspect due to the development within it of small prisms of clinozoisite. The red-brown biotite appears corroded and may be bounded by small grains of iron ore. The original red-brown biotite becomes paler brown in the altered pyroxenites, although at the same time it becomes cloudy owing to an increased amount of included iron-ore grains. It appears that more iron ore has been exsolved out of the red-brown biotite under these later conditions.

Conclusions

The nature of the alterations described above is such that the granulites show several stages of recrystallization to a mineral assemblage typical of lower metamorphic grade. The change in metamorphic grade is therefore retrogressive, although the final difference in grade is not very great when recrystallization is complete. Clearly the lowest grade of metamorphic recrystallization is characterized by the development of serpentine and talc, which in turn is followed by the development of fibrous actinolite and prismatic anthophyllite. Therefore, although the metamorphism is initially retrograde, its grade does appear to increase southwards across the Grenville front. The appearance of hornblende and the development of variable quantities of oligoclase, andesine, epidote, and brown-green biotite indicate that the metamorphic grade is within the albite–epidote amphibolite or almandine–amphibolite facies range, and is therefore similar to the grade of the rocks to the south of the Grenville front.

With the mobilization of the altered acid granulite along the Grenville front a certain amount of metasomatic alteration of the more basic granulites may have taken place, but more work is needed to be done on this point before any definite statement can be made. It can be established, however, that veins and tongues of aplogranitic rock crosscut and permeate biotite–hornblende-bearing schists and gneisses to a noticeable degree.

The development of anthophyllite appears to be temporary, as it develops either in rocks that carry excess potash in the form of potash feldspar, or in rocks that during their recrystallization release enough potash to lead to the eventual disappearance of anthophyllite. The anthophyllite develops at an early stage from the alteration of magnesium-rich orthopyroxene. The rocks with anthophyllite may even carry potash feldspar in considerable quantities, and in this instance the anthophyllite is saved from immediate destruction by the development of the outer corona of green biotite formed by reaction between the anthophyllite and potash feldspar or antiperthite. With continued recrystallization, however, the anthophyllite is completely made over to greenish brown biotite, while at the same time the actinolite is changing into more massive amphibole.

No attempt has been made to map zones of metamorphism across the Grenville front, for, in addition to the large scale of the area mapped and a limiting time factor, the overall relationships have been made more complex by the development of dislocation zones along the front. These dislocation zones appear to have caused a still later mineralogy to be impressed on the rocks adjacent to them. The typical rocks associated with these dislocation zones are calcite–chlorite–sericite-bearing schists and phyllonites with a steeply plunging lineation, numerous quartz veins, and a crinkled schistosity along their strike.

PETROGENESIS OF THE GRANULITES

Introduction

As the northern and western limits of the granulites were not observed where junctions with older rocks may be present, opinions presented here regarding origin and mode of formation must remain inconclusive. Along their southern boundary the granulites become recrystallized to an assemblage of gneisses of lower metamorphic grade, which is related to the Grenville orogeny. The metamorphic zone separating the normal granulites from those recrystallized into the lower grade gneisses is believed to be part of the so-called Grenville front, which even in this area is marked by some dislocation. This dislocation, although complicating the relationships, does not destroy the evidence that the front is essentially a metamorphic one, marked by progressive southward recrystallization of the granulites.

Opinions quoted here on petrogenesis are derived from data collected well within the granulite terrain and away from its northern and western boundaries. Such opinions must therefore be treated with some reserve since future work at these boundaries may produce alternative evidence. A consideration of the petrogenesis of these rocks is best approached through an examination of several separate but related aspects.

Nature of the Feldspars

The nature of the feldspars leads to some speculation in regard to the conditions present during the crystallization of the granulites. The potash feldspar was generally observed to be perthitic in nature, the most common intergrowth being the hair-type, while flame-type perthites were less noticeable. These two types of perthitic intergrowth are believed to have formed through exsolution from a homogeneous high-temperature alkali feldspar. According to Eskola (1952, p. 166), the flame perthites are more characteristic of the almandine–amphibolite facies, whereas the hair perthites are more typical of alkali feldspar crystallized under the pyroxene granulite facies. Both of these, however, are distinguishable from the vein and patch-type replacement perthites of Alling (1938), which are found in the partly recrystallized granulites and tentatively related to the later Grenville metamorphism.

The presence of exsolution perthites is thought to be indicative of high temperatures according to Ramberg (1952, p. 161). Fyfe, Turner, and Verhoogen (1959, pp. 159–161) suggested a temperature of more than 500°C if perthites are prevalent and noted that they are the main form in which potash feldspar occurs under conditions of the granulite facies.

Tuttle and Bowen (1958, p. 1) have published results of their experiments on phase-equilibrium relations in the system albite–orthoclase–silica–water. They found that alkali feldspar forms a complete series of solid-solutions above 660°C and that below this temperature a miscibility gap is present. Homogeneous synthetic feldspars that were formed above 660°C unmixed when held at lower temperatures. They stated that " . . . unmixing of alkali feldspar in the presence of water vapour was so rapid that it is surprising that fine perthitic intergrowths and homogeneous feldspars are found in nature – they must have formed in a dry environment."

In the present example, it will be shown that the mineral assemblage of the granulites appears to lie within the lower ranges of the granulite facies. In particular, the acid granulites are thought to have formed at a relatively late stage since they enclose and vein randomly orientated bodies of more basic granulite. Their period of crystallization may therefore have bridged the temperature ranges between the higher levels of the almandine–amphibolite facies and the lower levels of the granulite facies. Such a relationship may account for the occasional development of the coarser flame perthite in the acid granulites.

The effect of stress upon granitic rocks has also been cited by Chayes (1952, p. 213) as leading to the development of coarser perthites from fine perthites and cryptoperthites, in addition to causing the granulation of quartz. A more complete dissociation was suggested by Buddington (1939, p. 329) with the formation under stress of albite or oligoclase and microcline at the expense of perthitic feldspars.

In addition to the development of coarser perthites, the degree of triclinity and microclinization of the potash feldspar away from the cryptoperthitic and fine hair perthitic orthoclase form gives some insight into the history of the acid granulites. Both stress and temperature variations acting individually or together as in regional metamorphism are known to cause the formation of microcline from orthoclase.

The potash feldspar in the relatively unaltered intermediate granulites does not show any quadrille-type twinning; a similar relationship holds also for the least altered acid granulites, although here some potash feldspar may show a vague shadowy extinction, suggesting some degree of triclinity. With increasing alteration of the pyroxene, biotite, and plagioclase, the microcline most frequently makes its initial appearance as a patchy development of typical quadrille twinning, generally at the rim of a particular grain or, less frequently, in an irregular manner near its centre. In the former instance it may surround the grain or, more commonly, extend partly around it. The quadrille twinning has also been observed to develop locally about rounded inclusions of quartz or plagioclase and also adjacent to cross-fractures in the potash feldspar. The coarseness of the twinning is variable, being so fine in places as to appear as a shadowy extinction, whereas in other places it is so coarse that it can be mistaken at first for some form of perthitic intergrowth.

The development of microcline-type twinning over some parts of a grain and its absence over other parts would suggest that both monoclinic orthoclase and triclinic microcline may be developed not only in the same rock but within the same grain. Such an association of orthoclase and microcline has been noted by Eskola (1952, p. 148), Harker (1954, p. 130), and Goldsmith and Laves (1954b, p. 110).

However, the absence of characteristic quadrille twinning does not preclude microcline, since the twinning might occur on a submicroscopic scale. Likewise the presence of quadrille twinning does not indicate the degree of triclinity. Howie (1955, p. 746), for example, in an X-ray analysis of the position and separation of the (130) and ($1\bar{3}0$) reflection in six potash feldspars showing shadowy extinction has demonstrated that one was orthoclase (2V = 52°–60°), two others had microcline characteristics (2V = 84°–86°), and the remaining three had characteristics indicating an intermediate phase (2V = 60°–80°).

The fact that intermediate phases with or without sub-microscopic twinning may exist between the monoclinic symmetry of orthoclase and the triclinic symmetry of microcline signifies that care must be taken before potash feldspars can definitely be called orthoclase or microcline. In the present case 2V measurements consistently gave values of 78° to 86°, indicating that even in the apparent microscopically untwinned specimens a high degree of triclinity typical of microcline appears to be the rule. The typical potash-rich feldspar of the acid granulites is therefore microcline characterized by a twinning extremely variable in its scale, intensity, and distribution throughout a given grain.

The nature of the microcline has been considered and a few words can now be said with regard to its development both in other metamorphic terrains and in the present one. In several instances, the alteration of orthoclase to microcline has been attributed to a decreasing metamorphic grade. Eskola (1952, p. 148), for example, described the progressive microclinization of orthoclase, adding that " . . . the development of microcline from strain shadows seems to be specific for the granulite facies." The potash feldspars described by Eskola from Lapland have been X-rayed by Goldsmith and Laves (1954b, p. 110), who concluded that microclinization has developed hand-in-hand with variability of triclinity, thus alluding to the possible development of poorly or sub-microscopically twinned triclinic potash feldspar.

