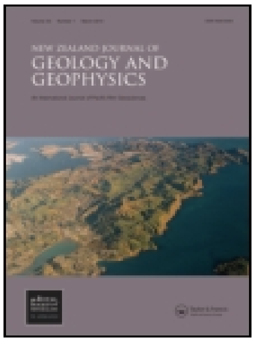

New Zealand Journal of Geology and Geophysics

ISSN: 0028-8306 (Print) 1175-8791 (Online) Journal homepage: https://www.tandfonline.com/loi/tnzg20

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To cite this article: M. G. Laird , G. D. Mansergh & J. M. A. Chappell (1971) Geology of the Central Nimrod Glacier area, Antarctica, New Zealand Journal of Geology and Geophysics, 14:3, 427-468, DOI: 10.1080/00288306.1971.10421939

To link to this article: https://doi.org/10.1080/00288306.1971.10421939

Published online: 09 Jan 2012.

NEW ZEALAND
JOURNAL OF GEOLOGY AND GEOPHYSICS

SIXTH SPECIAL ANTARCTIC ISSUE

Department of Scientific and Industrial Research, Wellington

Editor: Nancy Sutherland

Assistant Editor: Ian Mackenzie

VOLUME 14 SEPTEMBER 1971 NUMBER 3

GEOLOGY OF THE CENTRAL NIMROD GLACIER AREA, ANTARCTICA

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(Received for publication 5 April 1971)

ABSTRACT

The area studied includes the Cobham, Holyoake and parts of the Swithinbank, Surveyors and Queen Elizabeth Ranges and forms part of the Trans-Antarctic Mountains. The sedimentary rocks can be divided into three major groups separated from each other by an unconformity. The oldest sequence, the unfossiliferous Beardmore Group, is probably late Precambrian. It consists of isoclinally folded sediments and metasediments and comprises the Cobham Formation of regularly bedded marble, quartzite and schist and the younger Goldie Formation of argillite and graded sandstone with rare schist and marble beds. Overlying this group with angular unconformity is the predominantly calcareous Byrd Group comprising the Shackleton Limestone and Starshot Formation. It is characterized by north-west- to north-trending open folds of large amplitude with near vertical axial planes. The Shackleton Limestone consists

of limestone and marble with breccia and minor quartzite, conglomerate, sandstone and shale. Archaeocyatha found throughout the 8,300 m sequence date the formation as lower to middle Cambrian. Facies changes suggest biohermal development on a tectonically unstable shelf with a shoreline to the west. The Starshot Formation consists largely of graded fine conglomerate and sandstone locally interbedded with thin rhyolite and trachyte flows. Although the two formations comprising this group were not seen in contact they may be in part contemporaneous.

The Beacon Supergroup was deposited on the Kukri Peneplain which cuts across both the Beardmore and Byrd Groups, and five formations are recognised within it. The newly erected Castle Crags Formation comprises siltstone, carbonaceous shale and cross-bedded sandstone laid down in local depressions in the Kukri Peneplain. As subsidence continued, a coarse quartzose cross-bedded sandstone—the Alexandra Formation—was deposited. This is overlain disconformably by the Pagoda Tillite, which includes poorly sorted ice contact deposits (tillite) and fluvioglacial sandstone. The overlying Mackellar Formation, of dark carbonaceous shale and sandstone, was deposited mainly in proglacial lakes and streams after the ice front retreated. The youngest formation, the Buckley Coal Measures, consists of cross-bedded sandstone overlain by coal measures thought to have been deposited on a deltaic plain.

Both the Beardmore and Byrd Groups have been intruded by post-tectonic microcline-biotite granite and tonalite of the Granite Harbour Intrusives. The Beacon Supergroup has been intruded by tholeiitic dolerite sills of the Ferrar Group. The Holyoake Gabbro, a quartz gabbro, intrudes the Byrd Group and is thought to be a deeper equivalent of the Ferrar Group. Intrusions of finely disseminated hematite and veins carrying arsenic sulphide are also found in several localities within the Byrd Group.

INTRODUCTION

In the summer of 1964–65 a New Zealand Geological and Survey Expedition comprising three geologists—J. Chappell, M. Laird and G. Mansergh—and a mechanic and field assistant—D. Massam—mapped a 4,850 sq km area in the previously unexplored central Nimrod Glacier region (Fig. 1). Chappel fell ill and was replaced after two weeks by B. Ahern, a second field assistant. G. Mansergh and B. Ahern returned to base after a seven week survey of the north side of the Nimrod Glacier and were replaced by M. Gregory, geologist, and D. Lowe, field assistant, for the final fortnight during which the whole party worked on the south side of the glacier.

PREVIOUS WORK

Four parties had previously carried out surveying and geological work in the Nimrod Glacier region. J. H. Miller and G. W. Marsh of the New Zealand section of the Commonwealth Trans-Antarctic Expedition made the first exploration of the area in 1957, collecting basement rock samples from the Miller Range and Beacon samples, some with Permian plant remains, from the Queen Elizabeth Range. R. I. Walcott of the 1959–60 New Zealand Geological and Survey Expedition mapped the coastal ranges between the Nimrod and Beardmore Glaciers (Gunn and Walcott, 1962) and found that the ranges were composed of folded metagreywacke intruded by granite. In 1960–61 two parties led by Captain P. J. Hunt (Laird, 1963, 1964) and G. J. Matterson (Skinner, 1964) mapped the coastal ranges between the Byrd and Nimrod Glaciers. Laird mapped folded metagreywacke and granite in the Nash Range and thick folded limestone containing late lower Cambrian Archaeocyatha in the Holyoake Range. The limestone was thus

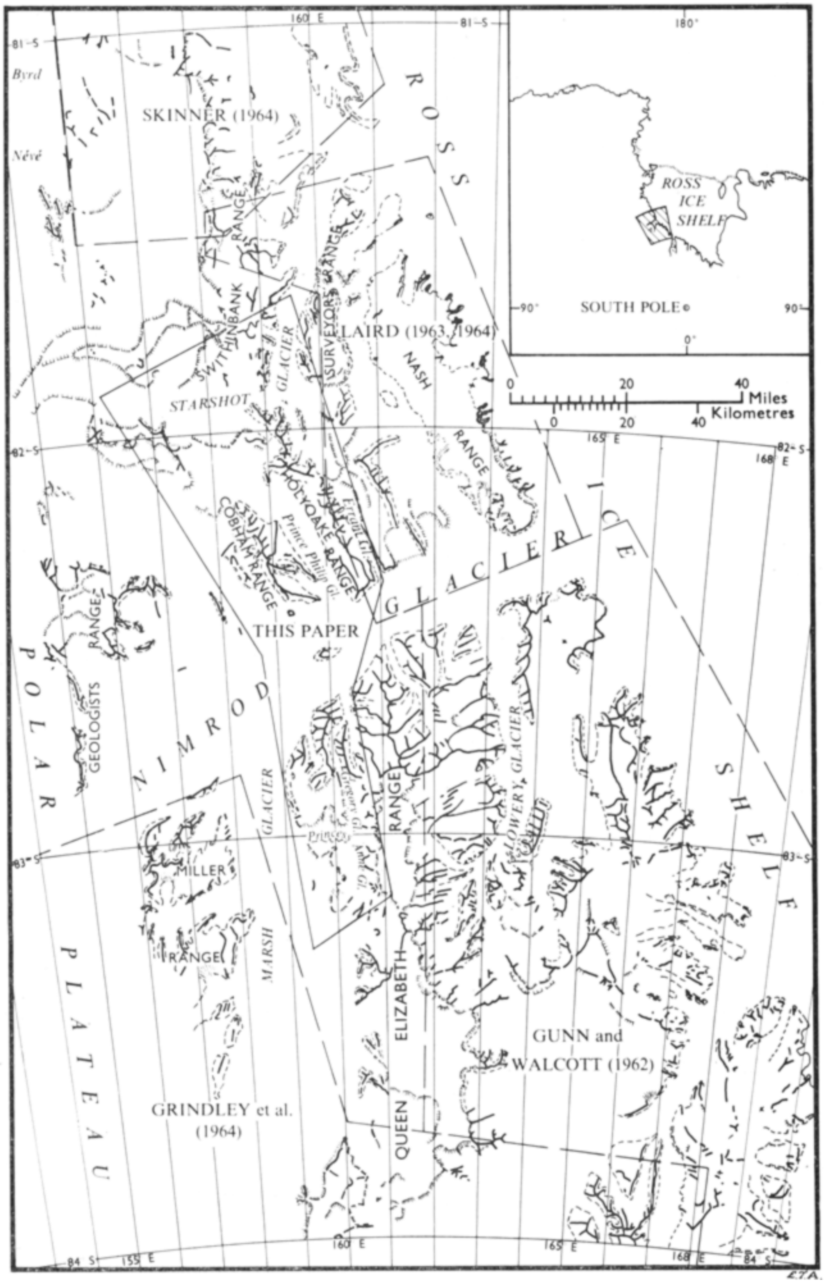

FIG. 1—Locality map showing the areas mapped by this and previous parties.

shown to belong to the basement complex and not to an early marine phase of the Beacon Group as suggested by David and Priestley (1914) and others. The Starshot, Dick and Douglas Formations of shallow-water calcareous conglomerate, sandstone and shale, probably contemporary with or younger than the limestone, were also described. In 1961–62 another New Zealand Geological and Survey party under R. I. Walcott working south of the Nimrod Glacier mapped the Miller Range (Grindley, 1963; Grindley *et al.*, 1964). Grindley *et al.* described a group of highly metamorphosed and deformed sediments and orthogneisses which they considered to be older than the metagreywacke and limestone further east, although no contact was seen.

The data collected by these various expeditions made it possible to infer a stratigraphic sequence for the major rock groups. Evidence obtained from aerial reconnaissance and distant ground views suggested that the relationship between the groups might be seen in the unexplored central Nimrod region. It was for this purpose that the 1964–65 expedition was organised.

TOPOGRAPHY

The area mapped comprises a section of the Trans-Antarctic Mountains flanking the Ross Ice Shelf between 82° 50′ S and 83° 10′ S. The major glaciers, all of which rise on the Polar Plateau, are the Starshot Glacier in the north and the Marsh and Nimrod Glaciers in the south (Fig. 1). The area between the Nimrod Glacier and the broad névé of the Starshot Glacier drains south into the Nimrod Glacier along parallel, south-east-trending glaciers separated by the Holyoake and Cobham Ranges. South of the Nimrod Glacier the land rises to 4,350 m and is deeply dissected by small alpine glaciers. It is stepped down in a series of fault blocks to the Marsh Glacier on the west.

STRATIGRAPHY

Summary

Three main sedimentary rock divisions, separated from each other by unconformities, occur in the mapped area (Figs. 2 and 3). The oldest (Beardmore Group) of late Precambrian age consists of isoclinally folded marble, sandstone, argillite, quartzite and schist. Unconformably overlying this sequence is the Cambrian Byrd Group which consists mainly of limestone and marble, with minor breccia, conglomerate, quartzite, sandstone, and shale. The youngest sediments, which belong to the Devonian to Permian Beacon Supergroup, rest on a flat-lying erosion surface which truncates both older groups.

Granite and tonalite (Granite Harbour Intrusives) intrude the Beardmore and Byrd Group sediments, while the Beacon Supergroup is intruded by sills of Ferrar Dolerite. Gabbro (Holyoake Gabbro), probably a deep-seated equivalent of the Ferrar Dolerite, intrudes limestone of the Byrd Group on the Holyoake Range.

Beardmore Group

The name Beardmore Group was proposed by Gunn and Walcott (1962) for strongly folded and thermally altered greywacke and argillite (Goldie Formation) in the coastal ranges between the Beardmore and Nimrod Glaciers and for higher-grade amphibolite and marble (Miller Formation) in the Miller Range near the head of the Nimrod Glacier. Grindley *et al.* (1964) considered that the more highly metamorphosed rocks formed an older basement on which geosynclinal sediment was deposited unconformably, and therefore excluded the high-rank Miller Formation from the Beardmore Group and placed it in the Nimrod Group. In the central Nimrod Glacier region greywacke, argillite and minor schist included in the Goldie Formation overlie quartzite, marble and hornfelsic schist, which is referred to a newly defined Cobham Formation.

