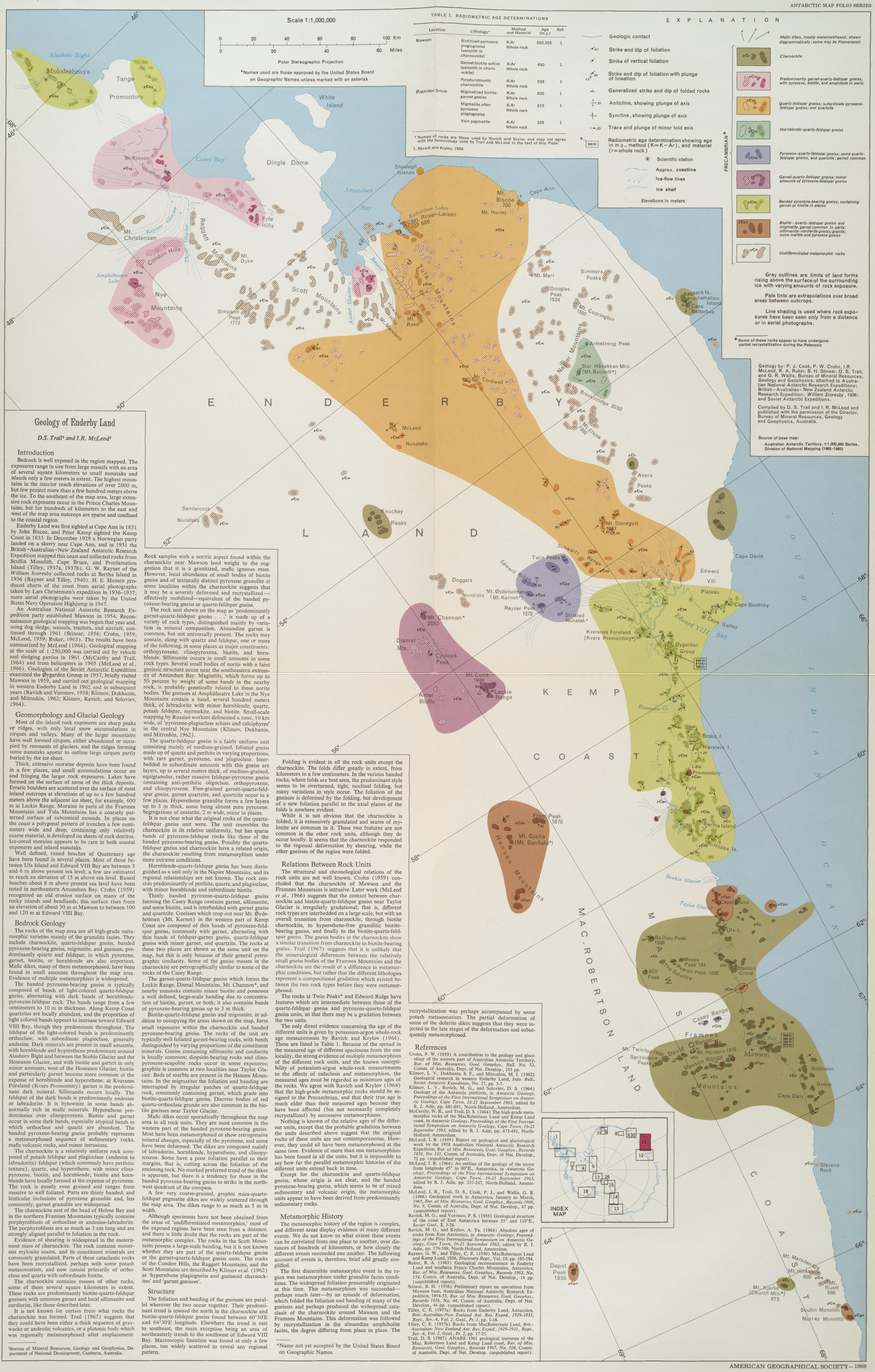

Geology of Enderby Land

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Introduction

Bedrock is well exposed in the region mapped. The exposures range in size from large massifs with an area of several square kilometers to small nunataks and islands only a few meters in extent. The highest mountains in the interior reach elevations of over 2000 m, but few project more than a few hundred meters above the ice. To the southeast of the map area, large extensive rock exposures occur in the Prince Charles Mountains, but for hundreds of kilometers to the east and west of the map area outcrops are sparse and confined to the coastal region.