The development of triclinity and microclinization with respect to metamorphic grade has been studied in potash feldspars from rocks in southern and northern Norway by Heier (1957, pp. 468–479), who concluded that "the orthoclase microcline transition takes place very close to the conventional granulite-amphibolite facies transition." Heier put the temperature of transition at about 500°C, i.e., slightly lower than the temperature of transition between the two facies. Hence the monoclinic orthoclase may be found in high-grade almandine–amphibolite facies rocks. In the present instance the development of microcline goes hand-in-hand with the degree of recrystallization, being best developed when the acid granulites are largely converted into light-coloured biotite–quartz–feldspar gneisses.

Where plagioclase occurs as inclusions within the potash feldspar, thin mantles of a clear albitic plagioclase surround the variably sericitized oligoclase grains, providing evidence of reaction between potash feldspar and plagioclase with falling temperature. These mantles are best developed where quadrille twinning is well exhibited by the potash feldspar. The fresh nature of these mantles suggests that they were formed by reaction, the albite molecule being derived from the enclosing perthitic feldspar. Supporting this relationship is the fact that the thin perthitic intergrowths wedge out and become less abundant adjacent to the plagioclase mantles.

Mention has already been made of the effects of stress during and after the initial crystallization of the acid rocks and recrystallization of the more basic types. The bending of the twin lamellae in the plagioclase grains and annealed microfractures in the feldspars is related to movement during the formation of the granulites. The microfractures observed within both the plagioclase and the potash feldspars have been annealed with the fractured material in each case. The presence of small iron-ore and quartz grains along these microfractures indicates that other material was able to migrate along these before they were annealed.

Microfracturing also took place at some period following the formation of the granulites, possibly during the Grenville orogeny. Along such microfractures in the potash feldspars smaller grains of the same mineral occur. Quadrille twinning is well developed in these grains. The different orientations of the twin patterns indicate movement and recrystallization along these microfractures. That these microfractures may be related to the effects of the Grenville orogeny is inferred from the development along them of colourless mica. In places the colourless mica becomes well enough defined to be termed muscovite.

Significance of Biotite and Hornblende

Evidence derived from the nature of the feldspars indicates that the liquid phase from which the acid granulites crystallized was at a high temperature and had a relatively low water content. The anhydrous nature of this liquid phase can be further considered in relation to the presence of the hydroxyl-bearing minerals biotite and hornblende.

The brownish red biotite in all the varieties of granulite has fairly constant optical properties, indicating a narrow compositional variation. These features suggest that the formation of the biotite, whether from a liquid phase or by recrystallization from a lower grade assemblage, was governed by a particular temperature-pressure environment. The biotite is most abundant in the pyroxene-rich basic granulites forming as much as 30 per cent of the mode. The intermediate granulites average 10 per cent biotite, the pyroxene–plagioclase basic granulites 3.5 per cent, the acid granulites 3.5 per cent, and the aplogranitic types only 0.6 per cent. In all these samples it was found, as shown earlier, that the biotite was commonly in apparent equilibrium with the pyroxenes and feldspars during the formation of the granulites. The observed replacement of pyroxene by biotite and quartz, while of significance, was not common. The pyroxene–biotite reaction in such instances is tentatively attributed to the effect of percolating granitic liquids that crystallized to form the acid granulites.

The presence of greenish brown hornblende in some of the basic granulites is attributed to local variations in bulk composition. This is suggested by its restriction to thin bands within these granulites, where it occurs at the expense of both biotite and pyroxene. The abundance of biotite throughout the group and the restriction of hornblende is a marked feature, which must be explained in terms of the chemical composition of the group and possibly of the effects of certain stress conditions.

According to Ramberg (1949), the following reaction takes place in oversaturated rocks on transition from the amphibolite facies to the granulite facies.

$$\underline{\text{Amphibolite facies}}$$

$$NaCa_2(Mg,Fe)_4Al_3Si_6O_{22}(OH)_2 + (Mg,Fe)_3Al_2Si_3O_{12} + 5SiO_2$$

Hornblende + Garnet + Quartz

$$\underline{\text{Granulite facies}}$$

$$\rightleftharpoons \quad 7(Mg,Fe)SiO_3 + NaCa_2Al_5Si_7O_{24}$$

Hypersthene + Plagioclase

In SiO_2 deficient rocks, however, hornblende will be stable at higher temperature-pressure levels than in those rocks that are quartz-bearing, i.e. the reaction,

$$NaCa_2(Mg,Fe)_4Al_3Si_6O_{22}(OH_2) + (Mg,Fe)_3Al_2Si_3O_{12} + 3(Mg,Fe)SiO_3$$

Hornblende + Garnet + Hypersthene

$$\rightleftharpoons \quad 5(Mg,Fe)_2SiO_4 + NaCa_2Al_5Si_7O_{24}$$

Olivine + Plagioclase

takes place at higher pressure-temperature levels than does the previous reaction.

As a result, it has been possible in the present example for hornblende, orthopyroxene, and labradorite to occur in stable equilibrium, in silica-deficient rocks alongside those containing orthopyroxene and excess silica, within the pressure-temperature interval between the reactions just listed above.

The presence of hydroxyl-bearing minerals in this granulite assemblage indicates that water was originally present as a free phase both in the recrystallizing intermediate and basic varieties and in the liquid phase crystallizing to give the acid granulites. In addition both temperature and water pressure conditions were favourable for the development of these hydroxyl-bearing minerals.

For many years after Eskola's definition of the granulite facies some geologists held that the presence of biotite in granulite facies rocks was an indication of chemical disequilibrium. Turner and Verhoogen (1951, p. 479), however, suggested that the presence of hydroxyl-bearing minerals in granulite facies rocks was possibly due to the presence of water and need not necessarily point to chemical disequilibrium.

These views indicate the nature of the controversy regarding the presence of water during metamorphism. Ramberg (1952, p. 269) observed that ". . . it is very interesting that water appears to be available wherever needed to form the hydrous minerals." Dunn (1942), Eskola (1952), and Ramberg (1952) have expressed the view that water was universally present and always in adequate supply during metamorphism, thus diminishing its importance as a controlling factor. Yoder (1955, pp. 569–627), however, objected to the views above and was of the opinion that the genesis of hydroxyl-bearing minerals would in many instances be prohibited due to lack of water, and he further emphasized (op. cit., p. 521) that

" . . . the role of water in metamorphism is dependent upon four variables — temperature, rock pressure, water content, and water pressure."

With regard to high grade assemblages, Yoder (op. cit., p. 518) was of the opinion that " . . . granulite may have formed in the absence of water at *low* temperatures, or at high temperatures in the presence of water above the stability range of hydrous minerals."

Ramberg (1949) and Eskola (1952) are of the opinion that the absence of water in a granulite environment was probably due to high temperature, making the latter the most important controlling factor.

In the present case, evidence indicates that though the temperatures were high enough for the formation of orthopyroxene, antiperthite, and hair perthite (an assemblage typical of the granulite facies), there was sufficient water, along with appropriate water pressure and rock pressure, to allow the formation of a hydroxyl-bearing phase. The temperature, therefore, was not beyond the stability range of the biotite and hornblende under the given water pressure and rock pressure values. The presence of biotite throughout the whole assemblage indicates relatively high K_2O:NaO, and MgO + FeO:CaO ratios for these rocks.

Before going on to consider the level of metamorphism, brief consideration is given to Yoder's controversial ideas in connection with the mineral facies concept. Yoder (1952) published the results of his experimental investigations of the stable mineral assemblages in the system $MgO–Al_2O_3–SiO_2–H_2O$. He concluded (1955, p. 615) that " . . . at approximately 600°C temperature and 1,500 p.s.i. pressure of water vapour, it is possible to have assemblages suggestive of every one of the now accepted metamorphic facies in stable equilibrium". Yoder continued, "The differences between these facies are the result of variation in bulk composition and need not represent variations of pressure and temperature. This conclusion based on experimental fact appears to be at variance with field observations." Furthermore, Yoder stated (op. cit., p. 616), "It is necessary, therefore, to construct a new facies classification based on a fixed composition, or on several independent compositions, particularly sensitive to temperature and pressure."

Eskola (1957, pp. 106–119) in his discussion of the mineral facies of charnockites considered Yoder's views in the light of field and petrological evidence gained both by himself and by other workers. Although acknowledging that difficulties arise from variation in bulk composition, Eskola maintained (p. 110):

> The belonging of a rock to a certain facies is ascertained from the so-called critical minerals or assemblages, stable in one facies only. It is particularly the amount of water and carbon dioxide that causes complications and this is especially true of the granulite facies. The mineral facies classification as Yoder says, must be reformed on an exact basis to meet these complications. It seems to me, however, that the experience gained in the application of the facies principle by various workers in many countries has proved its usefulness even in its present, only qualitative state, and that the cases where it has lead to erroneous results are neither numerous nor very serious.