COBHAM FORMATION

Name and Distribution

The name Cobham Formation is proposed for an interlayered sequence of quartzite, marble and schist of the albite-epidote hornfels facies lying conformably beneath greywacke and argillite of the Goldie Formation The formation crops out in the south-west portion of the Cobham Range as a strip about 2·4 km wide extending from west of Mt Kopere south to Gargoyle Ridge.

Type Locality

The type locality is at the western end of Gargoyle Ridge where about 510 m of strata are exposed (Table 1). The base of the section is obscured by ice and the top of the formation is taken as the highest marble bed in the sequence of hornfelsic marble, quartzite and schist.

Content

The Cobham Formation consists of interbedded biotite hornfels quartzite, marble and schist, the marble commonly showing mesoscopic folds (Fig. 4). Quartzite is the dominant lithology in the lower 300 m while marble is more common in the upper half of the section. Pelitic biotite hornfels in beds from only a few centimetres thick to 15 m thick alternate with quartzite throughout the sequence. Near the top, beds up to 46 m thick occur but lower in the sequence the beds are thinner, and in the lowest 80 m exposed do not exceed 10 m.

Petrography

The original sediments of the Cobham Formation comprised muddy quartz sand, pelite and impure limestone. The beds appear to have been subjected to two periods of metamorphism. The regular occurrence of relict almandine and the irregular appearance of remnant lepidoblastic texture suggest that during regional metamorphism the Cobham Formation may have been altered to a quartz-albite-epidote-almandine grade. Subsequently contact metamorphism has produced rocks of the albite-epidote-hornfels facies with the rocks normally showing a strong granoblastic texture.

Quartz and biotite, with lesser quantities of sericite, are the most common minerals found, and magnetite is often associated with the biotite. In the biotite hornfels, biotite porphyroblasts form the bulk of the rock. Tremolite and calcite appear regularly in the altered limestone beds. Albite is noticeably absent throughout the formation.

Environment of Deposition

Bedding and some fine parallel laminations were the only sedimentary structures seen in the Cobham Formation. The alternation of well-bedded quartzitic, calcareous and sandy metasediments suggest deposition in moderately shallow water, probably on the inner margin of a continental shelf.

Correlation

Similar lithologies to those found in the Cobham Formation are found in the Geologists Range 40 km to the west (R. G. Adamson, pers comm.), and the sequences may be correlatives. Grindley and McDougall (1969) place the schist in the Geologists Range in the Nimrod Group, exposed nearby in the Miller Range, and not in the Cobham Formation; they separated the deposition of the Nimrod and the Beardmore Groups by the Nimrod Orogeny (Grindley and Laird, 1969).

Radiometric dates (Grindley and McDougall, 1969) have been obtained for hornblende in amphibolite in both the Miller and Geologists Ranges. Of four samples collected in the Miller Range three date between 1,006 and 1,043 m.y.; the fourth is 504 m.y. The only sample collected from the Geologists Range gave an age of 618 m.y. Grindley and McDougall (ibid.) argue that the 1,000 m.y. date represents the age of metamorphism during the Nimrod Orogeny and the younger dates can be explained by partial loss of argon during the Ross Orogeny 500 m.y. ago.

The coincidence of the two younger dates (618 and 504 m.y.) with the ages given by Grindley and McDougall (ibid.) for the Beardmore and Ross Orogenies respectively suggest they may do no more than date these events, and thus it does not necessarily follow that the Geologists Range rocks should correlate with the Nimrod Group. They could be equally well correlated with the Cobham Formation.

GOLDIE FORMATION

Name and Distribution

This formation was first defined from a type locality at the junction of the Lowery and Nimrod Glaciers (Gunn and Walcott, 1962) and consists of thermally metamorphosed greywacke and argillite. The formation is widespread in the central Nimrod Glacier region and makes up the bulk of the Cobham Range, the Cotton Plateau and the north-west part of the Queen Elizabeth Range. Small areas of Goldie Formation are also present on the south-east flank of the Holyoake Range, on the end of the western spur of Mt Hunt and in the southern Chappell Nunataks.

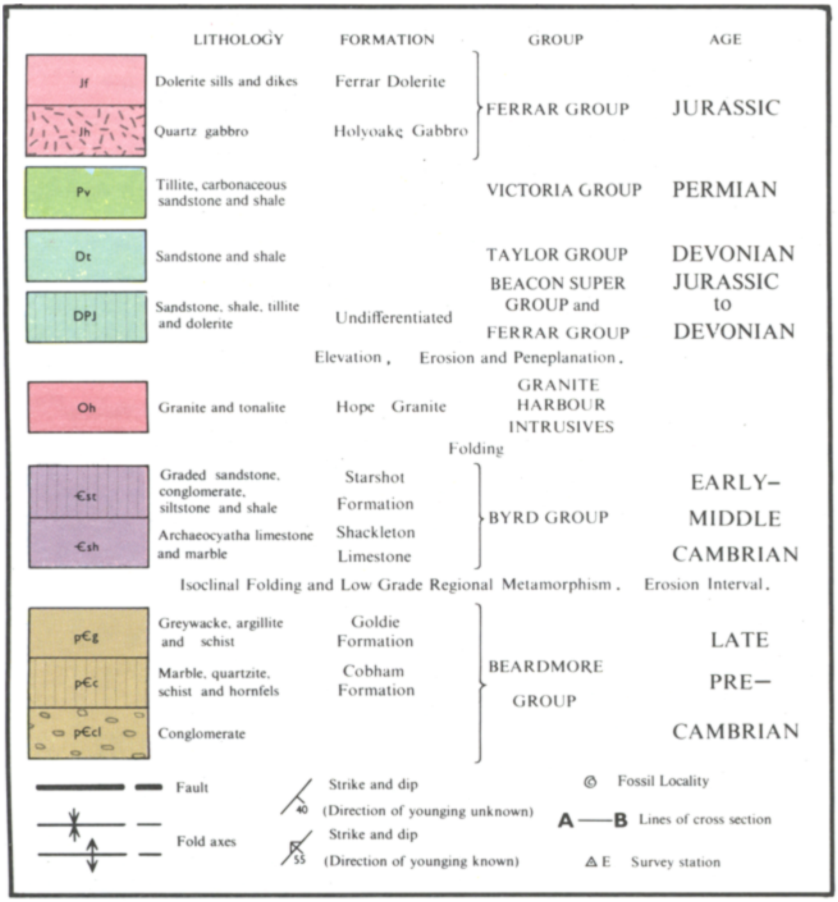
LITHOLOGY
FORMATION
GROUP
AGE
Jf
Dolerite sills and dikes
Ferrar Dolerite
Jh
Quartz gabbro
Holyoake Gabbro
FERRAR GROUP
JURASSIC
Pv
Tillite, carbonaceous sandstone and shale
VICTORIA GROUP
PERMIAN
Dt
Sandstone and shale
TAYLOR GROUP
DEVONIAN
DPJ
Sandstone, shale, tillite and dolerite
Undifferentiated
BEACON SUPER GROUP and FERRAR GROUP
JURASSIC to DEVONIAN
Elevation, Erosion and Peneplanation.
Oh
Granite and tonalite
Hope Granite
GRANITE HARBOUR INTRUSIVES
Folding
€st
Graded sandstone, conglomerate, siltstone and shale
Starshot Formation
€sh
Archaeocyatha limestone and marble
Shackleton Limestone
BYRD GROUP
EARLY– MIDDLE CAMBRIAN
Isoclinal Folding and Low Grade Regional Metamorphism. Erosion Interval.
p€g
Greywacke, argillite and schist
Goldie Formation
p€c
Marble, quartzite, schist and hornfels
Cobham Formation
p€cl
Conglomerate
BEARDMORE GROUP
LATE PRE– CAMBRIAN
Fault
Fold axes
Strike and dip
40
(Direction of younging unknown)
Strike and dip
55
(Direction of younging known)
Fossil Locality
A — B Lines of cross section
△ E Survey station

Fig. 2—Geological map of the central Nimrod Glacier region, and legend.

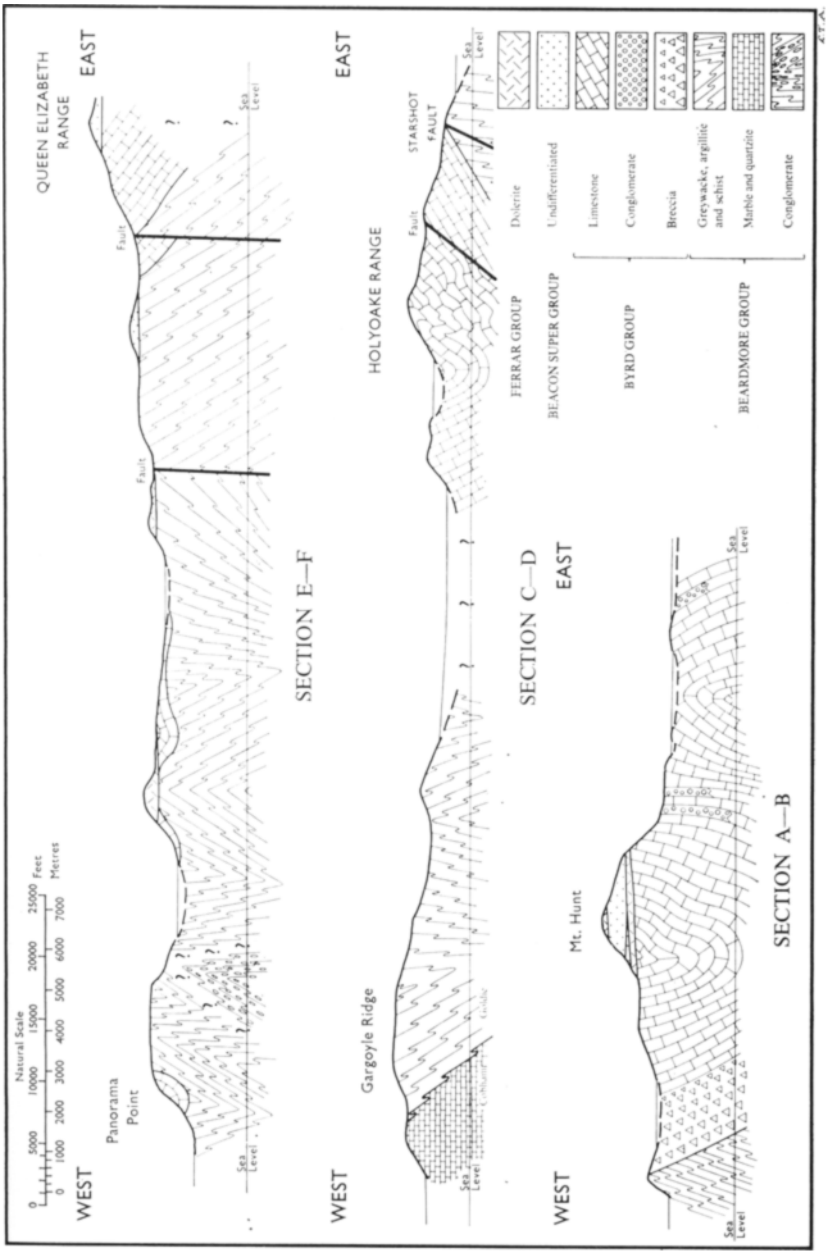

FIG. 3—Geological cross sections in the central Nimrod Glacier region.

