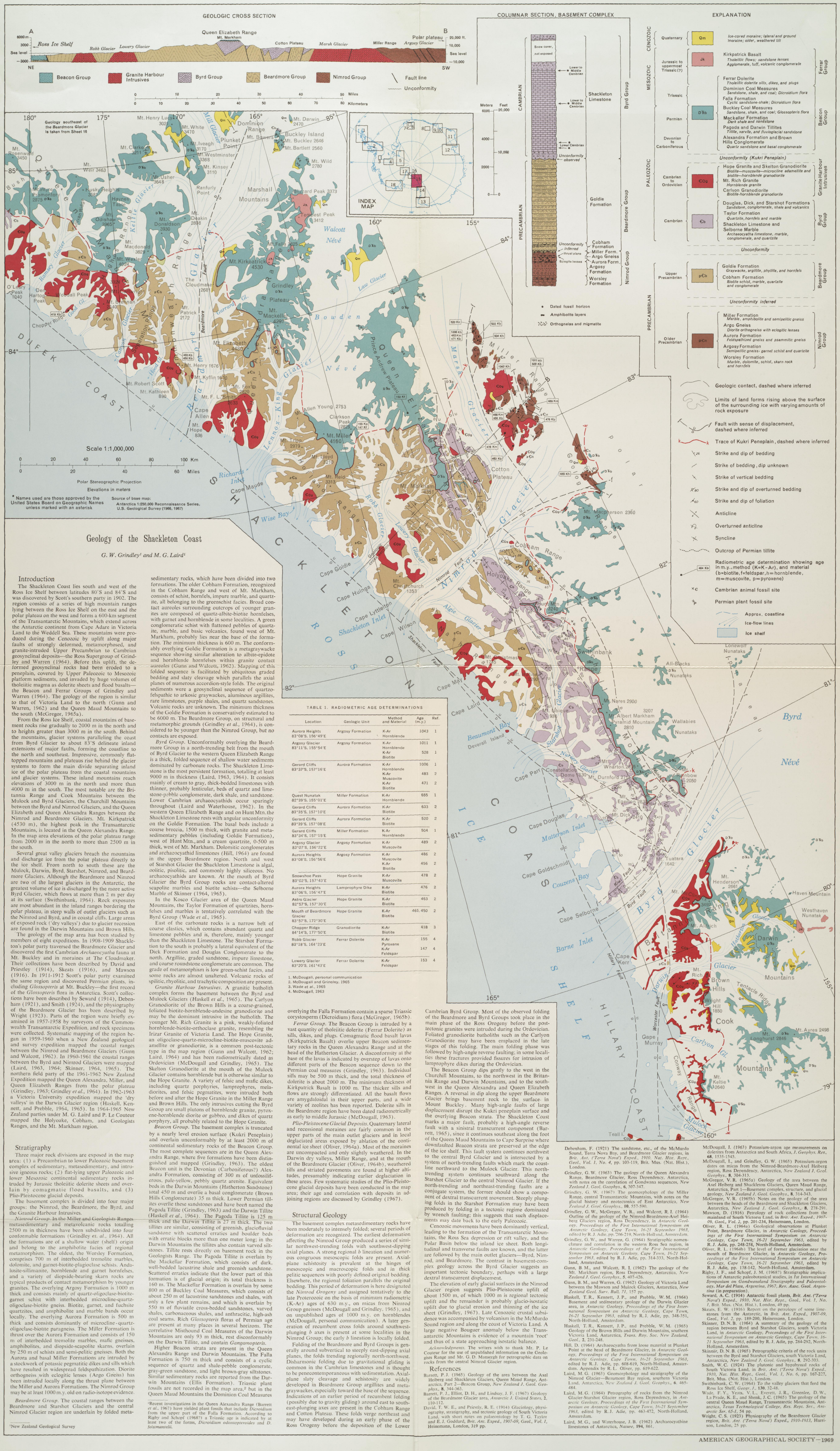

Geology of the Shackleton Coast

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Introduction

The Shackleton Coast lies south and west of the Ross Ice Shelf between latitudes 80°S and 84°S and was discovered by Scott's southern party in 1902. The region consists of a series of high mountain ranges lying between the Ross Ice Shelf on the east and the polar plateau on the west and forms a 600-km segment of the Transantarctic Mountains, which extend across the Antarctic continent from Cape Adare in Victoria Land to the Weddell Sea. These mountains were produced during the Cenozoic by uplift along major faults of strongly deformed, metamorphosed, and granite-intruded Upper Precambrian to Cambrian geosynclinal deposits—the Ross Supergroup of Grindley and Warren (1964). Before this uplift, the deformed geosynclinal rocks had been eroded to a peneplain, covered by Upper Paleozoic to Mesozoic platform sediments, and invaded by huge volumes of tholeiitic magma as dolerite sheets and flood basalts—the Beacon and Ferrar Groups of Grindley and Warren (1964). The geology of the region is similar to that of Victoria Land to the north (Gunn and Warren, 1962) and the Queen Maud Mountains to the south (McGregor, 1965a).

From the Ross Ice Shelf, coastal mountains of basement rocks rise gradually to 2000 m in the north and to heights greater than 3000 m in the south. Behind the mountains, glacier systems paralleling the coast from Byrd Glacier to about 83°S delineate inland extensions of major faults, forming the coastline to the north and southeast. Impressive, commonly flat-topped mountains and plateaus rise behind the glacier systems to form the main divide separating inland ice of the polar plateau from the coastal mountains and glacier systems. These inland mountains reach elevations of 3000 m in the north and more than 4000 m in the south. The most notable are the Britannia Range and Cook Mountains between the Mulock and Byrd Glaciers, the Churchill Mountains between the Byrd and Nimrod Glaciers, and the Queen Elizabeth and Queen Alexandra Ranges between the Nimrod and Beardmore Glaciers. Mt. Kirkpatrick (4530 m), the highest peak in the Transantarctic Mountains, is located in the Queen Alexandra Range. In the map area elevations of the polar plateau range from 2000 m in the north to more than 2500 m in the south.