In the present work, the writers, while acknowledging the significance of Yoder's works, are of the opinion that Eskola's mineral and metamorphic facies classification as refined by Turner and Verhoogen (1951) is a useful tool, which is consistent with the observed field and microscopic evidence.

The Level of Metamorphism

The mineral assemblages of the granulites from the Mount Wright region fit into the granulite facies of Eskola (1939, p. 360), except perhaps for the uncertain position of hydroxyl-bearing biotite and hornblende. Eskola has defined the granulite facies as comprising the crystalline rocks, which at normal granitic composition are composed of quartz, potash feldspar, sodic plagioclase, and almandine–pyrope garnet. At basaltic bulk composition the association hypersthene and plagioclase are typomorphic minerals of this facies (Eskola, 1952, p. 140). Garnet forms only where alumina exceeds the amount that can be contained in the feldspars. Further, if alumina exceeds the amount required for the garnet ratio, then sillimanite or cordierite is formed. Sometimes excessive alumina may first give cordierite. Ideally, the pair kyanite–garnet (or sillimanite–garnet) replaces mica, and the pair diopside–hypersthene replaces amphibole.

Subsequently, Fyfe, Turner, and Verhoogen (1958, p. 232) distinguished rocks with the characteristics above as belonging to the pyroxene granulite subfacies. These were distinguished from associations of hornblende–biotite–cordierite-bearing granulites so extensively developed in some terrains as to be given the separate status of the hornblende granulite subfacies. Turner and Verhoogen (1951) suggested that the hornblende granulite subfacies field occupies the area of overlap between the almandine amphibolite facies and the granulite facies. Hsu (1955, p. 223, *quoted by* Fyfe, *et al.,* 1958, p. 232) proposed the term biotite granulite subfacies for rocks with similar assemblages in the San Gabriel Mountains of California.

In the area under consideration, the critical and typomorphic minerals for the whole granulite assemblage are antiperthitic plagioclase, high temperature perthites, blue quartz, hypersthene, diopside, pyrope–almandine garnet, biotite, and hornblende. According to Turner's and Verhoogen's subdivision of the granulite facies, the presence of the latter two hydroxyl-bearing minerals in the granulites of the Mount Wright region would place these rocks into their hornblende granulite subfacies.

The main mineral assemblages are:

(1) Quartzo-feldspathic rocks (acid granulites).
    a) quartz, microcline plagioclase, biotite, hypersthene ± garnet (charnockite s.s.).
    b) quartz, plagioclase microcline, biotite, hypersthene ± garnet (enderbite).
    c) quartz, plagioclase, microcline ± biotite, ± garnet (alaskites).
(2) Intermediate assemblages (intermediate granulites).
    a) plagioclase, quartz, hypersthene, diopside, biotite (normal intermediate granulites).
    b) plagioclase, quartz, hypersthene, diopside, biotite, microcline (migmatized intermediate granulites).
(3) Basic assemblages (pyroxene-plagioclase granulites).
    a) plagioclase, diopside, hypersthene, biotite.

b) plagioclase, diopside, hypersthene, biotite, hornblende.
c) plagioclase, diopside.
(4) Pyroxene-rich assemblage.
a) Diopside, hypersthene, biotite, plagioclase ± hornblende.

The plots on an ACF diagram of the four chemically analyzed rocks are shown on Figure 12. Also inserted in this diagram are the plots of the eight specimens whose approximate chemical compositions were calculated from their modes. From the distribution of these plots it is seen that the actual mineralogy of these rocks agrees with that predicted by the phase-equilibria ACF diagram for granulite facies rocks with excess SiO_2.

The plot of the analyzed garnet-bearing hypersthene granulite lies well within the stability field anorthite–orthopyroxene–garnet, the presence of the garnet indicating an excess of alumina over the amount required by the feldspars and the small amount that may be taken up in the co-existing orthopyroxene. In the aplogranitic granulites, where garnet is the main ferromagnesian mineral, the amount of iron and magnesium available during the formation of these rocks did not generally exceed that required for the garnet ratio, the result being that orthopyroxene is either lacking in many of these rocks, or of minor importance. Sufficient iron and magnesium were available to react with excess alumina to form garnet and biotite so that neither sillimanite nor kyanite were formed in these rocks. Another factor related to the scarcity of orthopyroxenes in the granites and granodiorites was the formation of the red-brown biotite.

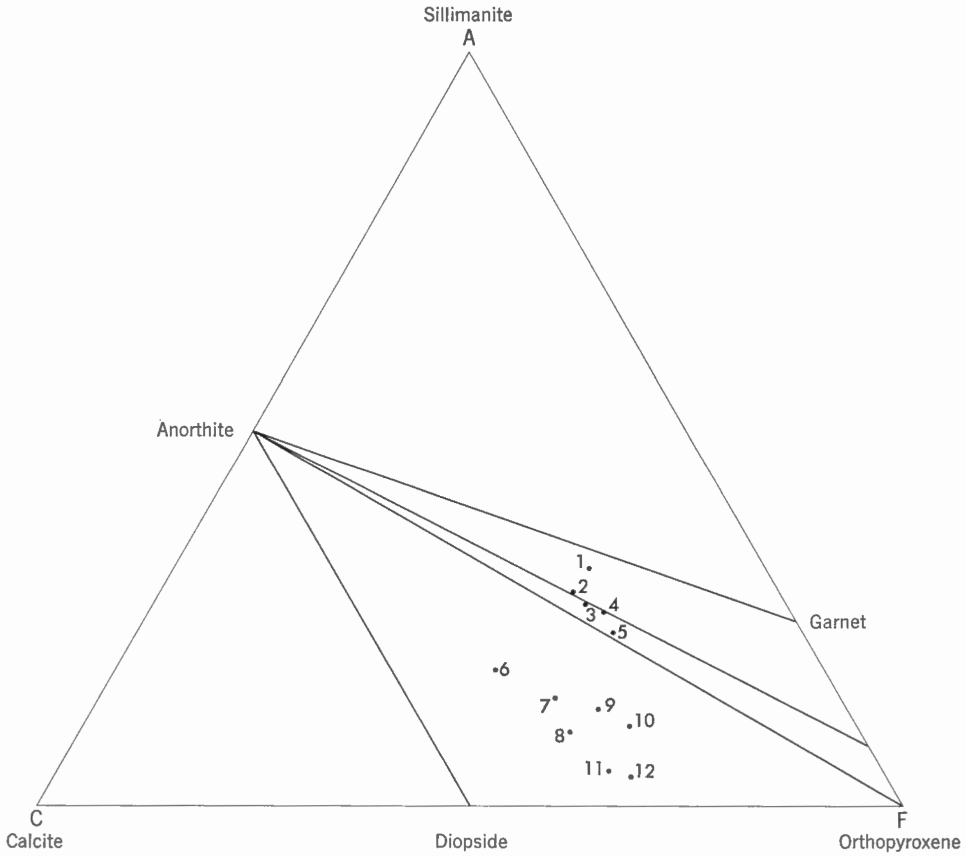
The intermediate granulites also lie within the two phase anorthite–orthopyroxene field. The ACF diagram (Fig. 12) shows the field anorthite–orthopyroxene extended to allow for an alumina content of as much as 8 per cent, which the orthopyroxenes of this facies may contain. The four plots of intermediate granulites are seen to fall within this extended field, a feature suggesting that the orthopyroxenes here involved are aluminous. The presence of minor amounts of diopside in these rocks is in accord with their position in the extended anorthite–diopside–orthopyroxene field, indicating a slight excess of calcium over the amount required by the feldspar ratios. The pyroxene–plagioclase granulites and pyroxene-rich granulites fall well within the anorthite–diopside–orthopyroxene field, the plots of the former falling nearer the calcite and sillimanite corners, the plots of the latter nearer the hypersthene corner.

The presence of biotite in all the rocks examined, except the plagioclase diopside granulites and some of the aplogranites, indicates that this mineral has an extended stability from the most acid through to the most mafic rock types. This suggests a wide diadochy of (Mg+Fe) to Al ratios, although the optical properties of the biotite suggest a fairly constant Mg/Fe ratio.

Ramberg (1952, p. 158) stated that the following reactions take place abruptly around the borderline between the granulite and almandine amphibolite facies.

$$(1)\ \underset{\text{(lower temp.)}}{\text{Biotite + sillimanite}} \rightleftharpoons \underset{\text{(higher temp.)}}{\text{garnet + potash feldspar + water}}$$

$$(2)\ \text{Biotite} \rightleftharpoons \text{hypersthene + potash feldspar + water}$$



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GSC

FIGURE 12. ACF diagram for the pyroxene-bearing granulite facies rocks with excess silica.

He maintained that these reactions depend upon the Mg/Fe ratio, and that they do in fact show that biotite may or may not be stable in the granulite facies. Petrological data reveal that pyroxenes have a greater Mg/Fe ratio than do co-existing biotite and garnet. In the present work this observed Mg/Fe relationship appears to hold, for optical data suggest nearly equal amounts of magnesium and iron in biotites whereas both the orthopyroxenes and diopsides show Mg > Fe. Further evidence of original iron enrichment in the biotites is seen in the presence of the stringers of iron-ore grains within the biotites, which have a form suggesting exsolution from an earlier higher temperature phase.