TABLE 1—Type section of the Cobham Formation, south-western end of Gargoyle Ridge

Unit No.	*Description*	*Thickness (m)*	*Cumulative Thickness (m)*
	Goldie Formation		
80	Grey marble	9·1	509·3
79	Banded gneiss	9·1	500·2
78	Grey marble	3·7	491·1
77	Banded gneiss	6·1	487·4
76	Grey marble	22·0	481·3
75	Brown quartzite	7·6	459·3
74	Grey and yellow banded marble	8·9	451·7
73	Banded gneiss	4·6	442·8
72	Alternating marble and pelitic biotite hornfels	46·0	438·2
71	Banded gneiss	15·0	392·2
70	Dark grey schist	9·1	377·2
69	Grey, finely laminated marble	3·0	368·1
68	Grey, finely laminated quartzite	9·1	365·1
67	Pelitic biotite hornfels	3·0	356·0
66	Banded grey marble	0·9	353·0
65	Grey quartzite	7·6	352·1
64	Cream grey marble	15·0	344·5
63	Dark grey marble	3·0	329·5
62	Pelitic biotite hornfels	0·6	326·5
61	Grey marble	0·9	325·9
60	Pelitic biotite hornfels	9·1	325·0
59	Cream-grey marble	12·0	315·9
58	Saccharoidal yellow marble	0·6	303·9
57	Grey, quartzitic rock	4·6	303·3
56	Grey marble	4·6	298·7
55	Yellow marble	0·9	294·1
54	Grey marble	6·1	293·2
53	Massive grey hornfels	12·0	287·1
52	Grey schist	3·0	275·1
51	Grey marble	2·4	272·1
50	Pelitic biotite hornfels with lens of yellow quartzite halfway up unit	15·0	269·7
49	Massive hornfels	9·1	254·7
48	Grey marble	1·5	245·6
47	Massive banded grey quartzite	9·1	244·1
46	Yellow finely laminated quartzite	0·9	235·0
45	Grey massive quartzite	0·9	234·1
44	Laminated grey marble	0·6	233·2
43	Grey quartzite	0·6	232·6
42	Grey banded marble	0·9	232·0
41	Finely laminated cream quartzite	1·8	231·1
40	Grey quartzite	18·0	229·3
39	Finely banded pelitic biotite hornfels	15·0	211·3
38	Grey quartzite	15·0	196·3
37	Grey laminated hornfels	9·1	181·3
36	Well bedded grey quartzite with thin interbeds of pelitic biotite hornfels	18·0	172·2
35	Finely laminated grey quartzite	1·2	154·2
34	Yellow laminated marble	9·1	153·0
33	Grey quartzite	0·5	143·9
32	Finely laminated schist	12·0	143·4
31	Massive banded grey quartzite	9·1	131·4

Unit No.	*Description*	*Thickness (m)*	*Cumulative Thickness (m)*
30	Finely laminated cream quartzite	6·1	122·3
29	Pelitic biotite hornfels	4·6	116·2
28	Massive dark quartzite	30·0	111·6
27	Cream quartzite	1·8	81·6
26	Finely laminated schist	1·8	79·8
25	Banded grey marble	3·0	78·0
24	Massive grey quartzite	6·1	75·0
23	Massive dark hornfels	9·1	68·9
22	Pelitic biotite hornfels with thin interbeds of quartzite and schist	5·8	59·8
21	Grey quartzite	3·0	54·0
20	Grey marble	0·9	51·0
19	Interlayered thin beds of quartzite and schist	4·6	50·1
18	Schist	0·6	45·5
17	Grey quartzite	0·8	44·9
16	Dark massive hornfels	2·4	44·1
15	Grey quartzite	0·6	41·7
14	Grey marble	0·9	41·1
13	Massive dark hornfels	6·1	40·2
12	Grey drag-folded marble	0·6	34·1
11	Grey quartzite	1·8	33·5
10	Grey marble	0·3	31·7
9	Schist	0·6	31·4
8	Grey quartzite	4·6	30·8
7	Pelitic biotite hornfels	0·8	26·2
6	Grey marble	7·6	25·4
5	Green hornfels	0·2	17·8
4	Schist	2·4	17·6
3	Fine quartz conglomerate	0·2	15·2
2	Grey drag-folded marble	3·0	15·0
1	Banded, thinly bedded quartzite, schist, and pelitic biotite hornfels	12·0	12·0
	SNOW		

Relation to Underlying Beds

The Goldie Formation rests conformably on the Cobham Formation at the south-west end of Gargoyle Ridge. The highest member of the Cobham Formation is a bed of grey marble 9 m thick. A biotite hornfels bed 30 cm thick and containing quartz segregations forms the base of the Goldie Formation and lies conformably on the marble. This is overlain by 1 m of quartzite, 3 m of biotite schist and massive metagreywacke. No other contacts between the two formations were seen.

Content

The formation consists of metagreywacke and argillite and interbedded quartzite, with lesser quantities of marble and biotite schist. A 6,700 m sequence of isoclinally folded rock is exposed on each side of the Gray Glacier as the western limb of a syncline. Near the base almost pure biotite

FIG. 4—Drag folded cream and grey marble in the Cobham Formation, Gargoyle Ridge.

schist forms beds up to 50 m thick, which alternate with quartzite beds up to 90 m thick and also a few thin beds of marble. Higher in the sequence biotite schist becomes less frequent and forms thin beds in a sequence of argillite and poorly sorted sandstone. Several metres of finely bedded purple and grey siltstone overlie the sandstone; these in turn are overlain by biotite schist and marble with thin interbeds of fine quartz conglomerate. These members form the core of a syncline. The biotite schist and marble is strongly deformed, varies in thickness from 26 m to 230 m and may represent only two units repeated by folding. Some 30 m of a similar marble, also containing thin interbeds of fine quartz conglomerate and lying along the same strike line, crop out at the tip of the west ridge of Mt Hunt and lie unconformably beneath greywacke breccia of the Byrd Group.

On the south-east flank of the Holyoake Range the Goldie Formation consists of metagreywacke, quartzite, fine conglomerate and rare marble.

South of the Nimrod Glacier the Goldie Formation consists of metagreywacke and argillite and passes into feldspathic hornfels on the western flank of the Cotton Plateau and migmatites on Moody Nunatak. Near the junction of the Marsh and Nimrod Glaciers a 6 m bed of actinolite schist occurs within a quartzite and greywacke sequence. On a ridge to the east of the Gregory Glacier, three beds 30 cm to 4·6 m thick of isoclinally folded marble are interbedded with greywacke, argillite and purple, laminated fine sandstone showing truncated ripple-drift cross-laminations. No other beds of marble were seen south of the Nimrod Glacier.

Petrography

The original sediments of the Goldie Formation in the central Nimrod region differ slightly from those described by Gunn and Walcott (1962) from the Lowery Glacier. The most common sedimentary type is a muddy quartzite which has been altered to a quartz-sericite-biotite schist. Calcareous greywacke, pelite and limestone make up the rest of the formation.

The sediments have been altered to the albite-epidote hornfels facies over most of the area but a thin zone of feldspathised sediment and garnetiferous migmatite was found close to the small granitic intrusions at Panorama Point and Moody Nunatak.

The quartzite shows either a mosaic of granoblastic or, less commonly, nematoblastic quartz separated by sericite. The latter texture indicates that in places there has been some dynamic as well as thermal metamorphism. Biotite occurs regularly and is invariably porphyroblastic both in the quartzitic and pelitic rocks. In the latter biotite normally comprises 50% of the rock, the remainder being plagioclase, sericite and minute crystals of epidote. The greywacke rock is altered to give an assemblage of quartz, biotite, muscovite, calcite, some ill-defined plagioclase, sericite and opaque ore. The limestone has been recrystallised and some secondary biotite formed.

Environment of Deposition

Graded bedding is common in the greywacke and sandstone beds but there are few other sedimentary structures. Ripple-drift bedding occurs in fine sandstone beds on the ridge immediately south of Panorama Point and in the purple sandstone to the east of the Gregory Glacier. Graded bedding, poor sorting and the angularity of the sand grains suggest that much of the Goldie Formation accumulated as turbidite deposits in relatively deep water.

Correlation

Thermally metamorphosed greywacke and argillite is common in the surrounding region, having been recorded from the lower Nimrod Glacier region (Gunn and Walcott, 1962; Laird, 1963) and from the Queen Alexandra Range north of the Beardmore Glacier (Grindley, 1963). Similar metasediments have been described from the lower Skelton Glacier region (Gunn and Warren, 1962) and from northern Victoria Land (e.g., Rastall and Priestley, 1921; Harrington *et al.*, 1964). Metasediments from the Skelton Group (Teall Greywacke) have been correlated with the Goldie Formation by Grindley and Warren (1964). South of the Beardmore Glacier, McGregor (1965) correlated isoclinally folded dark pelitic hornfels and schist (Duncan Formation) with the Goldie Formation. In the Pensacola Mountains the Patuxent Formation (Schmidt *et al.*, 1965) consists of strongly folded graded sandstone and slate and is overlain unconformably by a sequence of calcareous rocks containing Cambrian fossils. Correlation of the Pensacola sequence with the Beardmore and Byrd Groups appears reasonable.

OTHER METASEDIMENTARY ROCKS

Approximately 1,000 m of conglomerate altered to the albite-epidote facies crops out discontinuously on either side of the lower Princess Anne Glacier. The pebbles and boulders, up to 65 cm but averaging 2 to 5 cm in diameter, make up approximately half the rock and are about 90% quartzite and 10% ferromagnesian-rich pebbles. They are set in a green schistose matrix of quartz, albite, sericite, biotite, muscovite, chlorite, actinolite and unstrained crystals of calcite. The conglomerate pebbles are well rounded but notably stretched, deformation increasing eastwards where the quartzite pebbles become flattened into thin plates or lenses (Fig. 5). The rock can only be distinguished macroscopically from a banded gneiss by the presence of the ferromagnesian-rich pebbles that have resisted stretching. A strong lepidoblastic texture has developed in the groundmass where the pebbles are stretched, but a granoblastic texture has developed elsewhere.

The quartzite pebbles have been completely reconstituted to form lenses of granoblastic quartz with unstrained calcite and a trace of sericite. Ferromagnesian pebbles show little microscopic evidence of deformation and are probably spilitic pebbles with siliceous secondary minerals filling the amygdales. Epidote and actinolite make up the bulk of the rock together with minor biotite, sericite, some doubtful pumpellyite and opaque ore. Quartz is the main constituent of the amygdales and calcite appears as a replacement mineral. In one pebble the epidote is confined to small circular or irregular shard-like areas rimmed with opaque ore and the actinolite is found only outside these bodies.

FIG. 5—Stretched conglomerate in the north bank of the Princess Anne Glacier.

The conglomerate was not recognised elsewhere in the central Nimrod Glacier area and the contact with Goldie Formation rocks is obscured by snow. Because the attitude of the beds and the mineralogy and metamorphic grade of the matrix are similar to Beardmore Group rocks further down the Princess Anne Glacier, the conglomerate is thought either to be a local member of the Goldie Formation or, perhaps, an infaulted member of the Cobham Formation.

AGE OF THE BEARDMORE GROUP

No fossils or fossil traces have been found in the Goldie or Cobham Formations. Archaeocyatha of late Lower Cambrian age (Hill, 1964a) occur in the Shackleton Limestone lying unconformably over the Goldie Formation and provide a minimum age. Grindley and McDougall (1969), on the basis of radiometric data, place the orogeny (Beardmore Orogeny) between the Goldie Formation and Shackleton Limestone as 620–680 m.y. so that the Beardmore Group cannot be younger than late Precambrian.

Byrd Group

The name Byrd Group was proposed by Laird (1963) for the predominantly calcareous sedimentary rocks in the upper part of the basement south of the Byrd Glacier. The group includes the fossiliferous Shackleton Limestone and Starshot Formation and their correlatives further north between the Starshot and Byrd Glaciers (Skinner, 1964). Locally developed quartzite and breccia discovered on the present expedition lying unconformably on the Beardmore Group and passing up into limestone are also assigned to the Shackleton Limestone within the Byrd Group.

SHACKLETON LIMESTONE

Name and Distribution

This formation was proposed by Grindley (1963) and defined by Laird (1963) to include the Cambrian limestone cropping out between the Byrd and Nimrod Glaciers and in the upper Beardmore Glacier. The present field study has shown that reconstituted limestone and marble containing fossil Archaeocyatha also extends south of the Nimrod Glacier to underlie the Cotton and Bartrum Plateaux and the flat-lying Beacon and Ferrar Groups on the Markham Plateau and Mt Counts; these rocks are here referred to the Shackleton Limestone. The formation was not seen further south. North of the Nimrod Glacier it forms the bulk of the Holyoake and Swithinbank Ranges.

