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RECONNAISSANCE GEOLOGY OF THE PRECAMBRIAN SHIELD OF ELLESMERE, DEVON AND COBURG ISLANDS, ARCTIC ARCHIPELAGO: A PRELIMINARY ACCOUNT

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Critical Reader

W.C. Morgan

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CONTENTS

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Abstract

The extensively ice- and snow-covered upland areas of southeastern Ellesmere Island, eastern Devon Island and Coburg Island are underlain by granulite facies rocks of the northernmost Canadian Shield. Rocks of supracrustal origin abound and include migmatitic garnet-cordierite-sillimanite-biotite gneisses, marble with diopside, forsterite and wollastonite, sillimanite quartzite, clinopyroxene-orthopyroxene amphibolite, and orthopyroxene-bearing gneisses. Other orthopyroxene-bearing quartzofeldspathic gneisses are probably deformed intrusive rocks, which are also represented by massive to crudely gneissic, orthopyroxene-bearing granite and tonalite. The orthopyroxene-bearing rocks carry primary biotite invariably and primary hornblende commonly. Various kinds of granite have intruded all these rocks. Granite with biotitic pseudomorphs after orthopyroxene and locally with garnet is commonly intruded into fresh orthopyroxene-bearing granitoid rocks. A similarly retrograded orthopyroxene granite with prominent perthite porphyroblasts forms large bodies at the northern edge of the Shield. Peraluminous granite with garnet, cordierite and/or sillimanite and locally rich in aluminous metasedimentary inclusions is particularly widespread in Ellesmere Island. These granites are thought to have formed by anatexis of aluminous metasediments under granulite facies conditions. Amphibolite facies rocks are of minor importance in the area and were produced by retrogression from the granulite facies. The granulite facies metamorphism is provisionally envisaged to have taken place at moderate to low pressure and high temperature. The rare presence of the assemblage orthopyroxene + sillimanite + quartz, however, indicates that higher pressures may have prevailed locally. Limited radiometric data suggest a late Archean age for the main granulite facies metamorphism and possibly a major Hudsonian deformation. The basement rocks are overlain on the east coast of Ellesmere Island by unmetamorphosed clastic sediments and basalt of the Neohelikian Thule Group and are bordered on the west and north by lower Paleozoic strata of the Arctic Platform.

Résumé

Les terres de hauteur moyenne, largement recouvertes de glace et de neige, que l'on trouve dans le sud-est de l'île Ellesmere, dans l'est de l'île Devon et dans l'île Coburg, reposent sur des roches à faciès de granulites faisant partie de la région la plus septentrionale du Bouclier canadien. Les roches d'origine supracrustale abondent, notamment des gneiss migmatitiques avec biotite, sillimanite, cordiérite et grenat, des marbres avec diopside, forstérite et wollastonite, du quartzite avec sillimanite, de l'amphibolite avec clinopyroxènes et orthopyroxènes et des gneiss orthopyroxéniques. D'autres gneiss constitués de quartz et de feldspath avec orthopyroxènes sont vraisemblablement des roches intrusives déformées, également représentées par des granites et des tonalites orthopyroxéniques à grain massif ou même grossièrement gneissique. Les roches contenant des orthopyroxènes renferment invariablement de la biotite primaire et souvent de la hornblende primaire. Toutes ces roches comportent des intrusions de divers genres de granite. On trouve un peu partout des intrusions de granite avec de la biotite en pseudomorphes d'orthopyroxène et, par endroits, du granite à grenat dans des granitoïdes à orthopyroxènes plus récents. Un autre granite avec orthopyroxènes à métamorphisme rétrograde similaire, contenant des porphyroblastes à perthite bien en évidence, forme d'énormes masses à la limite septentrionale du Bouclier. Du granite hyperalumineux avec grenat, cordiérite et(ou) sillimanite et, par endroits, riche en inclusions métasédimentaires alumineuses, est particulièrement répandu dans l'île Ellesmere. Ces granites se seraient formés, croit-on, par anatexie de métasédiments alumineux à faciès des granulites. Les roches à faciès d'amphibolites sont de peu d'importance dans la région et sont le produit d'une rétrogression de roches à faciès de granulites. Pour l'instant, on croit que le métamorphisme de ces dernières se serait produit à une pression moyenne ou faible et à une température élevée. La rare présence d'orthopyroxène, de sillimanite et de quartz réunis révèle toutefois que des pressions plus fortes ont été exercées à certains endroits. Un nombre limité de données radiométriques laisse croire que la plus grande partie du métamorphisme des roches à faciès de granulites serait survenue dans un Archéen supérieur, tout comme, probablement, une importante déformation de l'Hudsonien. Les roches du soubassement sont recouvertes, sur la côte est de l'île Ellesmere, de basalte et de sédiments clastiques non métamorphosés du groupe Hélikien supérieur Thule et bordées, à l'ouest et au nord, par des couches paléozoïques de la plate-forme arctique.

INTRODUCTION

The northernmost part of the stable Canadian Shield constitutes extensive terrains in southeastern Ellesmere, eastern Devon and Coburg islands, District of Franklin (Fig. 1). Systematic reconnaissance mapping of this area began in 1977 and, at the time of writing, only some nunataks in the interior of Devon Island remain to be investigated.

Geological maps of the Shield in Ellesmere and Coburg islands at 1:250 000 scale are in press. Maps of the remaining area are in preparation and detailed laboratory studies are under way; much work remains to be done. However, in view of the scanty data so far published on this part of the Canadian Shield and the current debate on large-scale movement of Greenland relative to Canada in this region, it is opportune to present a summary account of the Precambrian geology, based chiefly on field observations and petrographic study of several hundred thin sections.

Physiographic and Geological Setting

The Shield terrane is a rugged upland region extensively covered by ice and snow and indented by numerous fiords and bays (Fig. 2). Heights of coastal cliffs average 500 m and nunataks commonly reach 1500 m above sea level. The highest peaks occur west of Jokel Fiord on Ellesmere Island, where the relief exceeds 2300 m.

The Shield is overlain to the west and north by lower Paleozoic rocks of the Arctic Platform. On Ellesmere Island, the western edge of the icefields follows the Precambrian-Paleozoic contact remarkably closely. Unmetamorphosed Neohelikian clastic sediments and basalts of the Thule Group rest unconformably on basement rocks at a number of localities on the eastern coast of Ellesmere Island (Frisch and Christie, 1982).

Exposures of Shield rocks are most numerous in Ellesmere Island where, in addition to coastal cliffs, nunataks provide extensive, if discontinuous, outcrop over most of the inland areas; only the larger nunataks are shown on the geological map accompanying this report (Fig. 3). On Devon Island, outcrops are mainly confined to the coast, the Devon Ice Cap extending largely unbroken over the interior.