Several great valley glaciers breach the mountains and discharge ice from the polar plateau directly to the ice shelf. From north to south these are the Mulock, Darwin, Byrd, Starshot, Nimrod, and Beardmore Glaciers. Although the Beardmore and Nimrod are two of the largest glaciers in the Antarctic, the greatest volume of ice is discharged by the more active Byrd Glacier, which flows at more than 2 m per day at its surface (Swithinbank, 1964). Rock exposures are most abundant in the inland ranges bordering the polar plateau, in steep walls of outlet glaciers such as the Nimrod and Byrd, and in coastal cliffs. Large areas of exposed rock ('dry valleys') due to glacier recession are found in the Darwin Mountains and Brown Hills.

The geology of the map area has been studied by members of eight expeditions. In 1908-1909 Shackleton's polar party traversed the Beardmore Glacier and discovered the first Cambrian *Archaeocyatha* fauna at Mt. Buckley and in moraines at The Cloudmaker. Their collections have been described by David and Priestley (1914), Skeats (1916), and Mawson (1916). In 1911-1912 Scott's polar party examined the same region and discovered Permian plants, including *Glossopteris* at Mt. Buckley—the first record of the *Glossopteris* flora in Antarctica. Scott's collections have been described by Seward (1914), Debenham (1921), and Smith (1924), and the physiography of the Beardmore Glacier has been described by Wright (1923). Parts of the region were briefly examined in 1957-1958 by surveyors of the Commonwealth Transantarctic Expedition, and rock specimens were collected. Systematic mapping of the region began in 1959-1960 when a New Zealand geological and survey expedition mapped the coastal ranges between the Nimrod and Beardmore Glaciers (Gunn and Walcott, 1962). In 1960-1961 the coastal ranges between the Byrd and Nimrod Glaciers were mapped (Laird, 1963, 1964; Skinner, 1964, 1965). The northern field party of the 1961-1962 New Zealand Expedition mapped the Queen Alexandra, Miller, and Queen Elizabeth Ranges from the polar plateau (Grindley, 1963; Grindley *et al.*, 1964). In 1962-1963 a Victoria University expedition mapped the 'dry valleys' in the Darwin Glacier region (Haskell, Kennett, and Prebble, 1964, 1965). In 1964-1965 New Zealand parties under M. G. Laird and P. Le Couteur mapped the Holyoake, Cobham, and Geologists Ranges, and the Mt. Markham region.