While the biotites in these rocks appear to be largely in equilibrium with the pyroxenes, there is some evidence to suggest that they are products of partial reaction with the latter:

(3) Biotite + quartz $\rightleftharpoons$ rhombic pyroxene + potash feldspar + water

The equilibrium temperature of the reaction will be a function both of water vapour pressure and Fe/Mg ratio. Under granulite facies conditions where P_{H_2O} is likely to be less than total load pressure, equilibrium may be established by a balance in reaction (3), water vapour pressure increasing with temperature along the univariant curve until P_{H_2O} equals P load. Over this range of temperature biotite and rhombic pyroxene can co-exist at equilibrium.

Environment of Deformation

The granulites, with a high-grade mineral assemblage, are typical products of plutonic metamorphism under high temperature and confining pressure, where deformation results in plastic flow, a mechanism illustrated by the highly disharmonic nature of the minor folds and the para-tectonic nature of the ptygmatic veins. It is thought that the intermediate and basic granulites were formed by recrystallization of a largely solid-state phase whereas the acid granulites crystallized out of a mobile phase that was largely liquid in character.

The nature of the mineral lineation and the absence of any marked degree of intercrystal granulation within the intermediate and basic granulites suggest that the formation of this mineral lineation was either para-tectonic or post-tectonic. If the crystallization is largely post-tectonic, then the mineral lineation and small-scale banding must be mimetic after an earlier fabric. The random orientation of inclusions of intermediate and basic granulite, however, within the acid granulites in certain localities, indicates the probable para-tectonic nature of much of the crystallization (Fig. 4D).

The constant orientation of the easterly plunging mineral lineation may indicate a major stress axis acting in an approximately north-south direction. This stress persisted during the emplacement and crystallization of the acid granulites as the latter may also exhibit a rude lineation parallel with that in the more basic granulites, particularly in the thinner bands and veins. The form of some of the ptygmatic veins also suggests veining during deformation.

The nature of the large-scale banding, i.e., banding produced by the alternation of bands of acid and intermediate granulite, appears to have been largely the result of the emplacement of an acid mobile phase along planes that were approximately parallel with the smaller scale banding within the intermediate granulites. The frequent and slightly discordant nature of the contact between the large- and small-scale banding (Pl. I) gives further support to the conclusion regarding the mobility and penetrating power of the acid mobile phase. The large-scale banding can therefore be looked upon as migmatitic in style. Some of the thinner bands and lenses of acid granulite have a form that could be related to metamorphic differentiation, while the ill-defined pods and irregular patches of acid granulite within more basic granulites (Pl. III) could likewise be related to metasomatic segregation.

The smaller scale banding within the intermediate and basic granulite, which is related to minor variations in the ratio of mafic to felsic minerals (Pl. I), could either be related to metamorphic differentiation or more probably it reflects an earlier banding. If the intermediate granulites are highly metamorphosed sedimentary rocks, then this banding may reflect original lithological variations. In this instance, the basic granulites could possibly represent volcanic horizons or intrusive bands within the original sedimentary sequence.

The subhorizontal nature of the banding indicates that the confining pressures were such that there was little relief of pressure and movement of material in a vertical direction, this being reflected in the apparent absence of large-scale folds with steep axial planes. Because of this high confining pressure, the minor fold structures that did form, as a result of the strong north-south horizontally acting stress axis, did not distort the banding on a large scale. Nevertheless, the lateral flow of material appears to have been considerable, with the result that many of the minor folds are overturned northwards or completely recumbent. The limbs of such minor folds often show various degrees of thinning and stretching until the form of the fold is lost and all that remains are subparallel bands and lenses of granulite with rare apparently isolated fold hinges.

The form of these minor folds suggests differential movement with upper bands moving relatively northwards over underlying bands. Under this regime the major S-surfaces would be potential shear- and slip-planes. Recrystallization along these surfaces has produced minerals that are generally larger and more poikiloblastic than is normal (Pl. IVA and B).

A fabric possibly related to differential flow has been observed in certain sections of intermediate granulite cut perpendicular to the mineral lineation. Here the biotites instead of lying with their (001) surfaces parallel with the banding, as is usual, appear to be orientated in such a manner as to form a spindle, the axis of which is approximately parallel with the mineral lineation (Plate IVB).

The possibility that the horizontal banding and overturned or recumbent minor folds may reflect the presence of large-scale recumbent folds has not been overlooked. Large-scale fold hinges that could possibly indicate the presence of such large structures, however, were not observed.

Origin of the Main Rock Types

The field evidence available supports the mineralogical evidence that the acid granulites were formed by the crystallization of a relatively mobile and partly liquid phase. Even if one allows for the solid nature at this stage of the orthopyroxene and red-brown biotite due to possible metamorphic origin, the remaining liquid phases were abundant enough to form a mobile acid magma, which under high pressure penetrated the more basic granulites without great difficulty. From this combination of minor crystal mesh and major interstitial liquid phase with a temperature somewhere between 660° and 750°C, the high temperature alkali feldspars crystallized out. Possibly a homogeneous alkali feldspar began to invert to orthoclase cryptoperthite or hair perthite as temperatures dropped below 660°C, and a homogeneous oligoclase began to invert to antiperthite at about the same temperature. The relationship of the potash-rich to soda-rich feldspars suggests that the latter began to crystallize out first.

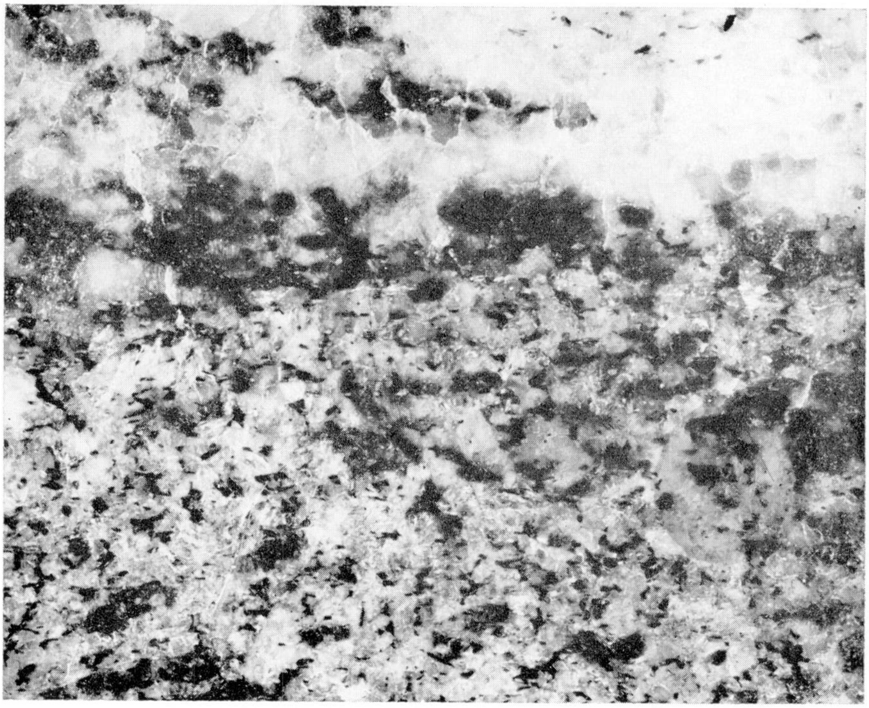
The nature of the ptygmatic veins, rare crosscutting veins of aplogranite, and the random orientation of inclusions of basic and intermediate granulite within the acid granulites all point to the mobility of the latter during its formation and emplacement. In addition, both field and mineralogical evidence point to a period of crystallization continuing after the more basic granulites had been recrystallized to their present assemblage and, as suggested earlier, this later period in the paragenesis of the granulites may have taken place when conditions were equivalent to the granulite–amphibolite facies transition. High-grade metamorphic conditions, however, appear to have continued after the initial crystallization of the acid granulites, as these exhibit a variable degree of recrystallization with the development locally of a granoblastic texture. The manner in which quartz indents and replaces the other minerals suggests that during this late phase the free silica was still active. On the other hand some quartz indentation may be related in part to reactivation during the later Grenville orogeny.

The aplogranitic granulites represent the latest phase to crystallize, having in places a crosscutting relationship even in the granitic and granodioritic granulites. Generally, however, they grade into the latter and as such are distinguished by their whitish colour, coarse rarely pegmatitic grain-size, and by the presence of red garnets. The aplogranitic granulites are thought to represent the late stage residuum of the acid magma, which crystallized to form the granitic and granodioritic granulites. Their poverty in orthopyroxene and biotite may reflect an excess of alumina, which combined with magnesium and iron to form the pyrope–almandine garnets. In some specimens where garnet is not so common, biotite is more abundant. These aplogranitic granulites must be carefully distinguished from microscopically similar rocks that are present along the Grenville front to the south. The latter are thought to have been produced during remobilization of the acid granulites in this zone. These later Grenville aplogranites are well represented in certain localities within the Grenville province to the south.