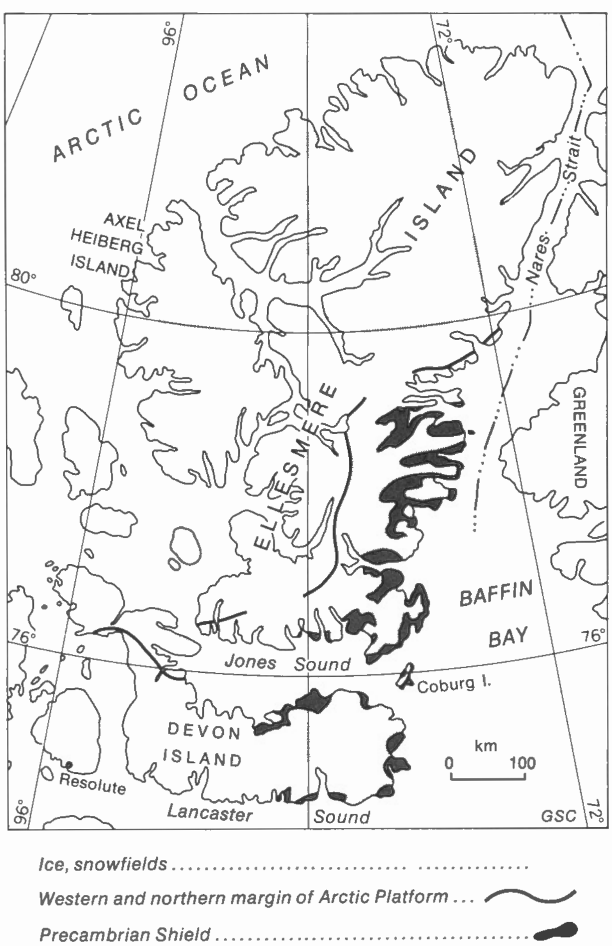


Figure 1. Location of the map area.

Field Work, Past and Present

Prior to 1977, only coastal exposures of the Precambrian had been investigated: on Ellesmere and Devon islands by Christie (1962a, b, 1978), using dog sledges as transport, and on northern Devon Island by Krupička (1973). Limited, but important, observations on basement geology of Ellesmere Island were made during two scientific expeditions around the turn of the century (Holtedahl, 1917; Low, 1906).

The Precambrian Shield of Ellesmere and Coburg islands was mapped in 1977 in a helicopter-supported reconnaissance by the author and W.C. Morgan. Numerous landings were made in the interior as well as on the coast. The rugged nature of the terrain prevents access to many nunataks but the great majority were at least observed from the air. More detailed work on foot was carried out where practical, much of it by G.R. Dunning.

About four weeks of field work have been done by the author on the Devon Island Precambrian: three weeks of foot traversing and helicopter reconnaissance in 1978 and one week of helicopter reconnaissance in 1980. Geological coverage of Devon Island is less detailed than that of Ellesmere Island.

Acknowledgments

The author is grateful to his colleague, W.C. Morgan, for undertaking to share the geological mapping duties on Ellesmere and Coburg islands. G.R. Dunning's work provided important detailed coverage of selected areas. Capable field assistance was rendered by D. Brisbin, E. Lisle and L. MacLaren. In 1978, R. Thorsteinsson freely provided base camp facilities and flying time. The Arctic Institute of North America kindly allowed use of their Truelove Inlet camp on Devon Island in 1978 and 1980. The field work could not have been carried out without the generous logistic support of the Polar Continental Shelf Project. The author also appreciated the support and co-operation of W. Blake, Jr. in 1977.

This paper was written while the author was a guest of the Precambrian Research Unit and Department of Geology at the University of Cape Town and he thanks Profs. A.O. Fuller, P. Joubert and A.M. Reid and their staff for their hospitality.

GENERAL GEOLOGY

The Precambrian Shield terranes of Ellesmere, Devon and Coburg islands constitute the Alexandra Subprovince of the Churchill Structural Province (Stockwell, 1982). This subprovince consists of rocks of sedimentary and igneous origin, all highly metamorphosed or at least "plutonic" in the sense of Read (1957); for the sake of simplicity and brevity, the prefix "meta" is generally omitted from rock names.

Figure 2

Makinson Inlet, the major fiord in the Precambrian Shield of southern Ellesmere Island, in late August, 1977. The view is to the southeast with Bowman Island visible in the centre. GSC 203740-K

Supracrustal rocks commonly form relatively well defined belts or zones, as in southeastern Ellesmere Island and easternmost Devon Island (Fig. 3). Granitic rocks of igneous aspect occupy large tracts on Jones Sound and at the northern edge of the map area. Quartzofeldspathic gneisses, many of uncertain origin, occur both in close association with, and independently of, metasediments.

The rocks are described lithologically under the headings of the units shown on the accompanying 1:750 000 geological map (Fig. 3) which is essentially a simplified compilation of 14 1:250 000 sheets (most of which are now in press) showing the main geological features in a convenient form.

Nomenclature of quartzofeldspathic granitoid rocks follows the IUGS scheme (Streckeisen, 1976) and, where necessary, important mineral constituents have been prefixed. For example, a rock of quartz diorite composition containing orthopyroxene is termed orthopyroxene tonalite, a granitic (two feldspars and quartz) rock with orthopyroxene and subordinate biotite is called biotite-orthopyroxene granite. Terminology for gneisses is analogous, e.g. hornblende-biotite-orthopyroxene gneiss. Where practical, the sequence of mineral modifiers to the rock name indicates the order of abundance of the minerals. However, in the case of pelitic gneisses with cordierite, garnet, biotite, and sillimanite, the proportions of these minerals range so widely that, for consistency, this variety of gneiss is termed garnet-cordierite-sillimanite-biotite gneiss, abbreviated to cordierite gneiss.

To avoid nomenclatorial confusion and controversy, names such as enderbite, charnockite and granulite are not used.

Supracrustal Rocks

In airborne reconnaissance mapping supracrustal rocks were commonly identified by their characteristic banded and heterogeneous appearance. The typical supracrustal sequence is composed of a variety of rocks, such as diverse gneisses with and without pyroxene, quartzite, marble and amphibolite. The rocks have been differentiated on the geological map where possible but in many cases are combined and shown as unit 1, which refers mainly to cordierite gneiss, one of the most abundant supracrustal rock types. Pyroxene-bearing gneisses, whether supra- or infracrustal, are described in a separate section.