Stratigraphy

Three major rock divisions are exposed in the map area: (1) a Precambrian to lower Paleozoic basement complex of sedimentary, metasedimentary, and intrusive igneous rocks; (2) flat-lying upper Paleozoic and lower Mesozoic continental sedimentary rocks intruded by Jurassic tholeiitic dolerite sheets and overlain by comagmatic flood basalts, and (3) Plio-Pleistocene glacial deposits.

The basement complex is divided into four major groups: the Nimrod, the Beardmore, the Byrd, and the Granite Harbour Intrusives.

Nimrod Group. In the Miller and Geologists Ranges metasedimentary and metavolcanic rocks totalling 2500 m in thickness have been subdivided into four conformable formations (Grindley *et. al.*, 1964). All the formations are of a shallow water (shelf) origin and belong to the amphibolite facies of regional metamorphism. The oldest, the Worsley Formation, comprises 700 m of interbedded tremolite marbles, dolomite, and garnet-biotite-plagioclase schists. Andalusite-sillimanite, hornblende and garnet hornfelses, and a variety of diopside-bearing skarn rocks are typical products of contact metamorphism by younger granites. The overlying Argosy Formation is 1000 m thick and consists mainly of quartz-oligoclase-biotite-garnet schist with interbedded microcline-quartz-oligoclase-biotite gneiss. Biotite, garnet, and fuchsite quartzites, and amphibolite and marble bands occur locally. The overlying Aurora Formation is 500 m thick and consists dominantly of microcline-quartz-oligoclase-biotite paragneiss. The Miller Formation is thrust over the Aurora Formation and consists of 150 m of interbedded tremolite marbles, mafic gneisses, amphibolites, and diopside-scapolite skarns, overlain by 250 m of schists and semi-pelitic gneisses. Both the Aurora and basal Miller Formations are intruded by a stockwork of potassic pegmatitic dikes and sills which have resulted in widespread feldspathization. Diorite orthogneiss with eclogitic lenses (Argo Gneiss) has been intruded locally along the thrust plane between the Miller and Aurora Formations. The Nimrod Group may be at least 1000 m.y. old on radio-isotope evidence.

Beardmore Group. The coastal ranges between the Beardmore and Starshot Glaciers and the central Nimrod Glacier region are underlain by folded metasedimentary rocks, which have been divided into two formations. The older Cobham Formation, recognized in the Cobham Range and west of Mt. Markham, consists of schist, hornfels, impure marble, and quartzite, all belonging to the greenschist facies. Broad contact aureoles surrounding outcrops of younger granites are composed of quartz-albite-biotite hornfelses, with garnet and hornblende in some localities. A green conglomeratic schist with flattened pebbles of quartzite, marble, and basic volcanics, found west of Mt. Markham, probably lies near the base of the formation. The minimum thickness is 600 m. The conformably overlying Goldie Formation is a metagraywacke sequence showing similar alteration to albite-epidote and hornblende hornfelses within granite contact aureoles (Gunn and Walcott, 1962). Mapping of this folded sequence is facilitated by ubiquitous graded bedding and slaty cleavage which parallels the axial planes of numerous accordion-style folds. The original sediments were a geosynclinal sequence of quartzo-felspathic to arkosic graywackes, aluminous argillites, rare limestones, purple shales, and quartz sandstones. Volcanic rocks are unknown. The minimum thickness of the Goldie Formation is conservatively estimated to be 6000 m. The Beardmore Group, on structural and metamorphic grounds (Grindley *et al.*, 1964), is considered to be younger than the Nimrod Group, but no contacts are exposed.

Byrd Group. Unconformably overlying the Beardmore Group in a north-trending belt from the mouth of Byrd Glacier to the western Queen Elizabeth Range is a thick, folded sequence of shallow water sediments dominated by carbonate rocks. The Shackleton Limestone is the most persistent formation, totalling at least 9000 m in thickness (Laird, 1963, 1964). It consists mainly of cream to gray, thick-bedded limestones with thinner, probably lenticular, beds of quartz and limestone-pebble conglomerate, dark shale, and sandstone. Lower Cambrian archaeocyathids occur sparingly throughout (Laird and Waterhouse, 1962). In the western Queen Elizabeth Range and on Hunt Mtn. the Shackleton Limestone rests with angular unconformity on the Goldie Formation. The basal beds include a coarse breccia, 1500 m thick, with granite and metasedimentary pebbles (including Goldie Formation), west of Hunt Mtn., and a cream quartzite, 0-500 m thick, west of Mt. Markham. Dolomitic conglomerates and archaeocyathid limestones (Hill, 1964) are found in the upper Beardmore region. North and west of Starshot Glacier the Shackleton Limestone is algal, oolitic, pisolitic, and commonly highly siliceous. No archaeocyathids are known. At the mouth of Byrd Glacier the Byrd Group rocks are contact-altered scapolite marbles and biotite schists—the Selborne Marble of Skinner (1964, 1965).