Enderby Land was first sighted at Cape Ann in 1831 by John Biscoe, and Peter Kemp sighted the Kemp Coast in 1833. In December 1929 a Norwegian party landed on a skerry near Cape Ann, and in 1931 the British–Australian–New Zealand Antarctic Research Expedition mapped this coast and collected rocks from Scullin Monolith, Cape Bruce, and Proclamation Island (Tilley, 1937a, 1937b). G. W. Rayner of the *William Scoresby* collected rocks at Bertha Island in 1936 (Rayner and Tilley, 1940). H. E. Hansen produced charts of the coast from aerial photographs taken by Lars Christensen's expedition in 1936–1937; more aerial photographs were taken by the United States Navy Operation Highjump in 1947.

An Australian National Antarctic Research Expedition party established Mawson in 1954. Reconnaissance geological mapping was begun that year and, using dog sledge, weasels, tractors, and aircraft, continued through 1961 (Stinear, 1956; Crohn, 1959; McLeod, 1959; Ruker, 1963). The results have been summarized by McLeod (1964). Geological mapping at the scale of 1:250,000 was carried out by vehicle and sledging parties in 1961 (McCarthy and Trail, 1964) and from helicopters in 1965 (McLeod *et al.*, 1966). Geologists of the Soviet Antarctic Expedition examined the Øygarden Group in 1957, briefly visited Mawson in 1959, and carried out geological mapping in western Enderby Land in 1962 and in subsequent years (Ravich and Voronov, 1958; Klimov, Dukhanin, and Mitroshin, 1962; Klimov, Ravich, and Soloviev, 1964).

Geomorphology and Glacial Geology

Most of the inland rock exposures are sharp peaks or ridges, with only local snow accumulations in cirques and valleys. Many of the larger mountains have well formed cirques, either abandoned or occupied by remnants of glaciers, and the ridges forming some nunataks appear to outline large cirques partly buried by the ice sheet.

Thick, extensive moraine deposits have been found in a few places, and small accumulations occur on and fringing the larger rock exposures. Lakes have formed on the surface of some of the thick deposits. Erratic boulders are scattered over the surface of most inland outcrops at elevations of up to a few hundred meters above the adjacent ice sheet, for example, 600 m at Leckie Range. Moraine in parts of the Framnes Mountains and Tula Mountains has a coarsely patterned surface of subconical mounds. In places on the coast a polygonal pattern of trenches a few centimeters wide and deep, containing only relatively coarse material, is developed on sheets of rock detritus. Ice-cored moraine appears to be rare in both coastal exposures and inland nunataks.

Well defined, raised beaches of Quaternary age have been found in several places. Most of those between Ufs Island and Edward VIII Bay are between 3 and 6 m above present sea level; a few are estimated to reach an elevation of 15 m above sea level. Raised beaches about 8 m above present sea level have been noted in northeastern Amundsen Bay. Crohn (1959) recognized an old erosion surface on many of the rocky islands and headlands; this surface rises from an elevation of about 30 m at Mawson to between 100 and 120 m at Edward VIII Bay.

Bedrock Geology

The rocks of the map area are all high-grade metamorphic varieties mainly of the granulite facies. They include charnockite, quartz-feldspar gneiss, banded pyroxene-bearing gneiss, migmatite, and gneisses, predominantly quartz and feldspar, in which pyroxene, garnet, biotite, or hornblende are also important. Mafic dikes, many of them metamorphosed, have been found in small amounts throughout the map area. Evidence of multiple metamorphism is widespread.

The banded pyroxene-bearing gneiss is typically composed of bands of light-colored quartz-feldspar gneiss, alternating with dark bands of hornblende-pyroxene-feldspar rock. The bands range from a few centimeters to 10 m in thickness. Along Kemp Coast quartzites are locally abundant, and the proportion of light colored bands appears to increase toward Edward VIII Bay, though they predominate throughout. The feldspar of the light-colored bands is predominantly orthoclase, with subordinate plagioclase, generally andesine. Dark minerals are present in small amounts, with hornblende and hypersthene predominant around Alasheev Bight and between the Scoble Glacier and the Hoseason Glacier, and with biotite and garnet in only minor amounts; west of the Hoseason Glacier, biotite and particularly garnet become more common at the expense of hornblende and hypersthene; at Kvarsnes Foreland (Kvars Promontory) garnet is the predominant dark mineral. Sillimanite occurs locally. The feldspar of the dark bands is predominantly andesine or labradorite. It is bytownite in some bands abnormally rich in mafic minerals. Hypersthene predominates over clinopyroxene. Biotite and garnet occur in some dark bands, especially atypical bands in which orthoclase and quartz are abundant. The banded pyroxene-bearing gneiss probably represents a metamorphosed sequence of sedimentary rocks, mafic volcanic rocks, and minor intrusions.