Relation to Underlying Beds: the Early Cambrian Unconformity

The Shackleton Limestone lies unconformably on an unweathered surface cut across beds of the Goldie Formation. The contact was seen in five places. At the junction of the Errant and Nimrod Glaciers limestone containing sandy lenses rests on an undulating surface cut across bedded greywacke, argillite and sandstone (Fig. 6). At Panorama Point, and on the ridge north of Mt Lowe, metamorphosed Shackleton Limestone rests on an undulating surface

FIG. 6—Unconformity between the Goldie Formation and the overlying Shackleton Limestone, north-east end of Cambrian Bluff.

with up to 12 m of relief cut into drag folded schist. At the former there is an angular discordance of 40° but at the latter little discordance was noted. Two miles south-west of Mt Hunt, greywacke breccia at the base of the Shackleton Limestone buries a karst-like surface with a relief of up to 9 m formed in marble of the Goldie Formation. The angular discordance is about 20°. At the fifth site, just north of the mouth of the Princess Anne Glacier, the contact between cream quartzite of the Shackleton Limestone and the underlying schist and sandstone is irregular and appears unconformable. This contact is slightly brecciated and slickensided.

The significance of the contacts as part of a regional unconformity between the Lower Cambrian and Precambrian is emphasised by the abrupt change from probably deep water, redeposited sediments to shelf limestone, breccia and quartzite.

Content

The Shackleton Limestone consists mainly of grey, white, cream and black limestone and dolomite but also contains thick breccia and conglomerate and minor sandstone, shale and quartzite members. A summary of the facies relationships is shown in Fig. 7. The thickest sequence was seen in the Holyoake Range north of Mt Hunt where an 8,300 m section is exposed on the eastern limb of a major syncline (Table 2); the top and base of the the formation are obscured by ice.

At Cambrian Bluff, 4,400 m of Shackleton Limestone is exposed resting unconformably on the Goldie Formation. Approximately 4,000 m of grey limestone, commonly oolitic and including a few thin beds of conglomerate and sandstone, contains, half-way up the sequence, a 13 m bed of finely bedded pink and grey highly pyritized Archaeocyatha limestone. A cream limestone 460 m thick and whose top is not exposed forms the core of the Holyoake Syncline and is correlated with the 600 m cream limestone seen at the northern end of the Holyoake Range.

The basal members of the formation are exposed on the western limb of the syncline on the ridge west of Mt Hunt where they overlie the Goldie Formation which locally contains beds of marble. The basal 1,200 m of Shackleton Limestone is a breccia containing blocks of metagreywacke up to 65 cm in diameter and a small percentage of quartz and marble clasts, the latter becoming less common away from the unconformity. Shale and sandstone form rare interbeds within the breccia. Breccia and conglomeratic breccia, correlated with the upper part of the basal breccia on Mt Hunt, are exposed on the western flank of the Holyoake Range 8 and 27 km to the south-east, and contain limestone clasts and rare pebbles of quartzite, sandstone and a few conglomeratic boulders derived by local reworking (Fig. 8).

South of the Nimrod Glacier the Shackleton Limestone has been metamorphosed to a coarse-grained marble with some spectacular crystal roses of wollastonite appearing close to the dolerite on Mt Lowe. No thick sequences were measured although apparently continuous sections a few thousand metres

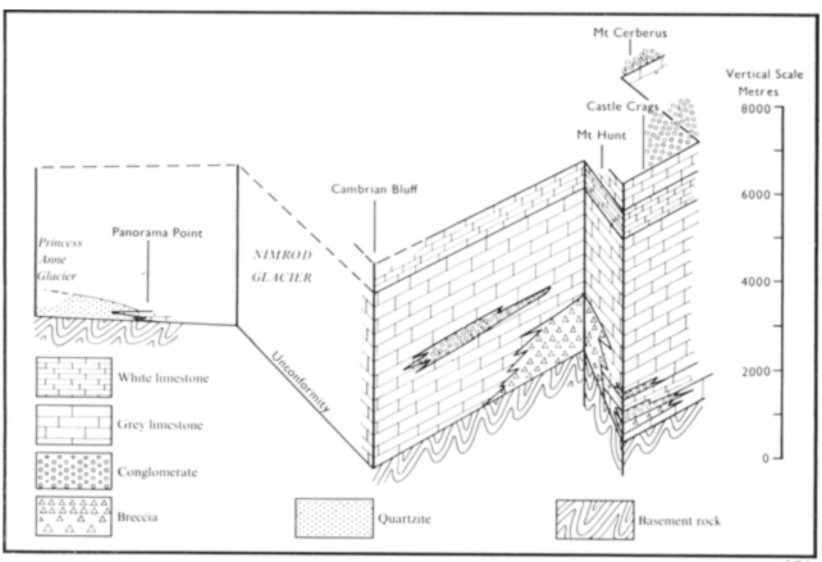

FIG. 7—Reconstruction of the facies relationships in the Shackleton Limestone before folding.

TABLE 2—Section Through Shackleton Limestone, Northern End of Holyoake Range

Unit No.	*Description*	*Thickness (m)*	*Cumulative Thickness (m)*
	SNOW		
11	Alternating beds of conglomerate and siltstone in 30 to 60 cm beds. Pebbles consist of subrounded quartz and greywacke in a matrix of sandstone	190	8,280
10	Arenaceous limestone	60	8,090
	SNOW	1,400	8,030
9	Conglomerate, pebbles consisting of limestone and shale	1,200	6,630
8	Light to dark-grey limestone, containing Archaeocyatha	600	5,430
7	Cream limestone	600	4,830
6	Well bedded light to dark grey limestone containing mud pellets and Archaeocyatha interbedded with shale in units up to 30 m thick	3,300	4,230
5	Limestone conglomerate. Grey limestone pebbles average 5 cm diameter but some boulders up to 65 cm. Large-scale cross-bedding in 65 cm to 1 m sets is characteristic, with notable grading. Irregular basal contact	90	930
4	Cream limestone with Archaeocyatha. Limestone pebbles, some with Archaeocyatha, in top 65 cm	250	840
3	Grey limestone	250	590
2	Orange-weathering conglomerate consisting of white limestone pebbles averaging 65 cm diameter, some with Archaeocyatha	250	340
1	Breccia composed of black and grey limestone fragments up to 1 cm diameter	90	90
	SNOW		

thick were viewed from a distance. Those that were measured indicate a distinct facies change south of the Nimrod Glacier, cream limestone or cream and grey quartzite without conglomerate forming the basal members of the sections (Fig. 9). Quartzite is absent on the eastern side of the Cotton Plateau where limestone lies directly on Goldie Formation, but thickens from an irregular bedded sequence 5 m to 13 m thick at Panorama Point to 500 m one and a half kilometres north of the mouth of the Princess Anne Glacier. Graphite was found in a bed 1 m thick in quartzite near the Princess Anne Glacier.

Petrography

The calcareous members of the Shackleton Limestone range from fine-grained limestone and quartzitic limestone to quartz dolomite. The remaining rocks comprise calcareous quartz arenite, pelite, limestone and greywacke conglomerate, all showing incipient recrystallisation, and quartz biotite schist.

FIG. 8—Limestone conglomerate and breccia near the base of the Shackleton Limestone 8 km south-east of Mt Hunt. Note the boulder of conglomerate to the left of the hammer handle.

The carbonates have all been recrystallised and have a fine saccharoidal texture. No difference could be determined petrographically between the limestone north and south of the Nimrod Glacier. Irregular veins of crystalline calcite, 0·01 to 0·05 mm wide, transect the rock and stylolites filled with opaque ore also appear. Finely divided hematite is present in some fine-grained limestones and gives the rock a red colour. Rhombic crystals of dolomite were identified petrographically, and the mineral was also recognised in saccharoidal carbonate rocks by chemical test and X-ray analysis. No pattern could be determined in the occurrence of the dolomite.

The fine-grained material within the clastic members of the formation has been recrystallised and sericite and some biotite formed. Cubes of pyrite up to 10 mm across have formed in pelites from Cambrian Bluff and, in a specimen from the south-east corner of the Cotton Plateau, strained crystals 1 mm across have been replaced in part by calcite.

Microbreccia from conglomerate in the basal section at Cambrian Bluff and the western side of the Holyoake Range contains angular fragments of metagreywacke typical of the Goldie Formation, large quartz grains and coarsely crystallised marble fragments. These are set in a matrix of biotite, muscovite, quartz and opaque ore.

Schist found in the Shackleton Limestone was collected from the junction of the Marsh and Nimrod Glaciers and from the spur to the west of Mt Hunt. Quartz-biotite schist from south of the Nimrod Glacier shows relict bedding, bands of elongate grains of biotite together with unstrained quartz and minor plagioclase alternating with bands of similar thickness of recrystallised calcite. The schist from near Mt Hunt comes from the breccia overlying the Goldie Formation and close to a dolerite sill. In thin section it is a microbreccia similar to those described above except that tremolite has developed in the matrix.

Environment of Deposition

The evidence available in the Shackleton Limestone suggests that it was laid down in shallow water. The limestone and sandstone are almost invariably parallel bedded with beds commonly 5 to 8 cm thick, but the conglomerate and breccia are usually massive or poorly stratified and in one instance cross-stratified. The conglomerate bed No. 5 (Table 2) is cross-bedded and shows evidence of strong local reworking, and possibly represents fore-reef deposits built up by the periodic avalanching of wave eroded reef material that had accumulated on the flank of a bioherm. The reworked fragments often contain Archaeocyatha, regarded as a reef builder in the lower Cambrian, and Hill (1964b, p. 235) stated that the most favourable depth for their growth was from 20 to 50 metres and that they are not known in sediments presumed to be deposited below 100 metres.

FIG. 9—Interbedded marble (light coloured) and quartzite (dark coloured) at the base of the Shackleton Limestone at Panorama Point.

Further evidence for a shallow-water environment may be provided by the presence, particularly in the Cambrian Bluff area and at the head of the Starshot Glacier, of oolitic limestone, which Newell *et al.* (1960) considered to be deposited most abundantly in the intertidal zone. Scour channels and oscillation ripples in the sand and shale members also imply a shallow-water environment.

Large scale disharmonic folds, affecting a few hundred metres of limestone but not affecting the beds above or below, and slump balls, sometimes several metres across, suggest penecontemporaneous slumping. The folds frequently have dislocated limbs and welded contacts, and balls of limestone of one colour are incorporated in limestone of a different colour.

The facies relationships as shown in Fig. 7 suggest a steep rising coastline not far to the west of Mt Hunt with less active uplift to the south. The great thickness of shallow-water calcareous sediment on the eastern limb of the syncline implies that deposition more or less kept pace with subsidence of the shelf. The repeated occurrence of reworked materials containing Archaeocyatha indicates that parts of the inner shelf were continually emerging and being eroded while the basin of deposition was subsiding possibly with outlying reef-building keeping pace with subsidence. The angularity and softness of the clasts preclude transport over large distances and they must have been derived from newly emergent land or a nearby growing reef. The picture is thus of an emergent coast rising more rapidly in some places than others and with an elongate Archaeocyatha bioherm parallel to the coast. On the offshore (eastern) side of the reef downwarp of the basin proceeded, sometimes outpacing sedimentation, accompanied by intermittent slumping.

Correlation

The Archaeocyatha-bearing limestone of the Holyoake and Swithinbank Ranges is probably continuous with that described by Skinner (1964) to the north of the Starshot Glacier. No Archaeocyatha were recorded from this area but lithologies are similar to those described in the present paper. The relationship to highly metamorphosed marbles and calc-gneisses in the Ferrar and Blue Glacier region west of McMurdo Sound (Koettlitz Group of Blank *et al.*, 1963) is not yet established but cylindrical siliceous objects resembling Archaeocyatha have been recorded from the marble and many of the metamorphosed calcareous rocks of the region may thus be correlatives of the Shackleton Limestone. The Anthill Limestone (Gunn and Warren, 1962) of the lower Skelton Glacier, although apparently unfossiliferous, has also been correlated tentatively with the Shackleton Limestone (Grindley and Warren, 1964).