In the Kosco Glacier area of the Queen Maud Mountains, the Taylor Formation of quartzites, hornfelses and marbles is tentatively correlated with the Byrd Group (Wade *et al.*, 1965).

East of the carbonate rocks is a narrow belt of coarse clastics, which contains abundant quartz and limestone pebbles and is, therefore, mainly younger than the Shackleton Limestone. The Starshot Formation to the south is probably a lateral equivalent of the Dick Formation and Douglas Conglomerate to the north. Argillite, graded sandstone, impure limestone, and coarse roundstone conglomerate are common. The grade of metamorphism is low green-schist facies, and some rocks are almost unaltered. Volcanic rocks of spilitic, rhyolitic, and trachytic composition are present.

Granite Harbour Intrusives. A granitic batholith complex forms the basement between the Byrd and Mulock Glaciers (Haskell *et al.*, 1965). The Carlyon Granodiorite of the Brown Hills is a coarse-grained, foliated biotite-hornblende-andesine granodiorite and may be the dominant intrusive in the batholith. The younger Mt. Rich Granite is a pink, weakly-foliated hornblende-biotite-orthoclase granite, resembling the Irizar Granite of Victoria Land. The Hope Granite, an oligoclase-quartz-microcline-biotite-muscovite adamellite or granodiorite, is a common post-tectonic type in the map region (Gunn and Walcott, 1962; Laird, 1964) and has been radiometrically dated as Ordovician (McDougall and Grindley, 1965). The Skelton Granodiorite at the mouth of the Mulock Glacier contains hornblende but is otherwise similar to the Hope Granite. A variety of felsic and mafic dikes, including quartz porphyries, lamprophyres, meladiorites, and felsic pegmatites, were intruded both before and after the Hope Granite in the Miller Range and Brown Hills. The only intrusives cutting the Byrd Group are small plutons of hornblende granite, pyroxene-hornblende diorite or gabbro, and dikes of quartz porphyry, all probably related to the Hope Granite.

Beacon Group. The basement complex is truncated by a nearly level erosion surface (Kukri Peneplain) and overlain unconformably by at least 2000 m of continental sedimentary rocks of the Beacon Group. The most complete sequences are in the Queen Alexandra Range, where five formations have been distinguished and mapped (Grindley, 1963). The oldest Beacon unit is the Devonian (Carboniferous?) Alexandra Formation, consisting of 300 m of unfossiliferous, pale-yellow, pebbly quartz arenite. Equivalent beds in the Darwin Mountains (Hatherton Sandstone) total 450 m and overlie a basal conglomerate (Brown Hills Conglomerate) 35 m thick. Lower Permian tillites overlie these sandstones and have been named the Pagoda Tillite (Grindley, 1963) and the Darwin Tillite (Haskell *et al.*, 1964). The Pagoda Tillite is 125 m thick and the Darwin Tillite is 27 m thick. The two tillites are similar, consisting of greenish, glaciofluvial sandstone with scattered erratics and boulder beds with erratic blocks more than one meter long; in the Darwin Mountains the tillites also contain varved siltstones. Tillite rests directly on basement rock in the Geologists Range. The Pagoda Tillite is overlain by the Mackellar Formation, which consists of dark, well-bedded lacustrine shale and greenish sandstone. Scattered erratics indicate that the lower part of this formation is of glacial origin; its total thickness is 160 m. The Mackellar Formation is overlain by some 800 m of Buckley Coal Measures, which consists of about 250 m of lacustrine sandstones and shales, with only a few plant remains, and which is overlain by 550 m of fluviatile cross-bedded sandstones, varved shales, carbonaceous shales, and anthracitic, high-ash coal seams. Rich *Glossopteris* floras of Permian age are present at many places in several horizons. The correlative Misthound Coal Measures of the Darwin Mountains are only 93 m thick, rest disconformably on the Darwin Tillite, and contain *Gangamopteris*.