The charnockite is a relatively uniform rock composed of potash feldspar and plagioclase (andesine to labradorite) feldspar (which commonly have perthitic texture), quartz, and hypersthene, with minor clinopyroxene, biotite, and hornblende; biotite and hornblende have locally formed at the expense of pyroxene. The rock is mostly even grained and ranges from massive to well foliated. Parts are thinly banded, and lenticular inclusions of pyroxene granulite and, less commonly, garnet granulite are widespread.

The charnockite east of the head of Holme Bay and in the northern Framnes Mountains typically contains porphyroblasts of orthoclase or andesine-labradorite. The porphyroblasts are as much as 3 cm long and are strongly aligned parallel to foliation in the rock.

Evidence of shearing is widespread in the easternmost mass of charnockite. The rock contains numerous mylonite seams, and its constituent minerals are commonly granulated. Parts of these cataclastic rocks have been recrystallized, perhaps with some potash metasomatism, and now consist primarily of orthoclase and quartz with subordinate biotite.

The charnockite contains masses of other rocks, some of them several square kilometers in extent. These rocks are predominantly biotite-quartz-feldspar gneisses with common garnet and local sillimanite and cordierite, like those described later.

It is not known for certain from what rocks the charnockite was formed. Trail (1967) suggests that they could have been either a thick sequence of graywacke or andesitic volcanics, or a plutonic body which was regionally metamorphosed after emplacement. Rock samples with a noritic aspect found within the charnockite near Mawson lend weight to the suggestion that it is a granitized, mafic igneous mass. However, local abundance of small bodies of biotite gneiss and of texturally distinct pyroxene granulite at some localities within the charnockite suggests that it may be a severely deformed and recrystallized—effectively mobilized—equivalent of the banded pyroxene-bearing gneiss or quartz-feldspar gneiss.

The rock unit shown on the map as 'predominantly garnet-quartz-feldspar gneiss . . .' is made up of a variety of rock types, distinguished mainly by variation in mineral composition. Almandine garnet is common, but not universally present. The rocks may contain, along with quartz and feldspar, one or more of the following, in some places as major constituents: orthopyroxene, clinopyroxene, biotite, and hornblende. Sillimanite occurs in small amounts in some rock types. Several small bodies of norite with a faint gneissic structure occur near the southeastern extremity of Amundsen Bay. Magnetite, which forms up to 50 percent by weight of some bands in the nearby rock, is probably genetically related to these norite bodies. The gneisses at Amphitheatre Lake in the Nye Mountains contain a band, several hundred meters thick, of labradorite with minor hornblende, quartz, potash feldspar, myrmekite, and biotite. Small-scale mapping by Russian workers delineated a zone, 10 km wide, of 'pyroxene-plagioclase schists and calciphyres' in the central Nye Mountains (Klimov, Dukhanin, and Mitroshin, 1962).

The quartz-feldspar gneiss is a fairly uniform unit consisting mainly of medium-grained, foliated gneiss made up of quartz and perthite in varying proportions, with rare garnet, pyroxene, and plagioclase. Interbedded in subordinate amounts with this gneiss are layers, up to several meters thick, of medium-grained, equigranular, rather massive feldspar-pyroxene gneiss containing anti-perthitic oligoclase, orthopyroxene, and clinopyroxene. Fine-grained garnet-quartz-feldspar gneiss, garnet quartzite, and quartzite occur in a few places. Hypersthene granulite forms a few layers up to 3 m thick, some being almost pure pyroxene. Segregations of enstatite, 2 m wide, occur in places.