Cordierite Gneiss (Unit 1)

Gneisses with garnet, cordierite, sillimanite, and biotite are the predominant pelitic-psammitic rocks in the area. They are generally migmatitic, medium grained, grey, white and pink, weather brownish to rusty, and may locally be dark and of mafic appearance. Their gneissic structure is largely due to the interlayering of white or pink quartzofeldspathic leucosomes and darker melanosomes rich in femic minerals. Where associated with marble, quartzite and other obvious metasediments, the cordierite gneisses are relatively easily identifiable from a distance; where interlayered with pyroxene gneiss, they are not so readily recognized.

Complex textural relations among the minerals characterize the gneisses. Outcrops and thin sections show segregation, to a greater or lesser degree, into (i) felsic aggregates rich in oligoclase (occasionally antiperthitic), dense stringlet- to hair-type perthite (commonly blue in plane light due to an optical effect), and quartz, and (ii) mafic aggregates rich in garnet, cordierite, red-brown biotite, sillimanite and green spinel. Garnet commonly occurs as ragged, skeletal porphyroblasts crowded with sillimanite needles and mantled by cordierite and spinel. This association is interpreted to record the reaction

$$\text{garnet} + \text{sillimanite} = \text{cordierite} + \text{spinel}$$

In many rocks these phases are joined by finely granular corundum, which is probably the product, along with cordierite, of reaction between spinel and sillimanite. Cordierite very commonly shows symplectic intergrowths with K-feldspar or quartz.

The segregation into felsic and mafic aggregates, visible on scales from outcrop to thin section, is attributed to anatexis, for which the conspicuously migmatitic nature of the rock is clear evidence. Anatexis has generated a Si, K, Na-rich, quartzofeldspathic leucosome and, as a restite, a Fe, Mg, Al-rich melanosome. As will become apparent later in this report, anatexis was a major process in the Precambrian Shield of the map area.

Marble (Unit 3)

Marble constitutes the most distinctive unit of the supracrustal successions on Ellesmere and Coburg islands and draws attention to their presence; it is notably absent from Devon Island. The marble is bright white and coarsely granular and weathers more readily than the adjacent metasediments and amphibolite. Being relatively incompetent, marble is commonly flow deformed and encloses boudins and fragments of bordering rocks. Diverse calc-silicate rocks may be associated with marble and are included in the map unit.

Besides calcite, the marble generally contains significant amounts of diopside and forsterite accompanied by one or more of phlogopite, scapolite, spinel, wollastonite, and humite group minerals.

Calc-silicate rocks show a great range in physical appearance and mineralogy, from coarse, carbonate-rich leucocratic varieties to finely banded dark mafic gneisses. They are characterized by abundant diopside, epidote and sphene and may contain distinctive orange garnet (andradite?) porphyroblasts.

Quartzite (Unit 4)

Quartzitic rocks are most abundant in the southeastern corner of Ellesmere Island, where they form a major component of a north-trending supracrustal belt extending from Coburg Island to Smith Bay; elsewhere they occur sporadically as thin beds associated with pelitic gneiss and marble.

The quartzites are white, fine grained (particularly where strongly sheared) or medium grained rocks, commonly veined by granite or pegmatite. They almost invariably contain abundant sillimanite and variable amounts of garnet, biotite and K-feldspar; the quartz grains generally exhibit signs of strong strain.

Amphibolite (Unit 5)

Although widespread, rarely does amphibolite outcrop to the extent that it would appear on the accompanying large-scale map. Amphibolite is, however, an important indicator of metamorphic grade, as Eskola (1920) based the original formulation of the metamorphic facies on rocks of basaltic composition. Because of the high grade of metamorphism in the map area, pyroxene may outweigh amphibole in abundance and the field term "amphibolite" may be a misnomer. It is here used in the field sense as denoting a dark green to black, foliated rock rich in amphibole and pyroxene.

Amphibolite is most common in supracrustal sequences, in which it tends to form conformable layers and lenses. Amphibolite also occurs as sheets and schlieren in pyroxene-bearing granitic rocks and gneisses.

The amphibolites typically consist of olive-green or brown-green hornblende, orthopyroxene and plagioclase; pale green clinopyroxene and reddish brown biotite may be additional constituents. Fe-Ti oxide and sphene are important accessory minerals. The plagioclase (andesine-oligoclase) exhibits excellent twinning and normal zoning, suggestive of an igneous origin for the amphibolites.

Ultramafite

The ultramafites are essentially Mg-amphibole – olivine (or serpentine pseudomorphs thereof) – orthopyroxene rocks with abundant oxide minerals, chiefly magnetite and green spinel. Ultramafite is generally found as pods and conformable sheets among supracrustal rocks, and is not shown on the map (Fig. 3). An unusually large body many hundreds of metres across is enclosed in orthopyroxene granite at the northern end of the Cory Glacier, Ellesmere Island.

Origin

The supracrustal assemblage is clearly of largely sedimentary, probably marine, origin but the high degree of metamorphism makes more detailed speculation difficult. The cordierite gneisses were probably derived from greywacke and shale, the quartzites from impure quartzose sandstone. Lack of pure "end member"-type rocks suggests that the original sediments were immature.

Pyroxene-bearing Gneisses (Unit 2)

Subdivision of the pyroxene-bearing quartzofeldspathic gneisses into map units is fraught with difficulties. Firstly, a complete gradation exists between strongly gneissic and totally massive pyroxene-bearing quartzofeldspathic rocks. In general, pyroxene-bearing gneisses shown on the map are those rocks which have an obviously gneissic structure in outcrop. Nevertheless they doubtless include, in many places, deformed granitic rocks that properly belong to the orthopyroxene granite-tonalite series of map units 6 to 8. Secondly, as most of these rocks are relatively coarse grained and tend to be homogeneous, the gneissic structure commonly is not readily apparent from a distance. Conversely, where a weak foliation is paralleled by distinctive but widely spaced structures such as quartzose layers, a rock that appears massive close up is clearly recognizable as a gneiss from a distance. Thirdly, there clearly are gneisses of igneous and of sedimentary origin, but to separate the two in reconnaissance mapping was seldom possible.

The pyroxene-bearing gneisses can be classified into two groups, those with abundant K-feldspar and those with minor or no K-feldspar. Although this subdivision is possible at 1:250 000 scale, all pyroxene-bearing gneisses have been combined in one map unit (unit 2) on the accompanying 1:750 000 map.

Information available indicates that the pyroxene gneisses are preponderantly K-feldspar-poor but there are no obvious physical features to distinguish them from K-feldspar-rich varieties in the field. On fresh surfaces, both types typically are dark grey or have the greasy green feldspar and blue quartz characteristic of granulite facies quartzofeldspathic rocks. Weathering is generally brown but can be reddish or, rarely, grey, and rusty weathering zones are common. Gneissic layering ranges from excellent to indifferent and where well developed is commonly ascribable to strong shearing. Pink or white granitic and pegmatitic veins, frequently orthopyroxene- or garnet-bearing, cut the gneisses but migmatites are not developed to the extent they are in the metapelitic cordierite gneisses. Pseudotachylite veins are not uncommon in zones of intense shearing.