Limestone containing Archaeocyatha was also collected in 1907, supposedly from Buckley Nunatak at the head of the Beardmore Glacier 160 km south of the Nimrod Glacier, by a party led by Sir Ernest Shackleton (David and Priestley, 1914; Skeats, 1916), and this has been correlated with the Shackleton Limestone by Grindley (1963). Young and Ryburn (1968) mapped the area at the head of the Beardmore Glacier and found that the Archaeocyatha limestone was confined to four small outcrops surrounded by ice immediately south of Mt Bowers; none is present on Buckley Nunatak.

Marble overlying metagreywacke in the Shackleton Glacier area 320 km south of the Nimrod Glacier has also been correlated with the Shackleton Limestone by McGregor (1965). Limestone which contains Cambrian fossils, and which unconformably overlies beds of sandstone and slate,, has also been reported from the Pensacola Mountains 1,450 km from the Nimrod Glacier on the Weddell Sea side of Antarctica (Schmidt *et al.*, 1965). Archaeocyatha limestone has been collected from moraine in the Whichaway Nunataks (Stephenson, 1966) and dredged from the Weddell Sea (Gordon, 1920), indicating that Cambrian limestone is extremely widespread.

Paleontology

Representatives of the Lower Cambrian phylum Archaeocyatha were found at numerous localities in the Holyoake and Swithinbank Ranges, in nunataks in the Mansergh Snowfield, in the head of the Starshot Glacier and in marble to the west of Mt Lowe. They were found both as individuals and in colonies most commonly in the grey limestone but also in the cream limestone. Individuals normally range from 1 to 5 cm maximum cup diameter with the stem up to 15 cm long. Some particularly large individuals measuring 15 cm across at the cup opening and up to 45 cm long were discovered together with some possible bryozoans in a small knoll 5 km south-east of Horseshoe Nunatak. As yet no systematic descriptions are available.

Doubtful organic trails were also seen on bedding planes in limestone one mile south of Horseshoe Nunatak.

STARSHOT FORMATION

Name and Distribution

The name Starshot Formation (Laird, 1963) was proposed for calcareous conglomerate, shale and sandstone exposed on the eastern side of the lower Starshot Glacier. Similar rocks crop out in the Surveyors Range and in nunataks east and south of the Mansergh Snowfield, and appear from aerial photographs to be continuous with the type Starshot Formation further north.

Relation to Underlying Beds

No contact was seen between the Starshot Formation and any other group of rocks. At the southern end of the Mansergh Snowfield the Starshot Formation crops out within 2·4 km of the Shackleton Limestone in the Holyoake Range; the contact is not exposed and may be faulted. Fragments of Goldie Formation rocks are found in the Starshot Formation and suggest an unconformity.

Content

Isolated exposures in the south-west part of the Surveyors Range and in the eastern and southern portions of the Mansergh Snowfield consist of an alternating calcareous sandstone/fine siltstone sequence with common coarse sandstone and fine conglomerate layers. The sandstone and conglomerate beds average 15 to 30 cm in thickness whilst the siltstone beds can be up to 65 cm thick. No coarse conglomerate beds or interbedded rhyolite or trachyte flows, present at the type locality (Laird, 1963, 1964), were seen.

Petrography

Only the coarse sandstone from the Starshot Formation was inspected. Subrounded fragments 2 to 3 mm across of metagreywacke, quartzite (some quartz grains showing strain extinction), marble and pelitic schist, all typical of the Goldie Formation, are set in a muddy matrix containing quartz, mica and plagioclase grains. Sericite shows incipient development in the matrix and limonite has been deposited around the coarser grains. The rock shows marked petrographic similarities with the rocks collected from the conglomerates at the base of the Shackleton Limestone at Cambrian Bluff and on the western side of the Holyoake Range.

Environment of Deposition

Sedimentary structures are commonly present but are of limited variety. The coarser beds are frequently graded in their lower portion, the graded part passing up into convolute laminae or, much more rarely, cross-laminations. These in turn are followed by a rapid gradation into finely laminated siltstone, the top of which is in sharp contact with the overlying graded sandstone bed. This sequence is typical of the deposits of turbidity currents. The similarity between the rocks of the Starshot Formation and the conglomerate of the Shackleton Formation both of which contain fragments of Goldie Formation, suggest that the Starshot and Shackleton Formations are correlatives. A solitary example of cross-lamination seen in the turbidite sequence suggests a northerly direction of provenance for the Starshot Formation. The increase in coarse conglomerate and the presence of local disconformities and oscillation ripple marks near the type locality (Laird, 1963) also suggests provenance from the north and a probable shallowing of the basin of deposition in this direction.

AGE OF THE BYRD GROUP

The age of the Shackleton Limestone is fixed as early to mid Cambrian by the presence of Archaeocyatha. A small collection of Archaeocyatha from beds thought to be within 1,000 to 1,300 m of the base of the formation near Station E in the Holyoake Range has been identified by Hill (1964a) as belonging to the lower Lena Stage (late lower Cambrian). The stratigraphically highest Archaeocyatha were collected at least 6,500 m above the base of the formation and thus the upper part of the limestone is unlikely to be older than early middle Cambrian. As noted earlier the Starshot Formation is regarded, at least in part, as being the same age as the Shackleton Limestone.

Granite Harbour Intrusives

HOPE GRANITE

Name and Distribution

Small granite bodies found near Panorama Point, on the Bartrum Plateau and at Moody Nunatak, all intruding Goldie Formation, are correlated with the Hope Granite (Gunn and Walcott, 1962) on petrographic grounds. Half Dome Nunatak was also mapped as granite although it was not visited. A

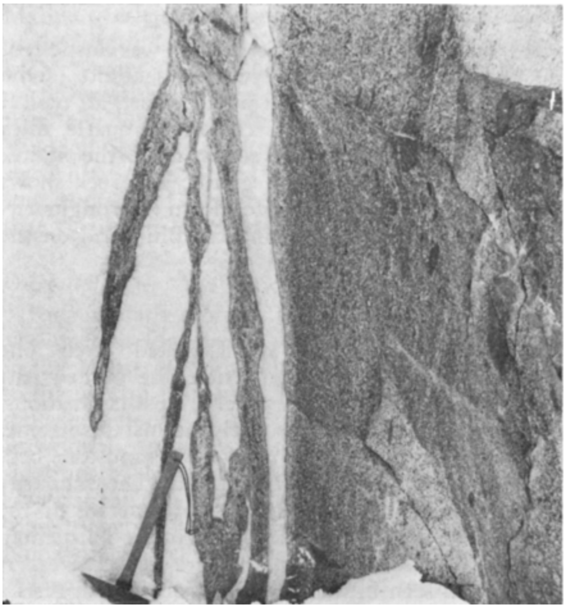

FIG. 10—Intrusive contact between xenolithic tonalite and marble of the Shackleton Limestone in the south bank of the Princess Anne Glacier.

xenolithic tonalite, also included within the Hope Granite, forms a large intrusion in the Shackleton Limestone on the north-east corner of the Bartrum Plateau (Fig. 10).

Petrography

Rock samples were collected for identification purposes only and no systematic petrographic study was made. The granite found in the central Nimrod region is similar to the typical Hope Granite described by Gunn and Walcott (1962). Microcline, oligoclase, biotite, quartz and some muscovite are the main constituents. Microcline-microperthite was not seen. Pink garnet enclosing light to dark green pleochroic biotite occurs in mobilized country rock in contact with granite at Moody Nunatak.

The tonalite from the Bartrum Plateau contains albite-oligoclase commonly showing oscillatory zoning, straw coloured to dark brown pleochroic biotite, dark green to brown pleochroic hornblende and quartz together with minor orthoclase, microcline and sphene. Nearer the contact with the marble the rock contains calcic augite, frequently uralitized around the edges, and biotite is absent.

Beacon Supergroup

The name Beacon, first applied by Ferrar (1907) to the flat-lying Devonian and younger sedimentary strata of southern Victoria Land, has since been extended to include all similar flat-lying sedimentary rocks of Eastern Antarctica (Harrington, 1958), and has recently been given supergroup status (Barrett *et al*, in press). Harrington (1965) subdivided the Beacon rocks into two groups, the Taylor Group of Devonian age, and the Victoria Group of Permian to Jurassic age. Both groups are represented in the area examined.

Rocks of the Beacon Supergroup occur in the upper parts of the high peaks of the northern Holyoake Range, as the summit rocks of the highest peaks of the Cobham Range, on the Chappell Nunataks and on Mt Hayter.

In the central Nimrod Glacier area the Beacon Supergroup is divided into five formations, all intruded by dolerite (Fig. 11). Four of these formations can be correlated lithologically with the formations erected by Grindley (1963) and his formation names are used here. An additional unit, the Castle Crags Formation, is proposed.

CASTLE CRAGS FORMATION

Name, Type Locality and Distribution

The name Castle Crags Formation is proposed for a sequence of shale and interbedded thin sandstone resting unconformably on the Shackleton Limestone. The type section (Fig. 12 and Table 3) 123 m thick, is at Castle Crags 10 km north of Mt Hunt. The only other exposure examined in this formation crops out on the north ridge of Mt Hunt. A dolerite sill occurs 30 m below the top of the formation in the type section and at the top of the exposure on the north ridge of Mt Hunt. West of Mt Hunt and Castle Crags the formation is absent and younger formations of the Beacon Group rest on basement.

Relation to Underlying Beds

The Castle Crags Formation lies on an undulating erosion surface cut across steeply dipping beds of the Shackleton Limestone. This surface is equated with the Kukri Peneplain of Gunn and Warren (1962).

Content

Five metres of horizontally bedded breccia comprising clasts of limestone, gneiss, granite and quartz in a clean sandy matrix lie on steeply dipping Shackleton Limestone. Finely laminated dark carbonaceous shale and siltstone overlie the breccia and comprise the bulk of the formation. The shale at the type locality is divided into three similar units between 24 and 37 m thick, these units being separated by coarse sandstone beds up to 6 m thick. Near the top of the formation there is a 30 cm bed of carbonaceous limestone. Clean quartzite overlying the topmost shale unit is correlated with the Alexandra Formation on lithology and stratigraphic position. The zone of transition is clearly seen as a uniform gradation over 3 m from cross- and parallel-laminated chocolate shale into strongly cross-bedded quartzite. The lithologies seen on the ridge north of Mt Hunt are similar but the units are thinner and several sandstone beds are intercalated with the shale. Cross-bedding is common throughout, and indicates currents from the south-east (Fig. 13).

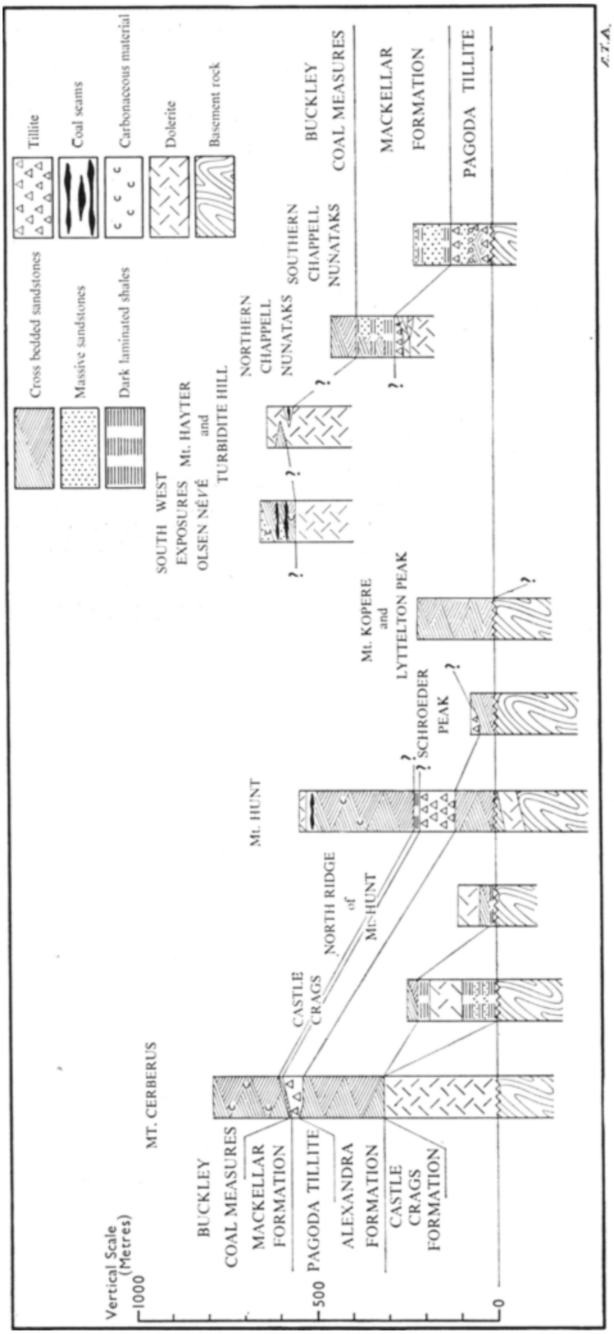

FIG. 11—Stratigraphic columns within the Beacon Group in the central Nimrod Glacier region.