Higher Beacon strata are present in the Queen Alexandra Range and Darwin Mountains. The Falla Formation is 750 m thick and consists of a cyclic sequence of quartz and shale-pebble conglomerate, gray-green sandstone, and light brown-gray siltstones. Similar sedimentary rocks are reported from the Darwin Mountains (Ellis Formation). Triassic plant fossils are not recorded in the map area,[2] but in the Queen Maud Mountains the Dominion Coal Measures overlying the Falla Formation contain a sparse Triassic corystosperm (Dicroidium) flora (McGregor, 1965b).

Ferrar Group. The Beacon Group is intruded by a vast quantity of tholeiitic dolerite (Ferrar Dolerite) as sills, dikes, and plugs. Comagmatic flood basalt lavas (Kirkpatrick Basalt) overlie upper Beacon sedimentary rocks in the Queen Alexandra Range and at the head of the Hatherton Glacier. A disconformity at the base of the lavas is indicated by overstep of lavas onto different parts of the Beacon sequence down to the Permian coal measures (Grindley, 1963). Individual sills may be 500 m thick, and the total thickness of dolerite is about 2000 m. The minimum thickness of Kirkpatrick Basalt is 1000 m. The thicker sills and flows are strongly differentiated. All the basalt flows are amygdaloidal in their upper parts, and a wide variety of zeolites has been reported. Dolerite sills in the Beardmore region have been dated radiometrically as early to middle Jurassic (McDougall, 1963).

Plio-Pleistocene Glacial Deposits. Quaternary lateral and recessional moraines are fairly common in the upper parts of the main outlet glaciers and in local deglaciated areas exposed by ablation of the continental ice sheet (Oliver, 1964a). Most of the moraines are uncompacted and only slightly weathered. In the Darwin dry valleys, Miller Range, and at the mouth of the Beardmore Glacier (Oliver, 1964b), weathered tills and striated pavements are found at higher altitudes, presumably indicating earlier deglaciation in these areas. Few systematic studies of the Plio-Pleistocene glacial deposits have been conducted in the map area; their age and correlation with deposits in adjoining regions are discussed by Grindley (1967).

Structural Geology

The basement complex metasedimentary rocks have been moderately to intensely folded; several periods of deformation are recognized. The earliest deformation affecting the Nimrod Group produced a series of similar northwest-trending folds with southwest-dipping axial planes. A strong regional *b* lineation and numerous congruous mesoscopic folds are present. Axial-plane schistosity is prevalent at the hinges of mesoscopic and macroscopic folds and in thick pelitic sequences with poorly defined original bedding. Elsewhere, the regional foliation parallels the original bedding. This period of deformation is here designated the *Nimrod Orogeny* and assigned tentatively to the late Proterozoic on the basis of minimum radiometric (K-Ar) ages of 630 m.y., on micas from Nimrod Group gneisses (McDougall and Grindley, 1965), and on unpublished ages of 1000 m.y. on hornblendes (McDougall, personal communication). A later generation of recumbent cross folds around southwest-plunging *b* axes is present at some localities in the Nimrod Group; the early *b* lineation is locally folded.

Folding of the Beardmore and Byrd Groups is generally around subvertical to steeply east-dipping axial planes, the folds trending regionally north-northwest. Disharmonic folding due to gravitational gliding is common in the Cambrian limestones and is thought to be penecontemporaneous with sedimentation. Axial-plane slaty cleavage and schistosity are widely developed in Beardmore Group argillites and metagraywackes, especially toward the base of the sequence. Indications of an earlier period of recumbent folding (possibly due to gravity gliding) around east to southeast-plunging axes are present in the Cobham Range and Cotton Plateau. These folds verge northeast and may have developed during an early phase of the Ross Orogeny before the deposition of the Lower Cambrian Byrd Group. Most of the observed folding of the Beardmore and Byrd Groups took place in the main phase of the Ross Orogeny before the post-tectonic granites were intruded during the Ordovician. Foliated granodiorite batholiths such as the Carlyon Granodiorite may have been emplaced in the late stages of this folding. The main folding phase was followed by high-angle reverse faulting; in some localities these fractures provided fissures for intrusion of lamprophyre dikes during the Ordovician.