K-feldspar-poor Pyroxene Gneisses

Plagioclase is generally abundant and well twinned. Zoning is common and of normal type and anorthite content typically is 30 ± 1 to 2 per cent. Extreme values recorded are An_{38} and An_{22}. Although it may be erratically and irregularly developed, antiperthite is rarely absent and most commonly takes a blocky or blebby form. Discrete K-feldspar, if present at all, generally forms 5 per cent or less, and never more than 15 per cent, of the rock. It is strongly perthitic (stringlet-type) and may, particularly in retrograded rocks, show shadowy cross-hatched twininng, indicative of incipient microclinization. Quartz is a major mineral and tends to be highly strained, with marked undulatory extinction and sutured borders.

Of the mafic silicates, orthopyroxene and biotite are normally the most abundant and in some gneisses are joined by clinopyroxene and/or hornblende. Orthopyroxene, typically, is distinctively pleochroic, from pale green to pale pink and fresh or slightly altered along cracks and grain borders to green biotite and/or fibrous green hornblende. Orthopyroxene in strongly retrograded gneisses is largely to completely replaced by a characteristic yellowish-green to orange fine grained mixture of biotite, chlorite and clay minerals.

Biotite is virtually ubiquitous in the pyroxene gneisses and appears in two forms. Most common is strongly pleochroic, from very pale yellow to reddish or chestnut brown, biotite spatially associated with orthopyroxene, with which it appears to be in equilibrium. Green or brownish-green biotite is common along margins of, and cracks in, pyroxene crystals. Such biotite appearing in discrete, relatively coarse flakes in fully retrograded gneisses is almost certainly a recrystallized replacement product of pyroxene; the accompanying primary brown biotite is generally chloritized.

More mafic varieties of pyroxene gneiss may also contain clinopyroxene and hornblende. The clinopyroxene is pale green, nonpleochroic and generally unaltered; a few samples show textural evidence of hornblende replacement of clinopyroxene (but not of orthopyroxene). Hornblende is rare in fresh pyroxene gneisses that lack clinopyroxene. It is olive or brownish green and, with the exceptions just noted, shows little evidence of being anything but a primary mineral. Hornblende in fully retrograded (amphibolite facies) gneiss is bluish green.

Garnet is not common in the K-feldspar-poor pyroxene gneisses and has not been found coexisting with clinopyroxene. It forms ragged, pink porphyroblasts, which are partly replaced by plagioclase and quartz and, along cracks, by pale green biotite.

K-feldspar-rich Pyroxene Gneisses

The only major difference between the two types of pyroxene gneiss is their K-feldspar content. K-feldspar forms irregular, fresh grains that are invariably perthitic. The perthite takes many forms, from fine, dense hair perthite to an open patchwork of irregularly developed blebs of Na-feldspar. In a few rocks, the K-feldspar shows a shadowy twinning resembling the cross-hatching of microcline and is interpreted to be incipient microcline. Coexisting orthopyroxene is only very slightly altered. Plagioclase is slightly more sodic than in the K-feldspar-poor gneisses, being on average $An_{27 \pm 2}$. The most calcic plagioclase found is An_{31} and is zoned to An_{27}.

The coexistence and appearance of orthopyroxene and biotite are as in the K-feldspar-poor gneisses. Additional pale green clinopyroxene and olive-green hornblende are not common. The occurrence of garnet is similar to that in the K-feldspar-poor gneisses and also shows signs of instability.

A specimen from the Stygge Glacier, in the northwestern part of the map area on Ellesmere Island, has the important assemblage orthopyroxene + sillimanite + quartz, along with perthite, subordinate plagioclase, biotite, garnet and green spinel. The orthopyroxene, which is largely fresh, appears both independently and as poorly developed overgrowths on garnet and spinel. Narrow zones of sillimanite separate spinel from orthopyroxene, and sillimanite also occurs as prisms included in perthite and quartz. The apparently stable coexistence of orthopyroxene and sillimanite signifies high pressure metamorphism (Newton, 1978).

Origin

The pyroxene gneisses almost certainly have more than one origin. Some are deformed igneous, probably intrusive, rocks. Others, particularly those associated with metasediments, are of supracrustal origin and may well be metavolcanics of intermediate to basic composition. Such volcanics would be expected in association with immature sediments.

Orthopyroxene-bearing Granite, Tonalite and Related Rocks

Massive to weakly gneissic rocks with orthopyroxene or pseudomorphs thereof occur throughout the area. They underlie large areas on the north side of Jones Sound and in Sverdrup Pass, west of Knud Peninsula, Ellesmere Island. Elsewhere similar rocks form more restricted occurrences, commonly intercalated with gneisses.

The great majority of the rocks can be classified as either orthopyroxene granite (units 8 and 8a) or orthopyroxene tonalite (unit 7); orthopyroxene-bearing diorite, granodiorite and syenite are much less common and appear to be local variations of the two main rock types. Undifferentiated orthopyroxene-bearing granitic rocks, i.e. units 7, 8 and 8a, are represented by unit 6.

The orthopyroxene-bearing granitic rocks are rarely free of pink and white quartzofeldspathic veins that cut discordantly across all earlier structures. Generally 0.3 to 0.7 m thick, they form from 5 to 30 per cent of outcrop faces. The veins range from fine grained granite to pegmatite and are leucocratic, although they may contain scattered garnet and pseudomorphs after orthopyroxene. They are similar in all respects to those cutting the gneisses and probably were generated by a similar, if not the same, melting event attending high grade metamorphism.

Orthopyroxene Granite (Units 8, 8a)

The granites typically are medium grained and green on fresh, and red or brown on weathered, surfaces. Rocks forming large bodies are perthite porphyroblastic and generally massive. The granites consist essentially of antiperthitic plagioclase (average An_{27}), perthitic K-feldspar, strained quartz, pleochroic orthopyroxene, and reddish brown biotite. Complex perthite textures and myrmekite are common. Orthopyroxene grains typically are irregular, embayed, and rarely fresh. Most grains are at least partly altered to fine grained biotite, chlorite and clay minerals and may be overgrown by narrow rims of colourless to pale green amphibole. In strongly retrograded rocks the K-feldspar shows patches of cross-hatched twinning.

Inclusions of metasediments, observed locally, attest to an intrusive origin for the larger bodies of orthopyroxene granite. The concordance of contacts with supracrustal rocks and lack of chill zones in the orthopyroxene granites suggest that they were intruded into hot rocks prior to or during tectonism.