The origin of the intermediate granulites poses a greater problem. In many areas where charnockitic rocks have been described, those of an intermediate composition have been called hybrids, and were supposed to have been formed by the impregnation, veining, and assimilation of more basic rocks by a charnockitic magma. In other instances, the magmatic differentiation of a plutonic intrusion with or without subsequent metamorphic recrystallization has been postulated for the origin of these pyroxene-bearing rocks, the intermediate varieties forming an integral unit midway between the acid and the basic differentiates.

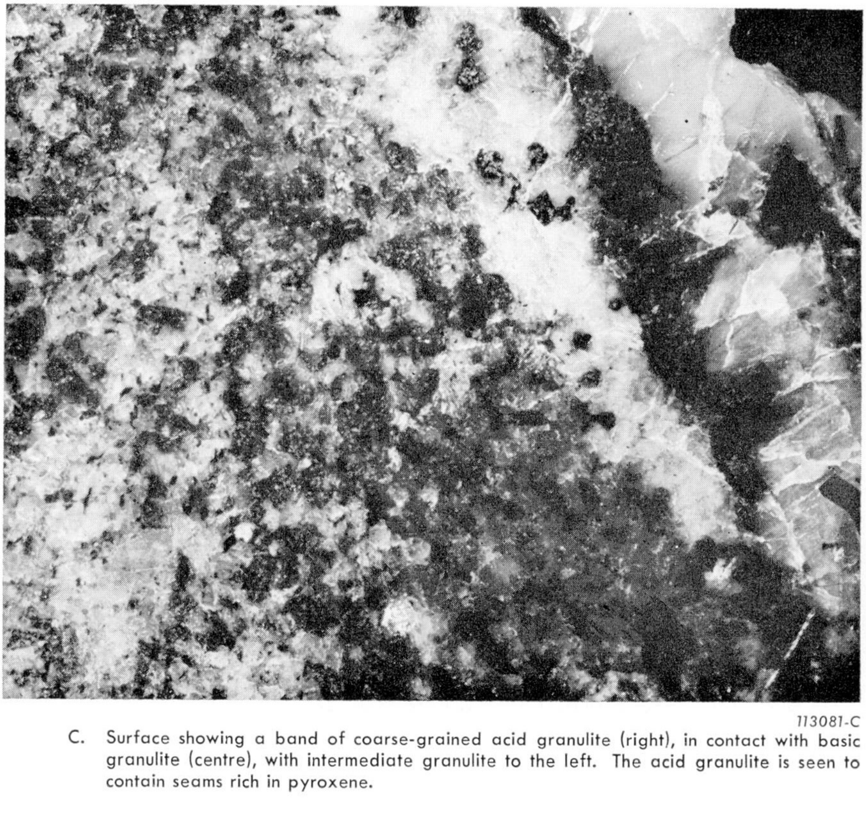
According to Howie, in his examination of the type charnockite area (1955a, p. 762), ". . . the charnockite series of Madras are either igneous rocks or igneous rocks which have subsequently undergone high-grade regional metamorphism."

PLATE IV. Polished surfaces of specimens from Seahorse Lake.



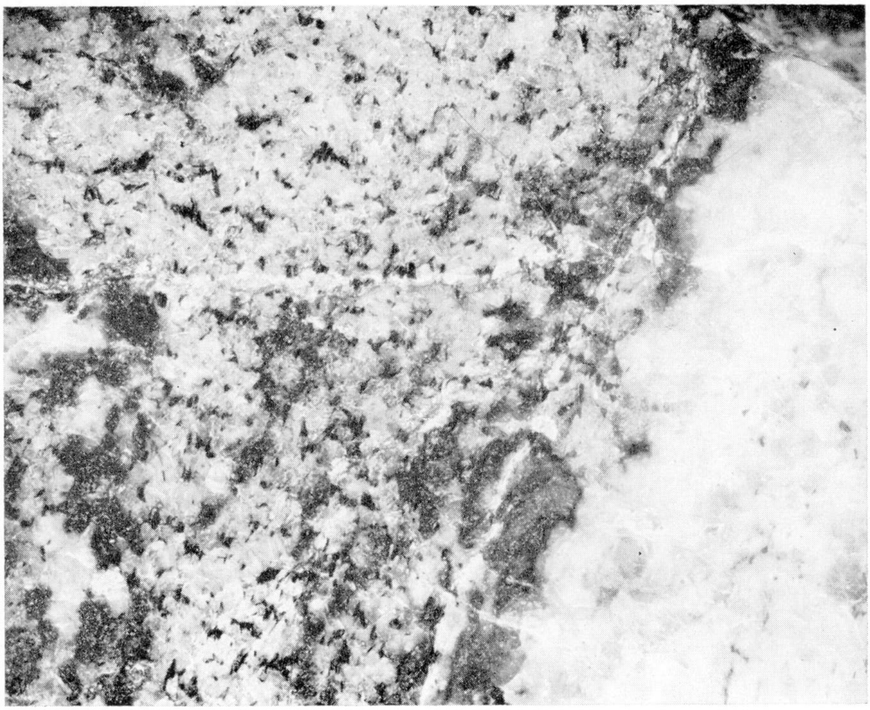
113081-A

A. Surface showing a junction between acid and intermediate granulite. The two rock types are separated by a zone richer in pyroxene and biotite. A preferred orientation of the biotite flakes and pyroxene grains is moderately well developed.



113081-C

C. Surface showing a band of coarse-grained acid granulite (right), in contact with basic granulite (centre), with intermediate granulite to the left. The acid granulite is seen to contain seams rich in pyroxene.



113081-B

B. A similar contact between acid and intermediate granulite. The intermediate granulite contains a zone of coarser pyroxene and plagioclase grains, which represents a slip-surface of the type described in the text.

113081-D

D. Intermediate granulite enclosing an irregular zone rich in quartz and potash feldspar.

Subramanian (1959), however, did not accept the conclusions of Howie (1955a) and Holland (1900). His conclusions (listed in Table I) indicate that rocks in the intermediate division are hybrids resulting from the partial assimilation and incorporation of basic pyroxene granulites by the charnockite magma.

A hybrid origin for the intermediate granulites in the Mount Wright region is not envisaged, for there these rocks form thick continuous bands, some of which may be completely free from veins and tongues of acid granulite or lenses and bands of more basic granulite. The composite gneisses previously referred to (Pls. II and III) are not related to hybridization but to the combined or separate processes of metasomatic segregation or localized palingenesis. Further, the textural and grain-size relationships between the acid and the intermediate granulites are quite distinct. The intermediate and basic granulites generally have a uniform texture and grain-size over large areas, whereas the acid granulites are generally coarser with a more variable texture. However, in those gneisses that show an intimate association of acid and more basic granulites (Pls. II and III), the distinction in grain-size and texture is less well emphasized. Further, in thinner bands and lenses of acid granulite the grain-size is finer and the texture more granoblastic.

Available evidence suggests that the intermediate granulites have been formed by solid-state recrystallization of older rocks, which future examination, especially at the northern limits of this granulite terrain, may show to be of either igneous or sedimentary origin. Whatever their initial origin, it seems that their homogeneous nature over such a large area must be the result of either original or imposed homogeneity due to plutonic metamorphism, with the final phase at the granulite facies level of metamorphism. In addition, any consideration of their origin must take into account their intimate and possibly genetic relationship with the acid granulites.

The banded relationship of the acid and intermediate granulites can be explained in one of two ways. First, the intermediate granulites may represent the solid-state phase remaining after the formation of the acid mobile phase by differential fusion or after the formation of the acid granulites by metasomatic segregation. In this instance the intermediate granulites may represent homogenized remnants of the original country rock. If the acid granulites represent a crystallized, largely autochthonous mobile phase, then some movement of this phase must have occurred prior to final crystallization in order to account for the present structural setting.

Alternately, the structural setting may be explained by supposing that the intermediate granulites represent a series of greywackes, which were highly metamorphosed and subsequently veined on a large scale by an acid magma originating from an extraneous source. Certainly the close similarity observed between the chemical analysis of the intermediate granulite and certain greywackes from other parts of the Canadian Shield (Table V, columns 2–4) would seem to favour a sedimentary origin for the former. These similarities cannot be taken as final proof of a sedimentary origin for the intermediate granulites, for many greywackes when analyzed have their chemical equivalents in certain andesites and quartz diorites (compare Table IV, columns 7 and 8 with Table VII, columns 2–4).

