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DEPARTMENT OF ENERGY, MINES AND RESOURCES

BULLETIN 183

GEOLOGY OF ORDOVICIAN TO PENNSYLVANIAN ROCKS, M'CLINTOCK INLET, NORTH COAST OF ELLESMERE ISLAND, CANADIAN ARCTIC ARCHIPELAGO

H. P. Trettin

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By
H. P. Trettin

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PREFACE

To the regional geologist, the M'Clintock Inlet area of northernmost Ellesmere Island is remarkable in two respects: the intersection of two orogenic systems is exposed, the Innuitian system of the Canadian Arctic islands and northernmost Greenland, and a north-trending system aligned with the Lomonosov Ridge; furthermore, it is the only area within the magmatic belt of the Franklinian Geosyncline where a nearly complete late Middle Ordovician to Late Silurian succession is exposed. The description and analysis of these two features are the main contributions of this report.

The present study forms part of a systematic investigation by the writer of the lower Paleozoic Franklinian Eugeosyncline. It is also one of several published reports resulting from Operation Grant Land, an aircraft-supported reconnaissance project of the Geological Survey directed by R. L. Christie.

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

OTTAWA, January 15, 1969

BULLETIN 183 — Über den geologischen Charakter des ordovizischen bis pennsylvanischen Gesteins der M'Clintockbucht an der Nordküste von Ellesmere Island—das kanadische arktische Archipel

Von H. P. Trettin

Die Geologie eines Schlüsselgebietes der magmatischen Zone des Franklin-Geosynklinales wird beschrieben und analysiert.

БЮЛЛЕТЕНЬ 183 — Геология горных пород ордовикского до пенсильванского возраста включительно в МакКлинтокском заливе северного побережья о-ва Элсмира, Канадский Арктический архипелаг.

Р. П. Трэттин

Описывается и анализируется геология ключевого района магматической зоны франклинской геосинклинали.

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GEOLOGY OF ORDOVICIAN TO PENNSYLVANIAN ROCKS, M'CLINTOCK INLET, NORTH COAST OF ELLESMERE ISLAND, CANADIAN ARCTIC ARCHIPELAGO

Abstract

The geology of a key area of about 380 square miles within the magmatic belt of the Franklinian Geosyncline is described and analyzed.

Three major stratigraphic sequences separated by angular unconformities are exposed: (1) A Middle Ordovician or older, unfossiliferous, partly metamorphosed sequence, more than 1,000 feet thick, consists of keratophyres, cherts, slates, and limestones. (2) A late Middle Ordovician (Wildernessian) to Late Silurian (Ludlovian) sequence, more than 14,600 feet thick, consists of carbonates, keratophyres, and clastic sediments assigned to seven formations. These strata were deposited in non-marine to deep-sea environments, predominantly under shallow-water marine and shelf conditions. The clastic sediments, generally coarse grained and immature, were derived from volcanic, sedimentary, and metamorphic terranes of sialic composition in the present Arctic Ocean region that were periodically above sea level. Volcanism was limited to the Wildernessian – early Richmondian interval, and was probably an after-effect of Middle Ordovician tectonism. (3) A Middle Pennsylvanian and (?) younger sequence, more than 4,400 feet thick, consists of clastic sediments, limestones, and evaporites, deposited in non-marine to shallow-water marine environments. The clastic sediments were partly or wholly derived from nearby northerly sources.

Igneous intrusions differ widely in size, composition, and age. Altered dykes and sills of intermediate to ultrabasic composition are Middle Ordovician and/or older; a major, serpentinized, ultrabasic pluton is Early Devonian or older; small quartz dioritic intrusions are probably Early Devonian (390 ± 21 m.y.).

Southerly trending structures, continuous with the extreme southeastern flank of the Lomonosov Ridge, characterize the northwestern part of the area. Easterly trends, conforming with the predominant structural grain of northern Ellesmere Island, are typical of the south half. Terrains continuous with the Lomonosov Ridge were elevated relative to terrains to the east in early and middle Paleozoic times.