Highly retrograded orthopyroxene granite, characterized by completely pseudomorphed orthopyroxene, microcline and partly chloritized biotite, is pink or red on fresh and weathered surfaces. Coarsely porphyroblastic varieties of such rock (unit 8a) constitute the basement in Sverdrup Pass, west of Knud Peninsula, Ellesmere Island. Although typically completely massive, these granites locally exhibit excellent alignment of perthite megacrysts. Inclusions of country rock gneiss demonstrate that the granites are intrusive (Christie, 1967).

Pink, even grained retrograded orthopyroxene granite, commonly garnetiferous, has invaded fresh orthopyroxene-bearing granitic rocks in many areas. Indeed, the intimate association of fresh, greenish orthopyroxene granite and altered (retrograded), pink granite with biotite pseudomorphs after orthopyroxene is one of the most characteristic features in the map area. Contacts between the two rock types are generally diffuse but the intrusive nature of the pink granite is clearly evident. In some places, intrusion was disruptive and produced a jumble of fragments in pink granite; in others, intrusion was lit-par-lit, resulting in a more regularly layered rock. Locally, later deformation has transformed such layered rock into banded gneiss.

Recent experimental work (Clemens and Wall, 1981) has provided clues to the possible origin of the widespread retrograded orthopyroxene granite intruding fresh orthopyroxene granite. Orthopyroxene has a wide stability field in the crystallization of melts derived from the anatexis of peraluminous materials, such as the cordierite gneisses that are so abundant in the map area. These water-undersaturated melts crystallize orthopyroxene at high temperature and garnet at high pressure, i.e. under granulite facies conditions. At lower temperatures, orthopyroxene tends to react with the melt to form biotite, which may explain the biotite pseudomorphs after orthopyroxene that characterize the retrograded granite. Alternatively, the pseudomorphs may be the result of deuteric hydration by water that must have been preferentially incorporated in the melt during anatexis.

An extremely coarse grained, leucocratic granite outcrops near the Cory Glacier, Ellesmere Island. Miarolitic structure and the coarse grain size have promoted deep weathering and tors are well developed. The granite is rich in microcline and quartz, has a little brown biotite and accessory fluorite. Overall lithological similarity suggests that this granite is a variety of retrograded orthopyroxene granite but no trace of orthopyroxene has been found. It is of interest that, when fluorine fugacity is high during granite crystallization, the stability field of orthopyroxene contracts in favour of biotite (Clemens and Wall, 1981), hence the absence of orthopyroxene in the fluorite-bearing granite would not be unexpected.

Orthopyroxene Tonalite (Unit 7)

The orthopyroxene tonalites in outcrop commonly resemble the fresh orthopyroxene granites and could not always be separated in reconnaissance mapping, in which case the rocks are included in unit 6. A distinctive, readily mappable variety of tonalite, which forms significant bodies on Coburg Island and in the Prince of Wales Mountains, Ellesmere Island, weathers dark grey to black and has only a faint greenish tinge on a fresh surface; this variety is shown as unit 7 on the geological map (Fig. 3). In detail, orthopyroxene tonalite can usually be recognized by the conspicuously striated faces of the larger plagioclase crystals. Porphyroblastic texture and retrograde alteration of mafic minerals are not as pronounced as in the orthopyroxene granites.

The orthopyroxene tonalites are made up of antiperthitic, zoned plagioclase, averaging An_{29-30}, strained quartz, pleochroic orthopyroxene, brown or reddish brown biotite, and, commonly, olive-green hornblende. The three mafic minerals appear to be in equilibrium and only orthopyroxene tends to be altered (as in the orthopyroxene granites). K-feldspar occurs in amounts of at most a few per cent by volume and commonly is entirely absent, except as a component of antiperthite. Seen with the unaided eye in thin sections of many tonalite specimens is a brownish clouding of the plagioclase, which is resolved under the microscope into a very fine opaque dust evenly distributed through the grains. Apatite is a characteristic accessory mineral.

The orthopyroxene tonalites are probably igneous rocks intruded at deep levels under granulite facies conditions but field evidence for their origin is lacking.

Anatectic Peraluminous Granite (Unit 10)

Occurring widely in the Ellesmere-Devon basement is a mineralogically distinctive granite. It is a leucocratic, medium grained, pink to red rock, generally massive, with one or more of the minerals, garnet, cordierite, sillimanite, and green spinel. Perthite with complex textures, in some instances showing microcline twinning, greatly predominates over plagioclase; indeed plagioclase is absent from some samples. Both feldspars, especially plagioclase, are sericitized and optical determination of An content is not always possible. The few measurements made indicate oligoclase. Moderately chloritized brown biotite is generally present. The former presence of orthopyroxene in some samples is suggested by fine grained biotitic aggregates. Most specimens of the granite contain minor amounts of two or three additional aluminous minerals: green spinel + cordierite ± garnet and garnet + sillimanite + cordierite include the most common assemblages. Garnet is partly altered to green biotite, cordierite is pinitized and sillimanite may be partly replaced by muscovite. The presence of these aluminous minerals indicates that the granite is of peraluminous composition.

The granite occurs in bodies ranging from irregular veins in quartzofeldspathic and metasedimentary gneisses (Fig. 4) to plutons several kilometres in diameter. It is particularly extensively developed in the area of Makinson Inlet, west of Jokel Fiord and north of Baird Inlet on Ellesmere Island. Although distinctive mineralogically, the granite from a distance is similar to pink weathering orthopyroxene-bearing granite, particularly the retrograded varieties. Hence aerial reconnaissance mapping has probably underestimated the amount present.

Inclusions of relatively mafic rocks, such as cordierite gneiss and orthopyroxene granite and tonalite, occur in trains, sheets and schlieren in the granite and are particularly conspicuous in the Makinson Inlet area. Border zones to the inclusions are commonly diffuse and garnetiferous.

Clemens and Wall (1981) have studied the experimental generation of granitic magma by the partial melting of aluminous high-grade metamorphic rocks under granulite facies conditions. Such a magma crystallizes highly aluminous minerals such as garnet, cordierite, sillimanite and even hercynite-rich spinel, depending on pressure, temperature and composition. The stability field of garnet is greater at higher pressures (4 to 5×10^5 kPa for the composition investigated by Clemens and Wall), whereas cordierite forms more readily at lower pressures ($< 3 \times 10^5$ kPa); sillimanite crystallizes from extremely aluminous melts, derived from a highly aluminous source. As pointed out earlier, orthopyroxene is also a major precipitate but usually reacts out with falling temperature.