TABLE VII *Chemical Analysis of the Intermediate Granulites and certain Greywackes from the Precambrian of Canada*

	1	2	3	4
SiO_2	62.8	62.40	61.52	60.51
Al_2O_3	16.1	15.20	13.42	15.36
Fe_2O_3	1.0	0.57	1.72	0.76
FeO	5.22	4.61	4.45	7.63
CaO	3.7	4.59	3.56	2.14
MgO	3.5	3.52	3.39	3.39
Na_2O	3.5	2.68	3.73	2.50
K_2O	1.9	2.57	2.17	1.69
H_2O+	0.76	1.56	2.33	3.38
H_2O-		0.07	0.06	0.15
TiO_2	0.6	0.50	0.62	0.87
P_2O_5	0.1			0.27
MnO	0.1			0.16
CO_2		1.30	3.04	1.01
Total	99.28	99.57	100.01	99.82

Key to Table VII

1. Intermediate granulite (quartz–pyroxene–plagioclase granulite). Analysis made from several specimens collected in the Seahorse Lake area, Mount Wright region. 58/133, 56/17, 58/90. Rapid methods analyst: K. Hoops, GSC Lab. No. A-749.
2. Archaean greywacke (average of three analyses), Minnesota. Pettijohn, 1956, p. 306, quoting Grout, 1929.
3. Archaean greywacke (average of three analyses), Kirkland Lake, Ontario. Pettijohn, 1956, p. 306, quoting Todd, 1928.
4. Archaean greywacke, Ontario. Pettijohn, 1956, p. 306. Analyst: B. Brunn.

Any consideration of the origin of the basic pyroxene–plagioclase granulites must take into account their wide and often regular distribution, generally as thin bands or lenses within the intermediate granulites. If they represent recrystallized basic tuff, lava, or intrusive tongues within an original sedimentary sequence largely composed of greywackes, then their present distribution indicates either small-scale volcanic activity during their formation, or large-scale tectonic drawing-out of originally thicker bands under plastic deformation during high-grade metamorphism. According to this latter process continuous bands would be stretched out into the isolated boudins frequently observed. These boudins and lenses would have their longer axes parallel with the regional mineral lineation, as is actually the case.

The basic pyroxene-rich granulites, which are even less common than the basic pyroxene–plagioclase granulites, occur in a similar manner. They are especially well developed where the acid granulites permeate and vein the more basic granulites on a large scale, and therefore probably result from metasomatic-metamorphic segregation and basification during the formation of the more acid granulites.

Igneous Versus Metamorphic Origin

It was argued earlier in this section that the several varieties of charnockitic granulites had obtained their similar critical mineral assemblages via different processes; the intermediate and basic granulites acquired theirs by metamorphic recrystallization largely in the solid state with a limited liquid phase, whereas the bulk of the acid granulites were formed by crystallization from a mobile phase largely liquid in character. The role of metasomatism, however, should not be underestimated, for the rather ill-defined patches, seams, and lenses of granitic rock within bands of more basic rock, and the development of thin basic selvedges in other rocks, are features that suggest some degree of metasomatism.

Several lines of evidence can be used in an argument against a direct magmatic origin for the whole assemblage of granulites, even if recrystallization was assumed to have occurred during or after emplacement of the granulites to account for their metamorphic texture. The first line of evidence concerns the spatial and volume relationships of the several rock types. If the granulites are thought to have formed through the differentiation of a magma of basic or intermediate composition then the basic granulites would be assumed to have been the first rocks to solidify. Yet they are present as thin bands and lenses within both the intermediate and acid granulites. Further, the intermediate granulites would stand unsupported unless the remaining liquid was so viscous under the prevailing pressures as to act in a relatively competent manner. Moreover, the observed proportions of acid, intermediate, and basic material in this assemblage do not fit into any other scheme of magmatic differentiation as the basic granulites are of minor importance compared to the other rock types. Sutton and Watson (1951, pp. 268–273) have used a similar argument in their discussion on pyroxene granulites from the Northwest Highlands of Scotland, in which they maintain that if the more basic varieties of the group represent relics of an originally continuous mass injected by hypersthene granite, then it would be necessary to postulate such an intimate penetration of the acid into the basic material that the process would have to be looked upon as one of migmatization and soaking rather than one of magmatic intrusion.

The overall spatial relationship in the Mount Wright region between the acid granulites on the one hand and the intermediate and basic granulites on the other is one of a large-scale layered complex with subhorizontal banding, similar to that described by Sutton and Watson (1951). This migmatitic type of banding is best explained by the regular and often intimate movement of the mobile acid magma within the more basic granulites during the solid state recrystallization of the latter. It is stressed, however, that this does not imply an extraneous source for this magma, for one of the difficulties is to decide to what extent this liquid phase was the product of local anatexis. Such a mixed relationship would imply differential fusion in situ with subsequent movement of the magma. The transformist school envisages limited wet or dry metasomatic diffusion to account for the irregular and intimately mixed relationship observed in many instances between the granitic rocks and their more basic counterparts.

The textural relationships do not in general suggest a magmatic origin for the whole sequence, as crystal outlines and sizes are variable between the acid granulites, on the one hand, and the intermediate and basic granulites on the other. The proxene-rich granulites have a texture and grain-size different from that of the pyroxene–plagioclase granulites. The basic and intermediate granulites have a typical metamorphic texture while the more acid rocks commonly have coarser grains with a more irregular relation. In the more intimately interbanded rock types these differences may be less apparent.

Several mineralogical features do not accord with a magmatic origin for the whole group. The presence of hornblende in the basic granulites and its apparent absence in the more acid rock types is not in keeping with the theory of magmatic differentiation according to which, as a result of the discontinuous reaction series, hornblende should crystallize late and at a lower temperature than orthopyroxene. According to Ramberg (1949, pp. 35–37), who described a similar relationship in a norite–enderbite series in Greenland, the explanation for their origin is that all the rock types he described were recrystallized and in part, formed at very nearly the same pressure-temperature conditions; i.e., it is the stability relationships of hornblende that allow the mineral to form in basic rock at the same temperature as that at which hypersthene forms in the more acid rocks.

The magmatists have called on unusual conditions of high temperature and pressure to account for this apparent reversal in the crystallization sequence of hornblende and orthopyroxene in these high-grade basic rocks. Howie (1955, p. 764), for example, to account for this relationship, has suggested that in the case of the Madras charnockites, the hornblende of the initial basic rock types had used up most of the available volatiles, leaving little for the more acid rocks. This reasoning cannot be applied in the present situation as hydroxyl-bearing biotite occurs in all the rock types. In addition, the very nature of the presence of the hornblende suggests that its development was governed by the bulk composition of certain bands within the basic granulites during metamorphic crystallization.

The composition of the pyroxenes is not in keeping with the theory of magmatic differentiation according to which the orthopyroxenes in the most basic granulites should be richer in magnesium than those in the more acid granulites and should show a gradual variation in composition. The pyroxene-rich granulites carry orthopyroxene En_{74-80}, the pyroxene–plagioclase granulites En_{72-78}, the intermediate granulites En_{71-80}, and the granitic and granodioritic granulites En_{69-80}. Therefore, it is evident that although the orthopyroxene in the pyroxene-rich granulites may be on the average slightly richer in magnesium than the intermediate and pyroxene–plagioclase granulites, there is no such relationship between the intermediate and basic granulites themselves, as both carry or appear to carry hypersthenes within the same general compositional range. The hypersthenes in the granitic granulites likewise have a composition within the range of those of the intermediate and basic granulites.

Although there is a certain variation in the composition of orthopyroxenes, the clinopyroxenes appear to be remarkably constant in composition throughout, a feature certainly not in keeping with the theory of magmatic differentiation according to which clinopyroxenes in the basic rocks should belong to the diopside–augite series and those in the acid rocks should be richer in iron. These factors