It is not clear what the original rocks of the quartz-feldspar gneiss unit were. The unit resembles the charnockite in its relative uniformity, but has sparse bands of pyroxene-feldspar rocks like those of the banded pyroxene-bearing gneiss. Possibly the quartz-feldspar gneiss and charnockite have a related origin, the charnockite resulting from metamorphism under more extreme conditions.

Hornblende-quartz-feldspar gneiss has been distinguished as a unit only in the Napier Mountains, and its regional relationships are not known. The rock consists predominantly of perthite, quartz, and plagioclase, with minor hornblende and subordinate biotite.

Thinly banded pyroxene-quartz-feldspar gneiss forming the Casey Range contains garnet, sillimanite, and some biotite, and is interbedded with garnet gneiss and quartzite. Gneisses which crop out near Mt. Øydeholmen (Mt. Kernot) in the western part of Kemp Coast are composed of thin bands of pyroxene-feldspar gneiss, commonly with garnet, alternating with thin bands of feldspar-garnet gneiss, quartz-feldspar gneiss with minor garnet, and quartzite. The rocks at these two places are shown as the same unit on the map, but this is only because of their general petrographic similarity. Some of the gneiss masses in the charnockite are petrographically similar to some of the rocks of the Casey Range.

The garnet-quartz-feldspar gneiss which forms the Leckie Range, Dismal Mountains, Mt. Channon*, and nearby nunataks contains minor biotite and possesses a well defined, large-scale banding due to concentration of biotite, garnet, or both; it also contains bands of pyroxene-bearing gneiss up to 3 m thick.

Biotite-quartz-feldspar gneiss and migmatite, in addition to occupying the areas shown on the map, form small exposures within the charnockite and banded pyroxene-bearing gneiss. The rocks of the unit are typically well foliated garnet-bearing rocks, with bands distinguished by varying proportions of the constituent minerals. Gneiss containing sillimanite and cordierite is locally common; diopside-bearing rocks and clinopyroxene-scapolite rocks occur in some exposures; graphite is common at two localities near Taylor Glacier. Beds of marble are present in the Hansen Mountains. In the migmatites the foliation and banding are interrupted by irregular patches of quartz-feldspar rock, commonly containing garnet, which grade into biotite-quartz-feldspar gneiss. Discrete bodies of red quartz-orthoclase granite are also common in the biotite gneisses near Taylor Glacier.

Mafic dikes occur sporadically throughout the map area in all rock units. They are most common in the western part of the banded pyroxene-bearing gneiss. Most have been metamorphosed or show retrogressive mineral changes, especially of the pyroxene, and some have been deformed. The dikes are composed mainly of labradorite, hornblende, hypersthene, and clinopyroxene. Some have a poor foliation parallel to their margins, that is, cutting across the foliation of the enclosing rock. No marked preferred trend of the dikes is apparent, but there is a tendency for those in the banded pyroxene-bearing gneiss to strike in the northwest quadrant of the compass.

A few very coarse-grained, graphic mica-quartz-feldspar pegmatite dikes are widely scattered through the map area. The dikes range to as much as 5 m in width.

Although specimens have not been obtained from the areas of 'undifferentiated metamorphics,' most of the exposed regions have been seen from a distance, and there is little doubt that the rocks are part of the metamorphic complex. The rocks in the Scott Mountains possess a large-scale banding, but it is not known whether they are part of the quartz-feldspar gneiss or the garnet-quartz-feldspar gneiss units. The rocks of the Condon Hills, the Raggatt Mountains, and the Scott Mountains are described by Klimov *et al.* (1962) as 'hypersthene plagiogneiss and gneissoid charnockites' and 'garnet gneisses'.

Structure

The foliation and banding of the gneisses are parallel wherever the two occur together. Their predominant trend is toward the north in the charnockite and biotite-quartz-feldspar gneiss found between 60°30′E and 64°30′E longitude. Elsewhere the trend is east to southeast, the main exception being an area of northeasterly trends to the southwest of Edward VIII Bay. Macroscopic lineation was found at only a few places, too widely scattered to reveal any regional pattern.

Folding is evident in all the rock units except the charnockite. The folds differ greatly in extent, from kilometers to a few centimeters. In the various banded rocks, where folds are best seen, the predominant style seems to be overturned, tight, isoclinal folding, but many variations in style occur. The foliation of the gneisses is deformed by the folding, but development of a new foliation parallel to the axial planes of the folds is nowhere evident.