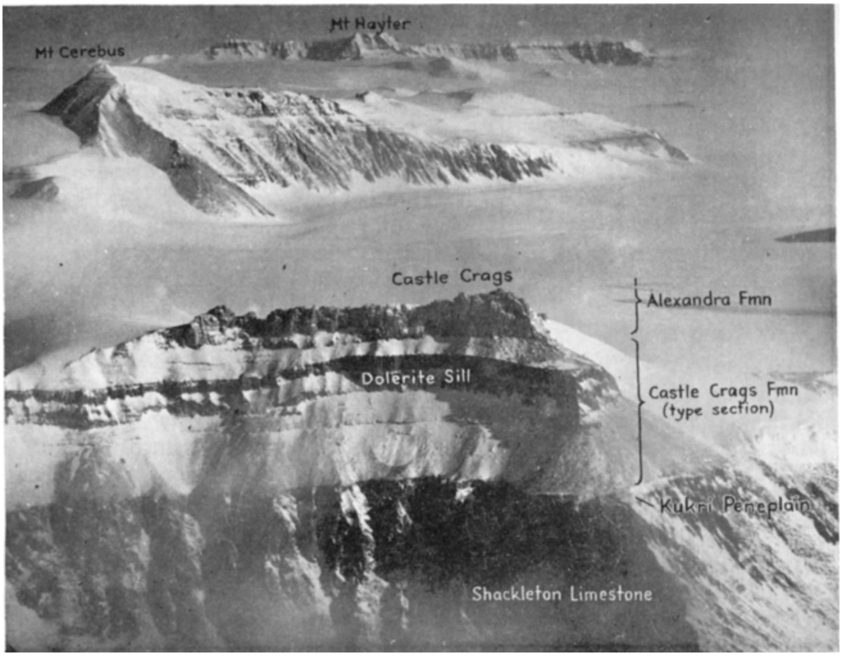

FIG. 12—Aerial view of the type locality of the Castle Crags Formation, looking west.

TABLE 3—Type Section of the Castle Crags Formation, Castle Crags

Unit No.	*Description*	*Thickness (m)*	*Cumulative Thickness (m)*
	Alexandra Formation		
11	Dark shale	37·0	122·6
10	Finely laminated carbonaceous limestone	0·3	85·6
9	Dark shale	0·6	85·3
	DOLERITE SILL, 90 m thick		
8	Massive coarse yellow sandstone	6·1	84·7
7	Dark shale	3·0	78·6
6	Massive coarse yellow sandstone	3·0	75·6
5	Finely laminated dark shale	40·0	72·6
4	Massive coarse yellow sandstone	3·0	32·6
3	Dark shale	24·0	29·6
2	Shale with thin beds of fine sandstone	0·6	5·6
1	Basal breccia	5·0	5·0
	UNCONFORMITY		
	Shackleton Limestone		

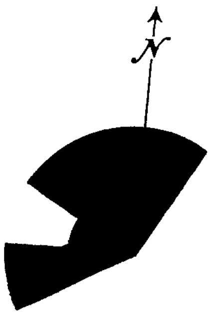

FIG. 13—Paleocurrent rose (9 readings) from cross-bedding in the Castle Crags Formation, North Ridge, Mt Hunt.

Environment of Deposition

The general fineness of the sediment comprising the bulk of the formation, and its carbonaceous nature, suggests mainly quiet deposition in a low energy continental or mixed environment. The lack of lateral continuation of facies, and the cyclic occurrence of the subordinate sandstone units probably reflects periodic influx of river-derived sediments into lakes or lagoons.

The absence of the formation to the west and the undulating nature of the Kukri Peneplain, the surface of which seems to rise rapidly to the south, suggests that the basin of deposition was of limited extent.

ALEXANDRA FORMATION

Name and Distribution

The name Alexandra Formation was proposed by Grindley (1963) for a 300 m sequence of clean quartz arenite immediately above the Kukri Peneplain in the Queen Alexandra Range. The quartzite in the type area is abruptly overlain by tillite and associated fluvioglacial sandstone, and a thick sequence of clean quartz arenite in a similar stratigraphic position in the Holyoake – Cobham Range area is correlated with this formation.

The transition from pale yellow clean quartz arenite into tillite and associated green and orange poorly sorted sandstone is seen in three sections: Mt Hunt, Mt Cerberus and Schroeder Peak (Fig. 11). Outliers of cross-bedded quartz arenite capping Mt Kopere and Lyttelton Peak are included in the Alexandra Formation on lithology and structural position. The thickness of the formation is very variable. It is absent on the Chappell Nunataks where tillite rests directly on Goldie Formation, and is at least 200 m thick on Mt Kopere 8 km away.

Relation to Underlying Beds

At all localities examined the base of the Alexandra Formation consists of cross-bedded quartz arenite which, except where it overlies the Castle

Crags Formation immediately north of Mt Hunt, rests directly and unconformably on Cambrian limestone and Precambrian basement rocks. The basal contact is everywhere sharp and clean with limonite-stained joint cracks being the only sign of weathering on the erosion surface.

Content

The Alexandra Formation was closely examined at Mt Kopere where an unbroken sequence of cross-bedded medium sandstone is exposed. Within the section coset units (terminology after McKee and Weir, 1953) up to 30 m thick occur. These are composed of medium scale planar sets of thinly cross-bedded strata interspersed with thinly bedded sets of parallel strata. Trough cross stratification sometimes occurs with trough units between 2 and 3 m long and up to 65 cm thick. Individual beds in all sets have an average thickness of 2 to 5 cm.

Units of calcareous quartz sandstone, from 65 cm to 1 m thick and consisting of one or two sets of indistinctly cross-bedded strata, occur sporadically within the formation. Individual beds are 10 to 15 cm thick. Finely recrystallised muddy calcite forms about 40% of the rock. No traces of shell fragments were seen and the original carbonate was probably micritic. Pebbles of quartz, greywacke and granite are scattered throughout the section. Fresh perthite and microcline and grains of quartz-albite-epidote metagreywacke are subordinate constituents. Epidote, garnet and biotite are common accessories.

Well defined meandering drag trails can be found on parallel-bedded surfaces of medium to fine sandstone. Burrows are not common; the most characteristic are straight infilled tubes about 1 cm in diameter and 8 cm long, which join one another in a loosely linked framework.

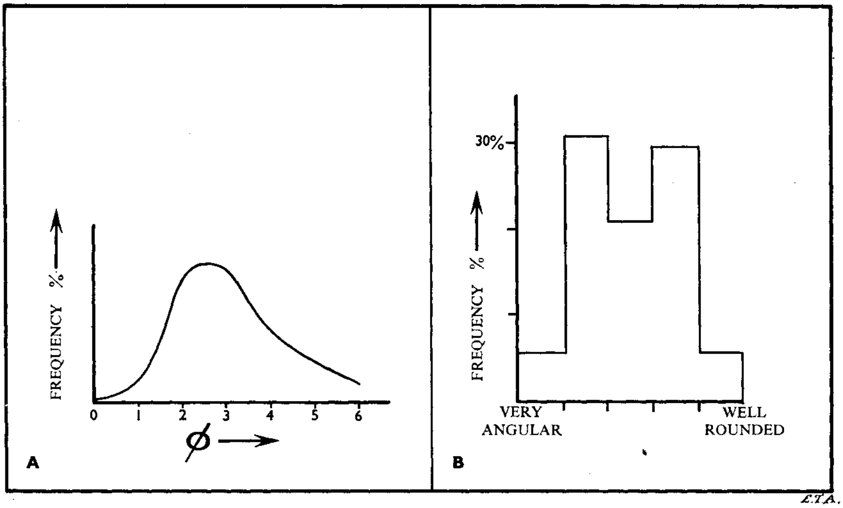

FIG. 14—Representative size and shape analysis of Alexandra Formation samples. A: Grain size distribution showing only moderately good sorting. B: Grain roundness distribution showing two peaks reflecting two separate grain populations.

The quartzite is only moderately well sorted (Fig. 14a). Grain shape analyses of the quartz fraction of two samples from the northern Holyoake Range show two shape populations (Fig. 14b), one being subangular and the other rounded to subrounded. These two populations may be derived from the two different rock types dominant in the basement; the more rounded fraction from the more distant Hope Granite and the more angular fraction from the nearby Goldie Formation. The presence of ragged metamorphic rock fragments which could have been derived locally from the Goldie Formation and rounded garnets which probably come from the granite support this view.

Paleocurrent direction measurements taken from trough axes in trough cross-bedded strata and the mean down-dip direction of beds within planar cross-bedded sets, indicate a regional flow towards the south-east (Fig. 15). Anomalous measurements from Mt Hunt and Schroeder Peak probably reflect the existence of local highs.

Environment of Deposition

The data available suggest that the Alexandra Formation was deposited in this area during submergence of a land of comparatively low relief. It seems likely that the landscape was gently undulating with a relief of perhaps a few hundred metres. The climate seems to have been dry as suggested by fresh microcline feldspar in the sand. Sporadic flooding in the source area associated with semi-arid climatic conditions may best explain the mixture of angular and comparatively poorly sorted sand with the population of rounded grains which together make up the sediment.

PAGODA TILLITE

Name and Distribution

The name Pagoda Tillite was introduced by Grindley (1963) for the tillite and associated fluvioglacial sandstone overlying the Alexandra Formation in the Beardmore region. There is a close similarity between the sequence in the Beardmore region and that in the Holyoake – Cobham Range area and the name Pagoda Tillite is extended to include the beds overlying the Alexandra Formation in the latter area. The upper boundary of the Pagoda Tillite in the Holyoake – Cobham Range region is taken as the stratigraphically highest horizon where tillite, or associated green or orange sub-mature sandstone, passes up into dark-coloured cross-laminated siltstone or, as on Mt Hunt, into massive quartzite. The formation crops out at Mt Hunt as a unit 110 m thick, on Mt Cerberus, on the Chappell Nunataks and as a small remnant at the top of Schroeder Peak (Fig. 11).

Relation to Underlying Beds

At Chappell Nunataks the Pagoda Tillite lies unconformably on rocks of the Beardmore Group and on Schroeder Peak it is seen to lie in a scour channel in the Alexandra Formation. The formation on Mt Cerberus, seen only from a distance, appears to wedge out to the north. The rapid variation in the thickness of the Alexandra Formation (Fig. 11) and the presence of scouring in at least one locality provides evidence of local erosion at the base of the formation.