The Beacon Group dips gently to the west in the Churchill Mountains, to the northwest in the Britannia Range and Darwin Mountains, and to the southwest in the Queen Alexandra and Queen Elizabeth Ranges. A reversal in dip along the upper Beardmore Glacier brings basement rock to the surface in Mount Buckley. Many high-angle faults of large displacement disrupt the Kukri peneplain surface and the overlying Beacon strata. The Shackleton Coast marks a major fault, probably a high-angle reverse fault with a sinistral transcurrent component (Barrett, 1965), since it continues southeast along the foot of the Queen Maud Mountains to Cape Surprise where downfaulted Beacon strata are preserved at the edge of the ice shelf. This fault system continues northwest to the central Byrd Glacier and is intersected by a system of north-trending faults which mark the coastline northward to the Mulock Glacier. This north-trending system continues southward along the Starshot Glacier to the central Nimrod Glacier. If the north-trending and northeast-trending faults are a conjugate system, the former should show a component of dextral transcurrent movement. Steeply plunging folds in the Starshot Formation may have been produced by folding in a tectonic regime dominated by wrench faulting; this suggests that such displacements may date back to the early Paleozoic.

Cenozoic movements have been dominantly vertical, leading to the formation of the Transantarctic Mountains, the Ross Sea depression or rift valley, and the Polar Basin below the inland ice sheet. Both longitudinal and transverse faults are known, and the latter are followed by the main outlet glaciers—Byrd, Nimrod, and Beardmore. The contrast in basement-complex geology across the Byrd Glacier suggests an important tectonic boundary, perhaps with a large dextral transcurrent displacement.

The elevation of early glacial surfaces in the Nimrod Glacier region suggests Plio-Pleistocene uplift of about 1500 m, of which 1000 m is regional tectonic uplift and the remainder is probably glacio-isostatic uplift due to glacial erosion and thinning of the ice sheet (Grindley, 1967). Late Cenozoic crustal subsidence was accompanied by volcanism in the McMurdo Sound region and along the coast of Victoria Land. A large negative Bouguer anomaly below the Transantarctic Mountains is evidence of a mountain 'root' and thus of a state approaching isostatic balance.

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TABLE 1. RADIOMETRIC AGE DETERMINATIONS

Location	Geologic Unit	Method and Material	Age (m.y.)	Ref.
Aurora Heights 83°08′S, 156°49′E	Argosy Formation	K-Ar Hornblende	1043	1
Argosy Glacier 83°11′S, 155°54′E	Argosy Formation	K-Ar Hornblende	1011	1
		K-Ar Biotite	528	1
Gerard Cliffs 83°37′S, 157°16′E	Aurora Formation	K-Ar Hornblende	1006	1
		K-Ar Muscovite	483	2
		K-Ar Biotite	471	2
Quest Nunatak 82°39′S, 155°01′E	Miller Formation	K-Ar Hornblende	655	1
Gerard Cliffs 83°35′S, 157°10′E	Aurora Formation	K-Ar Biotite	633	2
Gerard Cliffs 83°39′S, 157°08′E	Aurora Formation	K-Ar Biotite	520	2
Gerard Cliffs 83°34′S, 157°15′E	Miller Formation	K-Ar Hornblende	504	1
Argosy Glacier 83°07′S, 156°22′E	Argosy Formation	K-Ar Muscovite	489	2
Aurora Heights 83°08′S, 156°56′E	Argosy Formation	K-Ar Muscovite	486	2
		K-Ar Biotite	456	2
Snowshoe Pass 83°02′S, 157°43′E	Hope Granite	K-Ar Muscovite	478	2
Aurora Heights 83°06′S, 156°47′E	Lamprophyre Dike	K-Ar Biotite	476	2
Astro Glacier 82°57′S, 157°30′E	Hope Granite	K-Ar Biotite	463	2
Mouth of Beardmore Glacier 83°57′S, 172°30′E	Hope Granite	K-Ar Biotite	465, 450	2
Chopper Ridge 84°14′S, 177°50′E	Granodiorite	K-Ar Biotite	418	3
Robb Glacier 83°18′S, 164°23′E	Ferrar Dolerite	K-Ar Pyroxene	155	4
		K-Ar Feldspar	147	4
Lowery Glacier 83°20′S, 161°43′E	Ferrar Dolerite	K-Ar Feldspar	153	4

1. McDougall, personal communication
2. McDougall and Grindley, 1965
3. Wade et al., 1965
4. McDougall, 1963

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