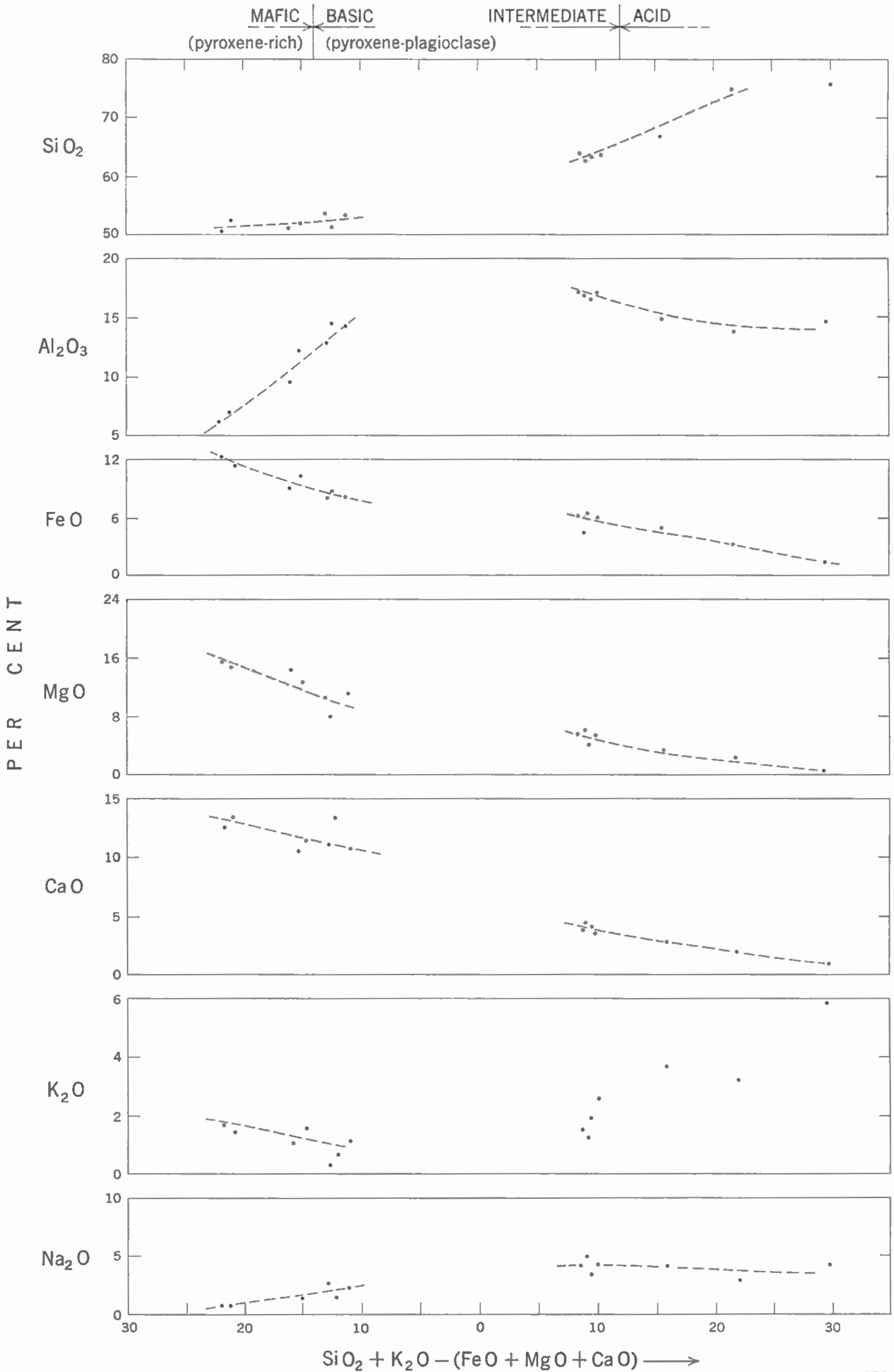


FIGURE 13. Larsen variation diagram showing the variation in the major elements of the pyroxene-bearing rocks.

appear to be inconsistent with the theory that the granulites form a differentiation series.

The plots of the four chemical analyses, the eight calculated chemical compositions of specimens of intermediate and basic granulite, and the analyses of the alaskite and biotite granodiorite from the adjacent Wabush Lake area (given by Gill, Bannerman, and Tolman, 1937) are shown on a Larsen-type variation diagram (Fig. 13). In this diagram the distribution of the plots brings out the apparent break in composition between the intermediate and basic granulites.

The SiO_2 curves show the gradual increase in silica percentage from the basic to the most acid rock types, and at the same time the SiO_2 contents of the pyroxene-rich and pyroxene–plagioclase granulites are seen to be similar. Table V shows that olivine is not a typomorphic mineral of this particular metamorphic grade, the main subsilicic mineral in the most silica-deficient rocks being represented by amphibole. The high pyroxene content and the lack of amphibole in the mafic rocks from the granulites of the Mount Wright region is reflected in a silica content more typical of a basic than of an ultrabasic rock.

The alumina curve is seen to follow the typical course for variation diagrams of this sort, reaching a maximum in rocks of an intermediate character. Of the two sections of this curve the left hand part shows a rapid rise in alumina content, which corresponds to the variations in pyroxene–plagioclase ratios as the pyroxene-rich granulites give place to the pyroxene–plagioclase granulites. The plots for total iron are seen to lie on a fairly smooth although partly interrupted curve. The same is true to a lesser extent of the MgO plots, whereas the interrupted CaO curve is still more poorly defined. The Na_2O curve shows a slight maximum for rocks intermediate in composition.

The distribution of the K_2O plots, however, reveals several important points. While the other curves could be used as an argument for the presence of a differentiation series, the distribution of the K_2O plots indicates the activity of metasomatic and metamorphic processes. The pyroxene-rich granulites are seen to be slightly richer in K_2O than the pyroxene–plagioclase granulites, as is reflected in the higher biotite percentage. The intermediate granulites have a K_2O content similar to that of the more basic rocks, whereas K_2O is higher in the more acid rocks. The fixation of K_2O in the pyroxene-rich granulites is thought to be a reflection of their origin, by some process of metasomatic segregation.

Comparison of the chemically analyzed specimens of pyroxene–plagioclase granulite and pyroxene-rich granulite (Table V, columns 1 and 5) indicates that relative to the pyroxene–plagioclase granulites, the pyroxene-rich lenses are richer in iron oxides, magnesia, and potash, and are poorer in alumina, lime, and soda. A somewhat similar fixation of potash within certain mafic rocks has been noted by Bowes (1961) in his geochemical study of metamorphic differentiation in banded amphibolites from North Rona, Scotland.

CONCLUSIONS

High-grade pyroxene-bearing metamorphic rocks outcrop over a large area north of the Grenville front and west of the Labrador Trough in New Quebec. The study of a small area of these rocks near Mount Wright has revealed that a group of granitic rocks and quartz–pyroxene–plagioclase granulites of intermediate quartz-dioritic composition constitute the major rock types. Plagioclase–pyroxene granulites of basic composition and pyroxene-rich granulites, although well distributed, are less common. These rocks are intimately banded, often in a regular manner on various scales, so as to produce a large-scale banded complex subhorizontal in attitude.

The mineralogy of these rocks is similar to that of the charnockite series in the type area at Madras, India. In this area, however, charnockite nomenclature is not used since it is felt that any new interpretation or application of charnockite nomenclature to the Mount Wright pyroxene granulites may lead to preconceived notions of their genesis. At the same time, however, reference to older works dealing with high-grade pyroxene-bearing metamorphic rocks, necessitates, on occasion, usage of the term 'charnockitic' when referring these rocks to those of the type area.

As there are differences of opinion concerning the genesis of the rocks forming the charnockite series in the type area itself, great care must be taken in applying the terms 'charnockite series' or 'charnockite suite' outside the type area. There is in fact a strong case for not using the terms, as various workers, in order to attach some genetic, textural, or compositional link to the pyroxene-bearing granulite facies rocks that they have encountered elsewhere, have applied such terms as 'hypersthene diorite', 'intermediate rock', 'hybrid diorite', 'basic charnockite', 'bahiaite', and 'bikremite' to various equivalents of Holland's charnockite series. The term 'hypersthene granite' or 'hypersthene melagranite' could replace the term 'charnockite *in sensu stricto*', but a clear and acceptable system of nomenclature is urgently needed for the more basic and intermediate pyroxene-bearing granulite facies rocks. This is especially so in view of the various uses made of the term granulite.

Greater emphasis should be placed on the position of pyroxene-bearing charnockitic rocks within the mineral and metamorphic facies classification. They form an integral unit within a greater field, which includes leptynites, khondalites, and high-grade calc-silicate rocks. This is the field of the granulite facies whereby rocks of various composition and origins have reached equilibrium under given temperature, rock-pressure, water-pressure, and water content conditions. The question as to whether these rocks are produced by solid-state recrystallization or

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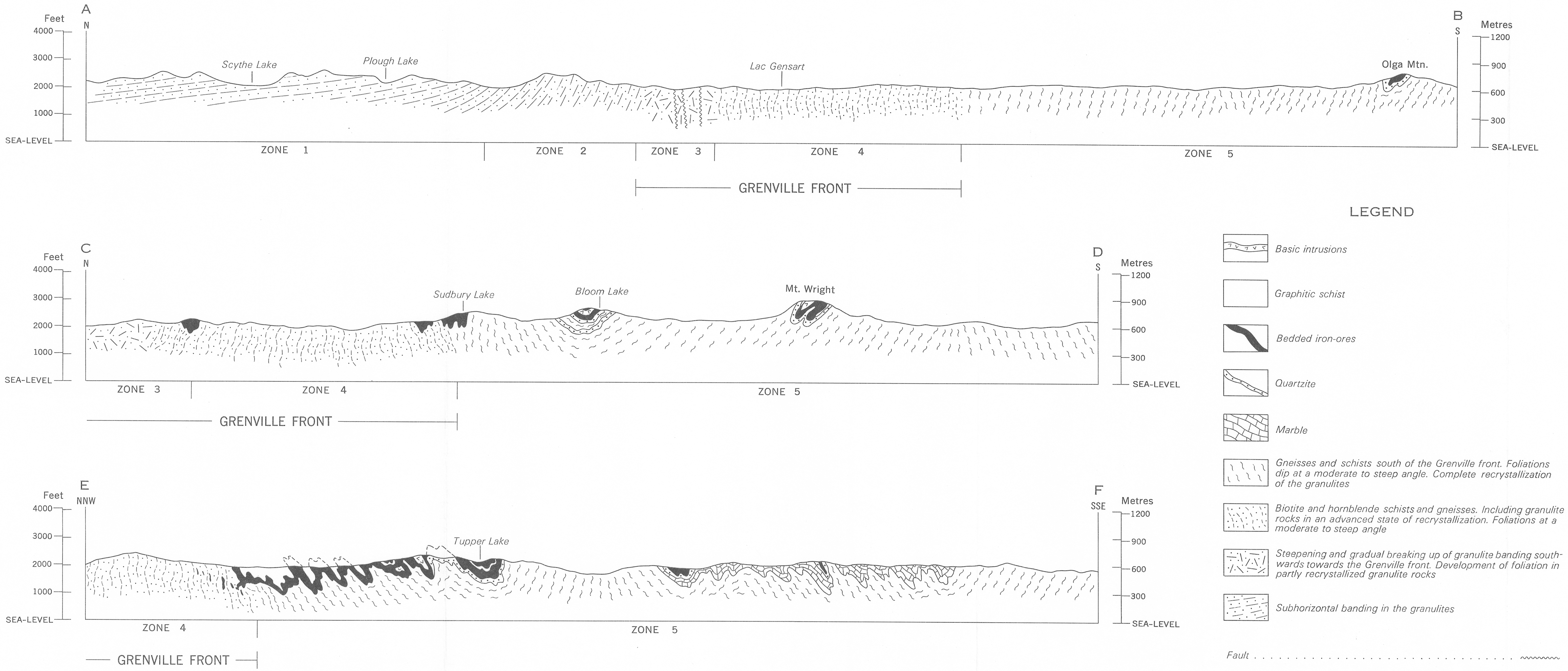