The experimental results are directly applicable to the peraluminous granites of the map area. The distinctive aluminous mineralogy of the granites, the common occurrence of garnet-cordierite-sillimanite gneiss inclusions and the abundance of granulite facies aluminous metasediments, characteristically migmatitic, combine to support an origin of the peraluminous granite by anatectic melting of aluminous rocks under generally high-temperature, high-pressure conditions. Although a similar origin is suggested for the retrograded orthopyroxene granites described in the previous section, those rocks, which contain orthopyroxene (replaced) and garnet but lack cordierite, sillimanite and green spinel, presumably formed under different pressure-temperature conditions (higher temperature?) and/or from different source materials.

Figure 4

Leucocratic garnet- and cordierite-bearing peraluminous granite has intruded darker biotite-orthopyroxene gneiss on the north shore of Makinson Inlet, Ellesmere Island. GSC 203740-J

Amphibolite Facies Rocks (Unit 9)

Despite the widespread retrogression of the granulite facies rocks, diagnostic amphibolite facies mineralogy is very localized. Rocks of the amphibolite facies occur in Ellesmere Island mainly at the western edge of the ice cap north of Makinson Inlet and northeast of Starnes Fiord. They appear to be more common on Devon Island but there also form a minor part of the lithology at widely scattered localities, not mappable at 1:750 000 scale.

Amphibolite facies rocks are invariably associated spatially with granulite facies rocks or their partially retrograded equivalents. Typical greenish orthopyroxene tonalite may contain layers spotted with biotite aggregates that appear to be replacements of pyroxene. In thin section this biotite is greenish brown and is accompanied by minor green biotite and/or epidote. Also present are blue-green hornblende, sericitized, weakly antiperthitic plagioclase An_{25-26}, and highly strained quartz, which may be bluish in hand specimen.

Pink or grey rocks whose precursors were orthopyroxene granite typically contain excellently cross-hatched microcline, oligoclase with little or no antiperthite, olive-green or greenish-brown biotite and minor epidote. Sheaf-like aggregates of colourless and pale green amphiboles (cummingtonite and actinolite) present in some samples are interpreted to be pseudomorphs after orthopyroxene.

Amphibolite facies supracrustal rocks (excluding amphibolite) are characterized by abundant, relatively coarse muscovite, which commonly is intergrown with, and may crosscut, pale brown or greenish biotite. Garnet porphyroblasts tend to be strongly altered to pale green biotite, and lensoid patches of fine grained muscovite probably represent former cordierite; even sillimanite may be partially replaced by muscovite. Associated amphibolites consist of bluish or pale green amphibole sieved with quartz droplets.

Only rarely is an amphibolite facies rock encountered that lacks all evidence of its precursor. In all other instances, amphibolite facies mineralogy is clearly a product of retrogression from granulite facies. Coupled with the lack of any prograde reactions, this suggests that virtually all amphibolite facies rocks in the map area were derived retrogressively from the granulite facies.

The localized occurrence of amphibolite facies rocks, commonly in narrow, planar zones enclosed by granulite grade rocks, and abundant evidence of strong deformation (e.g. highly strained quartz, flattened and granulated garnet) suggest that shearing was a factor in promoting severe retrogression (see also Krupička, 1973).

Dykes

Dykes in the map area may be divided into three groups: (1) granulite facies metadykes, (2) amphibolite facies metadiabase, and (3) unmetamorphosed diabase. Only dykes of the latter group (unit 13) are shown on the map (Fig. 3). All the dykes are pre-Paleozoic.

Granulite Facies Metadykes

These have been recognized only near the southern shore of Buchanan Bay, Ellesmere Island, and on Pim Island.

Near Buchanan Bay, orthopyroxene-bearing granitic rocks and metasediments are cut by a number of northwest-trending, retrograded orthopyroxene granite metadykes, typically 4 to 8 m thick. The dykes are slightly darker than the overall pink of the bordering granitic rocks but appear in the field to be indistinguishable from concordant darker layers in the latter. The metadykes consist of zoned, antiperthitic plagioclase An_{25-28}, perthitic K-feldspar, coarse and strained quartz, olive-green hornblende, reddish-brown biotite, iddingsite-like pseudomorphs after orthopyroxene, and abundant accessory Fe-Ti oxides. Although no chilled margins are preserved, these discordant, massive bodies must be metaigneous dykes of acid to intermediate composition, metamorphosed in the granulite facies.

A metadyke highly discordant to interlayered orthopyroxene granite and biotite granite at the western end of Pim Island is also considered to be a retrograded granulite facies rock. It is a dark greenish, fine grained, gneissic rock veined by granite and consisting of andesine, a little K-feldspar, quartz, slightly reddish biotite, chlorite aggregates after orthopyroxene, a trace of green hornblende and accessory apatite. Schei (Bugge, 1910) termed the rock kersantite but the mineralogy is clearly metamorphic and a result of retrogression from the granulite facies.

Metadiabase

Subconcordant amphibolite sheets that locally crosscut gneissic rocks but lack chill zones were noted at several places during reconnaissance mapping. More detailed work would probably turn up many more such bodies, which are interpreted as metadykes.

Metadiabase samples are black or greenish black and invariably foliated but differ in the extent to which original pyroxene has been replaced. Where preserved, the pyroxene is a brownish to neutral clinopyroxene and is partly altered to pale green amphibole. Coexisting biotite is orange-brown but where no pyroxene remains, it is greenish brown. A second amphibole, pleochroic from pale green to yellowish green, and showing no obvious relationship to pyroxene, is generally present. Plagioclase is andesine. The metadiabase dykes are in the amphibolite facies and may have never been at a higher grade.

Diabase (Unit 13)

Massive, brown or black weathering diabase dykes with well developed chill zones are widespread throughout the basement terrane cutting all pre-Paleozoic rocks. Indeed, on Devon Island, dykes form minor swarms trending east. On Ellesmere Island, dykes are more scattered and show no preferred orientation; they appear to be most common in the south.

The dykes generally are altered plagioclase + clinopyroxene + Fe-Ti oxide + olivine rocks. Typically, plagioclase is saussuritized and pyroxene slightly to moderately uralitized. Chemically, the rocks are olivine tholeiites (Frisch and Christie, 1982). Whole-rock K-Ar ages obtained on three such dykes from Ellesmere Island indicate a Hadrynian age of intrusion (600-800 Ma).

A dyke cutting orthopyroxene granite on the western shore of Starnes Fiord on Ellesmere Island has a very different mineralogy: zoned pinkish clinopyroxene (probably titaniferous augite), abundant brown hornblende (kaersutite?) and altered olivine, as well as altered plagioclase and oxide minerals. This dyke would appear to be of alkali basalt affinity and is the only such dyke known from the map area.