While it is not obvious that the charnockite is folded, it is extensively granulated and seams of mylonite are common in it. These two features are not common in the other rock units, although they do occur locally. It seems that the charnockite responded to the regional deformation by shearing, while the other gneisses of the region were folded.

Relations Between Rock Units

The structural and chronological relations of the rock units are not well known. Crohn (1959) concluded that the charnockite of Mawson and the Framnes Mountains is intrusive. Later work (McLeod *et al.*, 1966) suggests that the contact between charnockite and biotite-quartz-feldspar gneiss near Taylor Glacier is irregularly gradational; that is, different rock types are interbedded on a large scale, but with an overall transition from charnockite, through biotite charnockite, to hypersthene-free granulitic biotite-bearing gneiss, and finally to the biotite-quartz-feldspar gneiss. The gneiss bodies in the charnockite show a similar transition from charnockite to biotite-bearing gneiss. Trail (1967) suggests that it is unlikely that the mineralogical differences between the relatively small gneiss bodies of the Framnes Mountains and the charnockite are the result of a difference in metamorphic conditions, but rather that the different lithologies represent a compositional gradation which existed between the two rock types before they were metamorphosed.

The rocks at Twin Peaks* and Edward Ridge have features which are intermediate between those of the quartz-feldspar gneiss and pyroxene-quartz-feldspar gneiss units, so that there may be a gradation between the two units.

The only direct evidence concerning the age of the different units is given by potassium-argon whole-rock age measurements by Ravich and Krylov (1964). These are listed in Table 1. Because of the spread in the measured age of different specimens from the one locality, the strong evidence of multiple metamorphism of the different rock units, and the known susceptibility of potassium-argon whole-rock measurements to the effects of cataclasis and metamorphism, the measured ages must be regarded as minimum ages of the rocks. We agree with Ravich and Krylov (1964) that the high-grade metamorphic rocks should be assigned to the Precambrian, and that their true age is much older than their measured ages because they have been affected (but not necessarily completely recrystallized) by successive metamorphisms.

Nothing is known of the relative ages of the different units, except that the probable gradations between the units described above suggest that the original rocks of these units are not contemporaneous. However, they could all have been metamorphosed at the same time. Evidence of more than one metamorphism has been found in all the units, but it is impossible to say how far the parallel metamorphic histories of the different units extend back in time.

Except for the charnockite and quartz-feldspar gneiss, whose origin is not clear, and the banded pyroxene-bearing gneiss, which seems to be of mixed sedimentary and volcanic origin, the metamorphic units appear to have been derived from predominantly sedimentary rocks.

Metamorphic History

The metamorphic history of the region is complex, and different areas display evidence of many different events. We do not know to what extent these events can be correlated from one place to another, over distances of hundreds of kilometers, or how closely the different events succeeded one another. The following account of events is, therefore, brief and greatly simplified.

The first discernible metamorphic event in the region was metamorphism under granulite facies conditions. The widespread foliation presumably originated at this time. This metamorphism was succeeded—perhaps much later—by an episode of deformation, which folded the foliation and banding of many of the gneisses and perhaps produced the widespread cataclasis of the charnockite around Mawson and the Framnes Mountains. This deformation was followed by recrystallization in the almandine amphibolite facies, the degree differing from place to place. The recrystallization was perhaps accompanied by some potash metasomatism. The partial deformation of some of the dolerite dikes suggests that they were injected in the late stages of the deformation and subsequently metamorphosed.

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*Name not yet accepted by the United States Board on Geographic Names.

TABLE 1. RADIOMETRIC AGE DETERMINATIONS

Location	Lithology*	Method and Material	Age (m.y.)	Ref.
Mawson	Biotitized pyroxene plagiogneiss (xenolith in charnockite)	K-Ar Whole rock	650,555	1
	Garnet-biotite schist (xenolith in charnockite)	K-Ar Whole rock	490	1
	Porphyroblastic charnockite	K-Ar Whole rock	535	1
Øygarden Group	Migmatized biotite-garnet gneiss	K-Ar Whole rock	620	1
	Migmatite after pyroxene plagiogneiss	K-Ar Whole rock	615	1
	Vein pegmatite	K-Ar Whole rock	535	1

* Names of rocks are those used by Ravich and Krylov and may not agree with the terminology used by Trail and McLeod in the text of this Plate.

1. Ravich and Krylov, 1964

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