Geology by S. Duffell and R.A. Roach

To accompany G S C Bulletin 162 by R.A. Roach and S. Duffell

ZONE 1

Granulite facies rocks forming a layered complex. The granulite banding has a low dip towards the northeast, while mineral lineations plunge gently eastwards. Small scale overfolding northwards. No evidence of large-scale recumbent folding. Minor recrystallization of the granulites.

ZONE 2

The granulite banding becomes less regular, and at the same time becomes steeper in dip. The strike of the banding changes to a more east-west direction. Degree of recrystallization increases.

ZONE 3

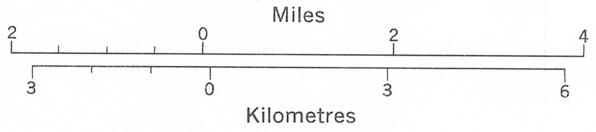
The granulite banding becomes poorly defined due to increasing recrystallization and the development of a WSW-ENE trending foliation. This foliation dips at a steep to moderate angle northwards. Inclusions of partly recrystallized intermediate and basic granulite are enclosed and veined by acid gneisses, which for the most part are recrystallized and remobilized acid granulites.

ZONE 4

Inclusions and bands of biotite and hornblende bearing schists and gneisses alternate with and are veined by granitic and granodioritic gneisses. Some Proterozoic metasediments are also included. The foliation generally strikes WSW - ENE.

ZONE 5

Various biotite and hornblende bearing schists and gneisses; separated by bands and more irregular bodies of granitic and granodioritic gneisses. Evidence of considerable migmatization in places. Occurring within these gneisses are recognizable bands and isolated bodies of Kaniapiskau Supergroup rocks (marble, quartzite and iron formation). The strike of the foliation generally follows one of two directions, namely - NNW-SSE (varying NW-SE), and WSW-ENE (varying SW-NE).



Note: For location of sections see Figure 2

Published 1967, the Centennial of Canadian Confederation
1867 1967

Printed by the Surveys and Mapping Branch

Figure 14. Geological sections across the Grenville front, Mount Wright area, Quebec and Newfoundland.

by crystallization from a liquid phase under high temperatures and pressures then becomes a less important factor with regard to classification, while at the same time problems arising from origins will not cause such great confusion when these are considered.

The term 'granulite' has been applied to pyroxene-bearing rocks of intermediate and basic composition that have been formed at the granulite facies level of metamorphism. These rocks of a medium to fine grain-size have an equigranular granoblastic or nematoblastic texture depending on the development of mineral lineation. The grain boundaries are interlobate. The pyroxene-rich granulites have a more inequigranular poikiloblastic texture while the granitic rocks are medium to coarse grained or pegmatitic, with a texture varying from granoblastic in the medium-grained representatives, to an inequigranular granitic texture in the coarser grained granitic rocks. On the basis of their texture many of the granitic rocks can be termed acid granulites. The authors realize that the term granulite has been used in different senses by French, German, and Scottish geologists, the French emphasizing grain-size and a granitic composition, the Germans grain-size, texture, metamorphic grade, and composition, and the British texture and bulk composition. On the other hand, Eskola (1952, p. 142) has called for all rocks belonging to the granulite facies to be termed granulites. In this report the authors have called the bulk of their rocks granulites in view of their textural characteristic and metamorphic grade.

The mineral assemblage of the granulites was produced under pressure-temperature conditions of the hornblende–biotite granulite subfacies of the granulite facies of plutonic metamorphism. This assemblage appears to have been largely stable under these conditions. The development of perthites, antiperthites, and rare reaction phenomena between orthopyroxene and biotite took place with falling temperature. Evidence of temperature-pressure conditions dropping to near the granulite facies almandine–amphibolite facies boundary may be indicated by the development in places of coarser exsolution perthites and exsolved iron-ore stringers in the biotite, and possibly the development of brown hornblende in the more basic granulites. The development of the hydroxyl-bearing minerals in both the granulites formed by solid-state recrystallization and those formed by crystallization out of a largely liquid phase, indicates that sufficient water was present throughout the whole complex. The additional implication is that temperature and water-pressure values were favourable for this water to become part of a mineral phase.

The intermediate granulites were formed by the recrystallization of an earlier assemblage, the original nature of which is uncertain. This recrystallization took place during the formation of the acid granulites. The relationship between the acid and intermediate granulites may be explained in one of two ways; firstly, the intermediate granulites may represent a highly metamorphosed sequence of greywackes veined in a migmatitic manner by granitic magma that came from an external source; or secondly, the acid granulites may be related to the differential fusion of the original country rock resulting in the formation of an acid mobile phase that was subsequently driven laterally along earlier S-planes to give the present banding. In the latter case the intermediate granulites represent the solid-state remnants following palingenesis. In both instances deformation continued during the formation of the acid granulites, since these show evidence of recrystallization.

The basic granulites may represent original horizons of basic tuff, lava, or intrusive tongues within a sedimentary sequence, while the pyroxene-rich bodies have a composition and relationship that are best explained on a basis of metasomatic-metamorphic segregation.

It is not clear to what extent metasomatic processes operated during the formation of the acid granulites. The presence of mafic selvedges and the manner in which the acid and intermediate granulites locally are intimately associated to produce composite gneisses suggests small-scale metamorphic-metasomatic segregation. The difficulty in ascertaining the relative roles of metasomatism, differential fusion, and magmatic crystallization is due in part to the fact that at high temperatures and pressures these processes may have operated to produce rocks of similar composition, texture, and spatial relationships. After the formation of the granulites, the region experienced a drop in pressure-temperature conditions along with gradual uplift to higher levels in the earth's crust. This change was probably accompanied by some slight concomitant mineralogical adjustments.

Proterozoic sedimentary rocks belonging to a shelf facies of the Labrador geosyncline were deposited unconformably on an eroded surface of granulites in the Mount Wright region and northwards towards Menihek Lake. Above an unknown thickness of micaceous sandstone and sandy shales (now metamorphosed to biotite–muscovite quartzo-feldspathic schists and gneissose schist) was deposited a sequence of quartzite, limestone, iron-formation, and carbonaceous shales (now metamorphosed to quartzite, marble, iron silicate or iron-oxide iron-formation and graphitic biotite schists). These latter units retain their distinctive lithology over a large area and as such are excellent marker horizons when one is analyzing the structures produced by the Grenville cross-folding.

The graphitic schists are overlain by hornblende-bearing gneisses and schists, which are thought to be metamorphosed equivalents of either the gabbro bodies or basic volcanic rocks that occur to the east of and overlie iron-formation in that part of the Labrador geosynclinal belt lying north of the Grenville front.

At some date prior to the Grenville orogeny the rocks of the Labrador geosyncline were folded about axes parallel with the length of the geosyncline. Thrust faulting took place with overfolding westwards. During this period, metamorphism increased along the eastern margin of the geosynclinal belt. Prior to the Grenville orogeny there was possibly a period of erosion and uplift. With the onset of the Grenville orogeny, the basement granulites and the overlying Proterozoic deposits to the south of the Grenville front were metamorphosed at the almandine–amphibolite facies level. At the same time the major stress axes produced complex cross-folding.

To the north of the Grenville front the granulites have retained their distinctive characteristics except for minor retrograde phenomena related to two periods of uplift (pre-Proterozoic and post-Grenville), and also to the minor fringe effects of the Grenville metamorphism.

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