Cover Rocks

Thule Group (Unit 12)

The crystalline basement in eastern Ellesmere Island is overlain with profound unconformity at several places by gently dipping, unmetamorphosed sedimentary and igneous rocks of late Precambrian age. These rocks belong to the Thule Group and can be correlated with the far more extensive exposures of this unit in North-West Greenland (Dawes et al., in press).

The major outcrops of the Thule Group on Ellesmere Island are found north and south of Cadogan Inlet and in the Cape Combermere-Clarence Head area. Equivalent rocks but in part of different lithology occur on the southern coast of Bache Peninsula on Ellesmere Island, where they are overlain by Paleozoic sediments (Christie, 1967).

Frisch and Christie (1982) have recently described the Thule Group of Ellesmere Island so only a brief summary of the stratigraphy is given here.

The thickest section of the Thule Group, located at Goding Bay, is a little over 1000 m thick; its top is an erosion surface. The lower part of the succession consists of tholeiitic basalt flows and sills and minor pyroclastics interbedded with red beds (sandstone and shale) and orthoquartzite; stromatolitic dolomite occurs among the lowermost strata. The remainder of the section is almost exclusively sedimentary: red and green shales and siltstones and clean white and buff orthoquartzites, all forming very distinctive units. Basalt sills and lava form subordinate components of this upper sequence.

The sedimentary rocks of the Thule Group are of shallow marine to terrestrial origin. Whole-rock K-Ar ages of igneous rocks cluster around 1100 Ma and the age of the Thule Group is considered to be Neohelikian.

Phanerozoic Strata (Unit 14)

Paleozoic and younger rocks were examined only briefly at a few localities and their distribution on the accompanying map is mainly based on airphoto interpretation. That the Paleozoic seas once extended far to the east of the present margin of the Arctic Platform (Fig. 1) is evidenced by the numerous outliers of lower Paleozoic strata in southeastern Ellesmere Island and on Philpots Island, off the east coast of Devon Island.

The Paleozoic succession is largely dolomite but the lowermost strata are white, conglomeratic, quartzose sandstone resting on basement that is generally hard and little altered. Higher sediments are commonly buff and reddish, ripple marked sandstone and silty sandstone.

Sandstone, shale and coal of the Cretaceous-Tertiary Eureka Sound Formation are exposed along the western edge of the ice cap on Ellesmere Island north of Makinson Inlet but have not been found resting on basement.

ECONOMIC GEOLOGY

Although no large concentrations of economic minerals were found in the area mapped, the Precambrian terrane of Ellesmere Island is far from barren.

The most significant showings are in metasedimentary rocks, chiefly cordierite gneisses, in the Alexandra Fiord area. Gossans up to 8 m wide with massive and disseminated pyrrhotite and chalcopyrite, rarely accompanied by sphalerite, are present in easternmost Thorvald Peninsula and south of Buchanan Bay.

Malachite (± azurite) staining is present in massive to gneissic orthopyroxene-bearing granitic rocks and associated amphibolite at the southern margin of Ekblaw Glacier. Disseminated chalcopyrite visible in some hand specimens is probably the source of the copper stain. White biotite granite veins in metasediments at this locality contain a little molybdenite.

Malachite staining has also been found in amphibolite facies (retrograded granulite facies) metasediments of calc-silicate affinity on the north shore of Makinson Inlet.

Near Clarence Head, copper mineralization occurs both in basement metasediments, in the form of disseminated chalcopyrite, and in the overlying Thule Group, where a large patch of malachite stain was noted from the air. The latter occurrence, on an inaccessible cliff face, lies in the lower part of the Thule sequence associated with either a basaltic unit or a sediment.

Clearly, a variety of rock types and associations hosts mineralization in the basement of Ellesmere Island. Prospects for systematic mineral exploration in the area are limited only by logistical and climatic considerations.

TECTONICS

Lithological boundaries and foliation tend to be parallel and dip steeply to moderately throughout the basement terrane. They follow a general northerly trend in Ellesmere and Coburg islands, whereas in Devon Island they are largely westerly; local deviations, however, are numerous.

The basement rocks have been folded at least three times. Early isoclinal folds are visible in finely layered gneisses and have themselves been tightly folded. Large recumbent isoclines are well seen in a number of cliff faces many hundreds of metres high. In a third period of folding, broad, open folds were produced but these are generally not conspicuous. Large-scale reconnaissance mapping and the discontinuous nature of the outcrop in a nunatak terrain impose severe restrictions on structural studies; more detailed work would undoubtedly reveal a more complicated history of folding.

All the crystalline rocks, with the sole exception of late granitic veins, are foliated or gneissic to some extent at least. Even such generally massive, coarse grained rocks as the retrograded orthopyroxene granites in the Sverdrup Pass locally exhibit strong alignment of feldspar megacrysts. The peraluminous anatectic granites of marked posttectonic aspect are locally perceptibly gneissic, even where forming large bodies. Thus all the major granitic rocks are pre- or syntectonic. Late granitic veining is regarded as syntectonic with a late period of deformation.

Post-lower Paleozoic faulting is conspicuous throughout the area. Blocks of Paleozoic strata have commonly subsided several hundreds of metres along steeply dipping normal faults. Many of these faults seem to parallel structural trends in the basement but it is not known to what extent they are regenerated Precambrian faults.

Outcrops of Thule Group strata forming caps to 700 m high mountains of basement in the Cape Combermere area attest to major uplift in southeastern Ellesmere Island. In contrast, the thin Paleozoic mantle on western Philpots Island adjacent to high, rugged basement of the Devon Ice Cap indicates significant subsidence along eastern Devon Island. These epeirogenic movements may be related to Tertiary activity.

AGE OF THE BASEMENT ROCKS

Until the results of a number of isotopic age determinations currently in progress are available, the geochronology of the basement rocks is largely speculative.

At the time of writing, few isotopic ages are available from the metamorphic rocks. Zircon fractions from interlayered biotite-orthopyroxene-hornblende tonalite gneiss and biotite granite gneiss (probably deformed anatectic granite) from southern Devon Island fall on a line intercepting the U-Pb concordia curve at 2426 Ma. K-Ar ages of hornblende from the tonalite gneiss and biotite from the granite gneiss are 1740 ± 47 Ma and 1769 ± 24 Ma, respectively. Biotite from gneiss between Cape Norton Shaw and Clarence Head on Ellesmere Island gave a K-Ar age of 1760 Ma (Christie, 1962b).