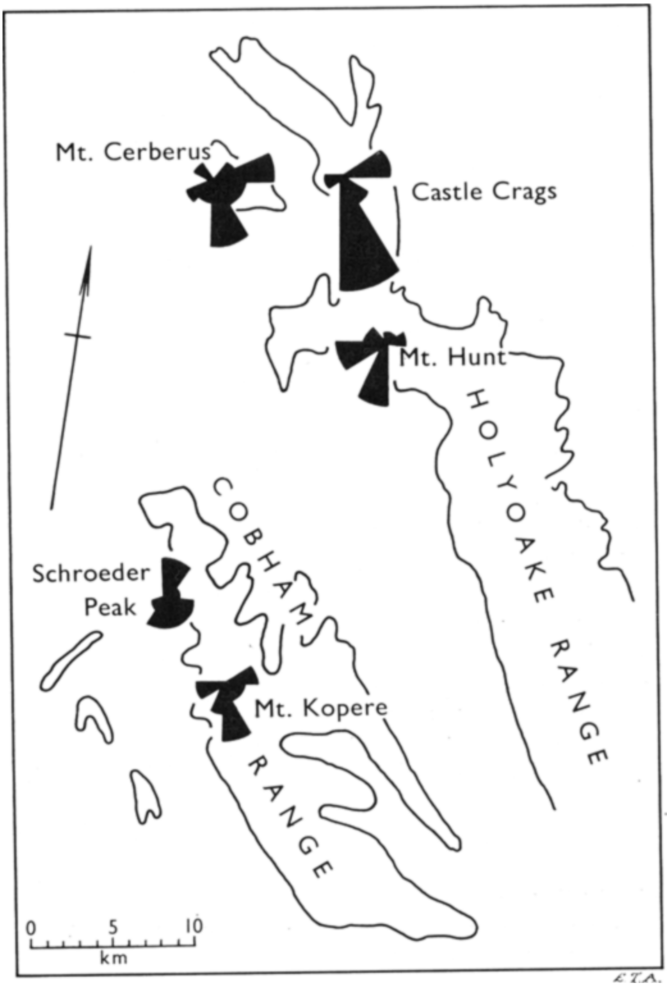

FIG. 15—Current azimuths in the Alexandra Formation.

Content

At the base of the formation in the southern Chappell Nunatak a moderately coarse massive tillite 5 m thick rests directly on metagreywacke of the Beardmore Group. No striations could be seen on the poorly exposed basal pavement in this exposure or on Mt Hunt. A small number of striated granite and metagreywacke blocks were found in the boulder beds at both localities. The Pagoda Tillite Formation includes sedimentary types ranging from coarse tillite through poorly sorted green silty sandstone to massive cream and orange sandstones which contain occasional angular cobbles.

The tillite forms massive unstratified grey-green boulder beds up to 12 m thick. No imbricate texture was seen. The matrix, comprising between 40% and 75% of the rock, is poorly sorted (σ about 1·5), and the particles are subrounded to angular. Pebbles and blocks vary greatly in size and shape, about 65% being rounded and the rest ranging from subangular to very angular. Sixty percent of the pebbles and blocks are granite, 25% metagreywacke and low grade greenschist and 5% small subrounded quartz pebbles. The remainder include cobbles of Shackleton Limestone, hornfelsic greywacke and pieces of arkosic Beacon Sandstone.

A sub-mature arkosic quartzite is interbedded with the tillite and forms units up to 20 m thick. These in places consist of cosets of planar cross-bedded sets of thin beds, each set being as much as 65 cm thick and 4 to 6.5 m long. More often the sand forms massive parallel beds up to 2 m thick. No burrows or other traces of organisms were seen in the sandstone. Thin conglomerates containing pebbles of very variable angularity are interbedded and isolated blocks up to 45 cm in diameter are scattered irregularly within sandstone beds.

Environment of Deposition

The thick massive beds, because of their lack of sorting, unweathered feldspar in the matrix and striated pebbles, are considered to have been deposited directly from glacial ice. The outwash streams sorted the interbedded sandstones and distributed thin uniform conglomerates. Stray boulders in the sandstone are thought to have been ice-rafted in proglacial lakes.

MACKELLAR FORMATION

Name and Distribution

A 150 m thick alternating sequence of dark carbonaceous shale and sandstone units overlies the Pagoda Tillite in the Beardmore region and has been named the Mackellar Formation by Grindley (1963). A similar succession of laminated carbonaceous shale and sandstone overlies Pagoda Tillite on Mt Hunt, Mt Cerberus and the Chappell Nunataks and the name Mackellar Formation is extended to include these rocks. The thickness of the formation varies from 115 m in the Chappell Nunataks to 13 m at Mt Hunt. There are no apparent breaks in the Mt Hunt succession and it is thought that the thick shale sequence in the south-east passes laterally north and north-east into carbonaceous sandstone. On Mt Cerberus the Pagoda Tillite passes up into sandstone and no shale was seen.

Relation to Underlying Beds

The Mackellar Formation lies conformably on the orange fluvioglacial sandstone which is the highest bed in the Pagoda Tillite.

Content

In its lower part the formation consists of dark ripple-drifted shale which occurs as cosets, up to 8 m thick, of parallel sets 0·5 to 4 cm thick of cross-laminae.

In sections from the Chappell Nunataks three shale units, each 8 to 13 m thick, are separated by cross-bedded medium-grained sandstone sequences up to 30 m thick. Quartz pebbles of variable angularity are present within the sandstone units. Only one shale unit is present in the Mt Hunt section and it is overlain by carbonaceous sandstone.

Within the shale units there is a rhythmic alternation between fine ripple-drifted carbonaceous siltstone and slightly coarser ripple-drifted silty fine sandstone. These rhythmites range from 10 to 90 cm thick but are normally about 20 cm thick. Current ripples in the siltstone indicate that currents flowed south and hence the implication of land to the north is consistent with the sand/shale distribution.

Environment of Deposition

The presence of thick shale units alternating with medium-grained sandstone suggests a lower energy environment than that of the Pagoda Tillite. The scattered angular pebbles, probably ice rafted, imply the continuation of glacial conditions. The rhythmites found within the shale unit closely resemble the "proglacial lake" cyclothems described from the Mackellar Formation in the Queen Alexandra Range (Grindley, 1963). A similar environment of deposition is envisaged for the deposits in the central Nimrod Glacier area.

BUCKLEY COAL MEASURES

Name and Distribution

The dark shale of the Mackellar Formation grades up into cross-bedded yellow and orange fluviatile sandstone containing in its upper part thin seams of coal. Greenish carbonaceous silt beds occur throughout. These beds comprise the youngest members of the Beacon Group in the Holyoake – Cobham Range area and are correlated with the Buckley Coal Measures (Grindley, 1963) on lithology and stratigraphic position. The formation forms the summit rocks of Mt Hunt and Mt Cerberus and coal measures are exposed in the Chappell Nunataks, in cliffs to the south-west of the Olsen Névé and as rafts in the dolerite near Mt Hayter (Fig. 11).

Relation to Underlying Beds

The Buckley Coal Measures lie conformably on the Mackellar Formation on Mt Hunt and the Chappell Nunataks. On Mt Cerberus the coal measures lie both on carbonaceous sandstone of the Mackellar Formation and directly on the Alexandra Formation where the Mackellar and Pagoda Formations wedge out. The exposures between Mt Hayter and Turbidite Hill are all large rafts within thick sills of dolerite.

Content

On Mt Hunt the basal 240 m of the formation is a cross-bedded coarse yellow sandstone containing carbonaceous fragments. This passes up into coal measures similar to those described by Grindley (1963) from the upper Beardmore Glacier and by Barrett (1965) from the Axel Heiberg area. At Chappell Nunataks 100 m of carbonaceous sandstone overlie the Mackellar Formation but no coal is present. Coal is also absent on Mt Cerberus. Thin mudflake conglomerates and pebble beds are interbedded with cross-bedded sandstones in some exposures.

The yellow-orange medium to coarse sand in the lower 240 m occurs as cosets of cross-bedded strata with lenses and thin parallel units of grey-green carbonaceous siltstone appearing irregularly between the coset units. Sets are usually parallel but some are wedged. The sand is moderately well sorted and is composed dominantly of subangular to rounded quartz with 15 to 30% feldspar which, although subangular to subrounded, is frequently kaolinitized. Variably cemented calcareous beds occur in the lower 65 m at Chappell Nunataks.

Current azimuths measured from cross-bedding show no consistent trend, but the dominant sources of supply appear to be to the north and west (Fig. 16). The medium scale cross-bedding indicates a medium to high energy environment but the sand is not highly mature in either sorting or rounding and chemically precipitated cement is negligible throughout.

The mineral suite indicates that the area of provenance was largely granitic with some metamorphic rock present. Microcline, including microcline microperthite, and oligoclase occur in subequal amounts and the quartz contains rods of rutile, rows of gas bubbles and crystal intergrowths similar to that of the Hope Granite. A few rounded garnets also occur together with accessory green biotite, epidote and sericite.

Samples from cross-bedded sands of the coal bearing or upper part of the coal measures have grain boundaries sutured during the contact metamorphism by the adjacent dolerite sills. The sand appears to be moderately to well sorted and composed of subrounded to rounded quartz and feldspar grains.

The coal bearing members of the formation are well exposed on Mt Hayter and the small nunataks east towards Turbidite Hill. The rocks comprise cross-bedded medium- and coarse-grained clean sandstone, cross-bedded and thin silty carbonaceous sandstone and siltstone (Fig. 17), and thin coal seams. A sequence containing convoluted and cross-laminated sandstone alternating with ripple-drifted or laminated muddy siltstone is well exposed at Turbidite Hill. In this sequence beds of silty sandstone show load structures and contain in their bottom few centimetres a contorted breccia derived from the underlying siltstone (Fig. 18). Laminated beds of fine sandstone passing up into ripple-drifted and convoluted siltstone are common. Each bed is overlain abruptly by a sandstone that is sometimes graded.

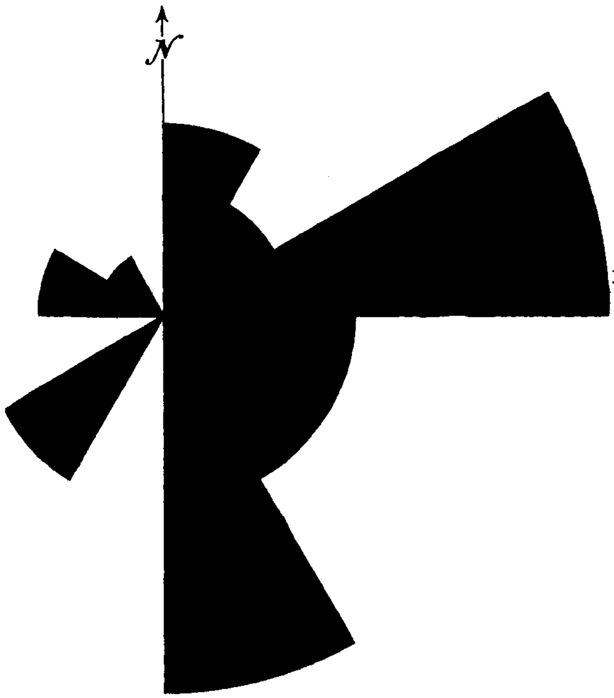

FIG. 16 —Paleocurrent rose (30 readings) from cross-bedding in the Buckley Coal Measures, from localities immediately west of Mt Cerberus and 15 km north of Turbidite Hill.

On Mt Hayter and on an isolated bluff located to the south-west of the Olsen Névé, cyclic sequences containing thin coal seams alternate with 25 to 30 m units of parallel sets of cross-laminated fine to medium sand.

Environment of Deposition

Since the sand grains are not markedly well rounded and deep weathering is absent, a nearby source of moderate relief is implied. Weathered feldspars and the presence of coal seams suggest that the climate had become warmer and was humid rather than arid. The absence of seat earths beneath the coal seams indicates that vegetable material drifted into its present position rather than grew in place. The cyclic occurrence of many of the coal seams suggests that the environment of deposition is best interpreted as deltaic.

Ferrar Group

FERRAR DOLERITE

Name and Distribution

Dolerite sills intruded into the Beacon Supergroup are correlated with the Ferrar Group (Harrington, 1958). The dolerite forms an extensive sill at the northern end of the Holyoake Range and crops out around the head of the Starshot Glacier west of the Holyoake Range. South of the Nimrod Glacier dolerite caps much of the Markham Plateau and occurs to the west on Mt Lowe and Mt Counts.

FIG. 17—Facies of the Buckley Coal Measures at Turbidite Hill. Cross-bedded medium sandstone passing up into ripple-drifted muddy siltstone. Overlying is carbonaceous sandstone containing a mud-flake breccia in its lower few centimetres.

A dolerite sill 100 m thick 90 m above the Kukri Peneplain extends from the northern end of the Holyoake Range south to Adams Bluff. The sill dips and thickens to over 350 m under Mt Cerberus where it rests on the Shackleton Limestone. It then wedges out until it is only 70 m thick 5 km west of Mt Cerberus where it intrudes Beacon Supergroup rocks. Several sills totalling over 750 m of dolerite are exposed on the Laird Plateau. Rafts of Beacon sediments lie between and within the sills both on the Laird Plateau and east to Turbidite Hill.

Petrography

A section through the 100 m Castle Crags sill shows little variation in mineralogy. The rock is an augite-pigeonite-labradorite dolerite with interstitial opaque ore. Small pegmatoid schlieren similar to those described by Gunn (1962) up to 0·8 mm long make up 12 to 15% of the rock between 10 m and 13 m from the top of the sill. Pegmatitic veins 5 to 10 cm wide in the same zone show a similar texture to the smaller schlieren. The pegmatite comprises radiating and micrographic intergrowth of orthoclase, quartz and albite-oligoclase. A pegmatite vein from Mt Cerberus contains crystals of pigeonite up to 7 mm long surrounding cores of inverted pigeonite together with some augite in a similar micrographic groundmass.

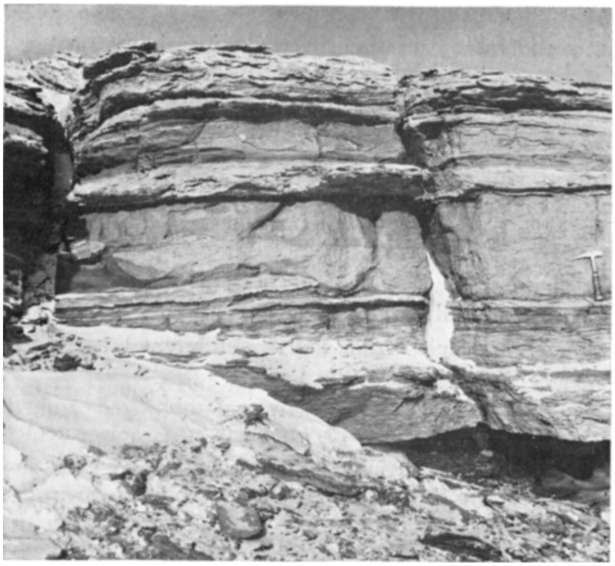

FIG. 18—Facies of the Buckley Coal Measures at Turbidite Hill. The hammer rests on a composite massive silty sandstone which has load structures at the base and contains convolute lenses of the underlying silty beds. Alternating with the sandstone is laminated, ripple-drifted and convoluted siltstone.

The top 130 m of a sill exposed at the base of Mt Hayter has an identical mineralogy to the Castle Crags sill. Schlieren were seen towards the top of the sill but no pegmatite veins were found. A hypersthene-rich layer is developed towards the base of the overlying sill which is over 300 m thick. The hypersthene is deeply embayed and rimmed with pigeonite. Higher in the section, augite is the dominant ferromagnesian mineral with some pigeonite also present. Pegmatitic schlieren are common in this sill also.

HOLYOAKE GABBRO

Name and Distribution

The name Holyoake Gabbro was given by Laird (1963) to small post-tectonic intrusions of basic rock found in the Shackleton Limestone. No new outcrops were mapped but collections were made from intrusions not previously visited between Cambrian Bluff and the Errant Glacier. One such intrusion about 130 m thick and 50 m wide is made up of alternate layers between 15 and 40 cm thick of medium and coarse grained gabbro. In the fine-grained beds the crystals measure 0·5 to 1 mm in diameter and in the coarse-grained beds 2 to 3 mm.

Petrography

There is considerable variation in the mineral assemblage within the Holyoake Gabbro. In the thin dike-like intrusions and on the chilled margins of the larger intrusions augite, frequently uralitized, is the dominant ferromagnesian mineral present. Elsewhere, hornblende and biotite comprise the bulk of the ferromagnesians with pyroxene making up only 1 to 2% of the rock. Labradorite and opaque ore appear in all phases of the rock together with varying quantities of biotite and some muscovite. Microcline and quartz appear in the dike rocks and quartz makes up 3% of the fine crystalline phase in the layered intrusion but is absent in the medium-grained beds. Quartz veins were also found near the base of the intrusion between well banded gabbro and a highly altered marginal gabbro.

A point count of samples from the two different types of bands within the layered intrusion is given in Table 4.

The feldspar throughout the gabbro is kaolinitized and the mica is chloritized in places. Calcite appears regularly as a replacement mineral.

The gabbro is saturated in silica and can be classed as a quartz-bearing hornblende gabbro. The sections cut from the larger bodies suggest that the gabbro is more closely related in bulk chemical composition to the Ferrar Dolerite than Gunn (*in* Laird, 1964) originally considered; it is therefore probable that the Holyoake Gabbro is a deeper seated equivalent of the Ferrar Dolerite.

Mineral Deposits

Ore Skarns

A massive dull micro-crystalline material crossed by 3 mm veins of micaceous hematite appears as a *lit part lit* injection over a 260 m section in the Shackleton Limestone below Station E, Cambrian Bluff. The base of the section is hidden by scree 65 m above the Nimrod Glacier.

In thin section, grains 0·1 mm across of fluorapatite, are surrounded by finely disseminated hematite. There is also minor quartz, epidote and possibly some wollastonite. Blue iron phosphates are associated with the ore and are visible on the contacts between the limestone and the intrusion.

TABLE 4—Point Count of Selected Samples from Coarse and Fine Bands in Layered Intrusion, Holyoake Gabbro, at Cambrian Bluff

	Coarse-grained gabbro	*Fine-grained gabbro*
Quartz	0	3
Labradorite	41	46
Hornblende	40	20
Biotite	18	29
Opaque minerals	1	2

Recent Hydrothermal Deposits

Realgar and orpiment veins a few centimetres thick are present in the Shackleton Limestone on the ridge immediately south of the junction of the Starshot and Ahern Glaciers, and travertine is being deposited downslope. Both the travertine and sulphides appear fresh and there is little sign of either being removed by weathering or erosion.

STRUCTURE

Folding

In the central Nimrod Glacier region the folded sequences of the Beardmore and the Byrd Groups are separated by an unconformity and are overlain by the flat-lying Beacon Group which rests on another widespread erosion surface, the Kukri Peneplain.

Both formations of the Beardmore Group appear to have suffered two periods of deformation. The earlier period resulted in recumbent isoclinal folding about subhorizontal axial planes and occurred prior to the deposition of the Byrd Group. The second period of deformation post-dates the deposition of the Byrd Group and caused open folds of large amplitude to be developed about subvertical axial planes.

Large scale isoclinal folding is common in both the Goldie and Cobham Formations but, because of the greater and more rapid lithologic variation in the latter, it is more readily recognisable in the Cobham Formation (Fig. 19). Axial plane schistosity is well developed in some of the thinner beds, particularly near the noses of isoclinal folds. In the few places where measurements could be taken the fold axes plunge at 15°–25° between 095° and 150°. Mesoscopic folding is common, the fold axes striking between 120° and 180° and plunging at shallow angles to the north or south. Most axes strike between 150° and 175°, conforming to the regional strike imposed by the second period of deformation.

The second period of deformation, which affected both the Byrd and Beardmore Groups, formed folds about horizontal north- and north-north-west-trending axes with subvertical to steeply east-dipping axial planes. Axial plane cleavage is present only locally. The Holyoake Syncline forms a major fold (Fig. 2) whose axis follows approximately the crest of the southern Holyoake Range from Cambrian Bluff north to Mt Hunt, beyond which its axial portion and western limb are not exposed. Several subsidiary folds of small amplitude and parallel trend were observed immediately to the west of the syncline. A section exposed across the syncline at Cambrian Bluff shows that many of the massive beds have been disrupted and impacted during folding. An anticline diverging from the inferred northern extension of the Holyoake Syncline can be traced from the southern side of the Starshot Glacier southwards as far as the southern limit of the Mansergh Snowfield. No folds could be traced into the Swithinbank Range where the limestone strata are vertical or subvertical.

FIG. 19—Recumbent isoclinal fold in the lowest members exposed of the Cobham Formation at the western end of Gargoyle Ridge, Cobham Range.

On Gargoyle Ridge, vergence of second period mesoscopic folds and axial plane cleavage indicates that the beds are on the western limb of a major syncline. This may be the north-north-west-trending syncline that passes along the crest of the ridge separating the Gray from the Prince Philip Glaciers. Its axis is subhorizontal and the axial plane dips steeply to the east. Graded beds and axial plane cleavage in strata occupying both flanks of the syncline show that the structure is right way up.

South of the Nimrod Glacier, the Shackleton Limestone exposed on the Cotton Plateau is deformed into a series of north-striking symmetrical folds with an average wavelength of approximately five km (Figs 20 and 3, cross section E–F). Further south on the Bartrum Plateau the rocks are also folded but because of the poorer exposures and widespread intrusion of tonalite, correlation of folds with those on the Cotton Plateau is difficult.

Folding in the Starshot Formation is highly complex, particularly in the north-eastern corner of the Mansergh Snowfield where folds plunge steeply about east-west axes and frequently have one limb overturned. At the southern end of the snowfield the beds strike uniformly north-west or north-north-west and parallel the strike of the adjacent Shackleton Limestone. They are vertical or overturned, dipping steeply to the north-east. No major fold axes were mapped in the Starshot Formation.

FIG. 20—A syncline in marble and quartzite of the Shackleton Limestone just below Panorama Point, Cotton Plateau. Geologists Range to the left of the photograph. Laird Plateau in the centre, distance.

Faulting

There are several major faults most of which parallel the regional strike of the Precambrian and Cambrian sediments.

South of the Nimrod Glacier two north-trending faults lie to the west of the Queen Elizabeth Range. The base of the Beacon Group is downthrown 750 m to the west by the easterly fault which cuts across the flank of the Queen Elizabeth Range, and is downthrown a further 450 m to the west by a fault passing up the Gregory and upper Princess Anne Glaciers. A small north-east-trending fault cuts across the south-west tip of the Cotton Plateau and separates Goldie Formation greywacke from quartzite of the Shackleton Formation.

North of the Nimrod Glacier at least three faults can be recognised. The rocks forming the Chappell Nunataks have been downthrown relative to those of the Cobham Range by a fault trending parallel to the range. To the east of the southernmost Chappell Nunatak the throw of the fault is 600 m but decreases to the north and dies out in the Olsen Névé. The north-north-west-trending Starshot Fault downthrows Shackleton Limestone to the west against Goldie Formation on the south-west corner of the Holyoake Range. The fault continues up the Errant Glacier and crosses the Mansergh Snowfield to pass down the lower Starshot Glacier. In the Mansergh Snowfield and in the Starshot Glacier it separates Shackleton Limestone from Starshot Formation. A third fault trends north-north-west at the head of Ahern Glacier. It is normal and dips at 55° to the east. On the south side of the glacier it is visible as a crush zone varying from a few centimetres to half a metre in width but it is probably a local feature as there is no sign of it continuing on the other side of the glacier.

An apparent fault dipping to the west cuts across Cambrian Bluff and separates planar beds of grey limestone intruded by iron ore from highly crumpled cream, pink and grey limestone lying in the core of the Holyoake syncline (Fig. 3).

The trends of all but two of these faults parallel the strike of the basement rocks. There is a notable change in the strike of both the faults and the bedding across the Nimrod Glacier and, as there is no evidence to suggest the continuation of any particular structure across the glacier, the northern and southern areas can be considered as individual blocks separated by the Nimrod Fault which passes down the glacier. This fault is downthrown to the north and has displaced the base of both the Shackleton Limestone and the Beacon Group by some 2,000 m.

ACKNOWLEDGMENTS

The authors wish to thank Dr J. B. Collinson of Oxford University and members of the New Zealand Geological Survey, the following people especially, for their help and criticism: Drs W. A. Watters and A. Wodzicki, and Messrs G. Warren and G. W. Grindley. Thanks also go to Mr D. Rainey of the New Zealand Lands and Survey Department; VX6 Squadron of the U.S. Navy; and Antarctic Division, D.S.I.R., New Zealand.

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