Rb-Sr and K-Ar age determinations from the North-West Greenland crystalline basement, which is closely correlated with the Ellesmere-Devon terrane (Frisch and Dawes, in press), provide evidence that granulite facies metaigneous rocks there are late Archean and underwent major deformation in Hudsonian time (Larsen and Dawes, 1974; Kalsbeek and Dawes, 1980). A similar geochronological history is provisionally envisaged for the Ellesmere-Devon basement.

PHYSICAL CONDITIONS OF METAMORPHISM

The crystalline basement of Ellesmere, Devon and Coburg islands bears the imprint of a pervasive granulite facies metamorphism. Retrogression to the amphibolite facies is a local phenomenon only.

Turner (1981) considers the assemblage (in mafic rocks) plagioclase + clinopyroxene + hypersthene + hornblende to be diagnostic of the granulite facies. "Granolites" of Winkler's (1979) "regional hypersthene zone (granolite high-grade)" by definition contain hypersthene and feature certain mineralogical characteristics, which are listed in Winkler's Table 16-2. The appropriate rocks of the Ellesmere-Devon terrane satisfy all these requirements. Further, the basement rocks are marked by the complete absence of primary muscovite in the presence of quartz and feldspar; sillimanite is widespread and the only aluminosilicate mineral found. Vast areas of aluminous metasediments contain the assemblage cordierite + garnet + sillimanite + biotite and are strongly migmatitic. Substantial bodies of peraluminous granite of anatectic origin are common.

The following are the most common or critical mineral assemblages in the map area:

Pelitic-psammitic

1. Quartz + plagioclase + perthite + biotite + sillimanite + cordierite + garnet + green spinel
2. Quartz + K-feldspar + sillimanite
3. Quartz + plagioclase + perthite + biotite + orthopyroxene + cordierite + garnet + green spinel
4. Quartz + plagioclase + perthite + biotite + garnet + orthopyroxene + sillimanite + green spinel

Quartzofeldspathic

5. Quartz + plagioclase + perthite + orthopyroxene + biotite (± hornblende)
6. Quartz + plagioclase + orthopyroxene + biotite + hornblende (± clinopyroxene)
7. Quartz + plagioclase + orthopyroxene + biotite

Basaltic

8. Plagioclase + hornblende + orthopyroxene + clinopyroxene (± biotite)

Calcareous

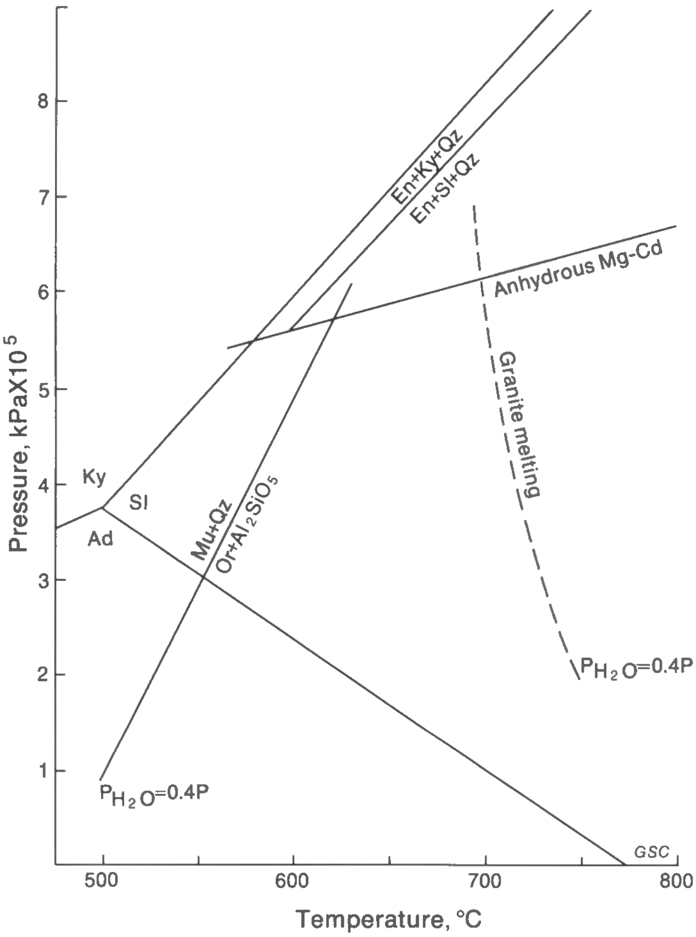
9. Calcite + diopside + forsterite (± grossularite)
10. Calcite + diopside + wollastonite + plagioclase + scapolite + sphene
11. Calcite + diopside + wollastonite + quartz

Assemblage 4 has been found in only one sample and is probably uncommon; it is listed because of its importance in defining temperature-pressure conditions.

Absence of muscovite, abundance of sillimanite and widespread anatexis indicate that temperatures of metamorphism certainly exceeded 600°C and probably 700°C (Fig. 5). A reasonable temperature range for the granulite facies is 650° to 850°C (Winkler, 1979; Turner, 1981).

Accepting the generally held belief that water pressure is only a fraction of total pressure in the granulite facies and arbitrarily choosing a value of $P_{H_2O} = 0.4\ P_{total}$, we can postulate, based on experimental equilibrium data on garnet and cordierite of common compositions, that total pressure did not exceed 3 or 4×10^5 kPa at 700-750°C (Turner, 1981, p. 440).

The presence of diopside + forsterite and of wollastonite in marble commonly associated with cordierite gneiss in the map area tallies with relatively low pressures (Turner, 1981; Winkler, 1979). Furthermore, if, as suggested



Kyanite .... Ky	Quartz .... Qz
Sillimanite .... Sl	Mg-cordierite .. Mg-Cd
Andalusite .... Ad	Muscovite .... Mu
Enstatite .... En	Orthoclase .... Or

Aluminosilicate stability diagram after Holdaway (1971)
En+Ky+Qz=En+Sl+Qz and the upper stability limit of Mg-cordierite in the water-free system after Newton (1978)
Remaining curves after Turner (1981, Fig. 4-5)

Figure 5. *Mineral stability fields, reaction boundaries and the curve for initiation of "granitic" melting pertinent to the granulite facies metamorphism in the map area.*

by Turner, garnet-free mafic rocks are lower grade than garnet-bearing ones in the granulite facies, then this provides additional evidence of low grade granulite facies in the Ellesmere-Devon basement.

The moderate P,T conditions suggested above are subject to modification as results of chemical work, now under way, appear. Attention is drawn to the existence, albeit only at one locality in the northern part of the map area, of the assemblage sillimanite + orthopyroxene + quartz. According to Newton (1978) this assemblage, if an equilibrium one, indicates a pressure of at least 6×10^5 kPa (Fig. 5). Either significant differences in pressure existed between different parts of the basement terrane or the provisional pressure estimate is too low.

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