The intersection of the easterly and the southerly trending structures, marked by a structural trough and by ultrabasic intrusions, was repeatedly a site of crustal extension.

Résumé

L'auteur décrit et analyse la géologie d'une région-clef d'environ 380 milles carrés à l'intérieur de la zone magmatique du géosynclinal Franklinien.

Trois successions stratigraphiques importantes séparées par des discordances angulaires demeurent visibles: 1) Une succession partiellement métamorphisée, non fossilifère, de l'Ordovicien moyen ou plus ancienne, de plus de 1,000 pieds d'épaisseur, formée de kératophyres, de cherts et d'ardoises.

2) Une succession de la fin de l'Ordovicien moyen (Wildernessien) à la fin du Silurien (Ludlovien), de plus de 14,600 pieds d'épaisseur, formée de carbonates, de kératophyres et de sédiments clastiques attribués à sept formations. Le dépôt de ces strates s'est effectué dans des milieux allant du non marin à la mer profonde, mais surtout en mer peu profonde et sur des plateaux. Les sédiments clastiques, généralement à grains grossiers et non évolués, proviennent de terrains volcaniques, sédimentaires et métamorphiques de composition sialique s'étendant dans la région actuelle de l'océan Arctique, lesquels se trouvaient périodiquement au-dessus du niveau de la mer. Le volcanisme, limité à la période du Wildernessien au début du Richmondien, résulte probablement du tectonisme de l'Ordovicien moyen. 3) Une succession du Pennsylvanien moyen et (?) plus récent, de plus de 4,400 pieds d'épaisseur, comprend des sédiments clastiques, des calcaires et des évaporites déposés dans des milieux allant du non marin à des eaux peu profondes. Les sédiments clastiques proviennent, tout ou en partie, de sources avoisinantes.

Les intrusions ignées varient considérablement en dimension, en composition et en âge. Les dykes et les filons-couches altérés de composition intermédiaire à ultrabasique datent de l'Ordovicien moyen ou plus ancien; un immense pluton, serpentinisé, ultrabasique, date du Dévonien inférieur ou plus ancien; l'origine de petites intrusions dioritiques de quartz remonte probablement au Dévonien inférieur (390 $\pm$ 21 millions d'années).

Des structures à direction sud, longeant l'extrémité sud-est du flanc de la crête Lomonosov caractérisent la partie nord-ouest de la région. Des structures à direction est, en concordance avec la trame structurale prédominante du nord de l'île Ellesmere, constituent le genre typique de la partie sud. Les terrains longitudinaux à la crête Lomonosov étaient surélevés par rapport aux terrains formés à l'est au cours du Paléozoïque inférieur et moyen.

L'intersection des structures à direction est et sud, marquée d'une auge structurale et d'intrusions ultrabasiques, constitue chaque fois l'emplacement d'une extension corticale.

INTRODUCTION

Location and Accessibility

The area mapped, comprising about 380 square miles, lies along both sides of M'Clintock Inlet, a major indentation on the north coast of Ellesmere Island. Its geographic centre is approximately at 82°45′N latitude, 77°30′W longitude.

The region is moderately rugged, and transport is best accomplished by helicopter. There are a few landing places for small planes; a Piper Super Cub was used in 1965 and 1967. The nearest permanent settlement is Alert weather station on the northeastern extremity of Ellesmere Island, about 120 miles east of M'Clintock Inlet. This station is served regularly by military aircraft, which bring cargo either directly from southern Canadian airports or from Resolute Bay, the nearest civilian airport and harbour. Resolute Bay, in the southern Queen Elizabeth Islands, is 700 miles southwest of Alert.

Physical Features

The map-area includes both unnamed coastal ranges and parts of the Challenger Mountains. These and other ranges make up the Grant Land Mountains, which dominate northern Ellesmere Island.

The highest peaks, which occur in the southwest, rise to altitudes above 4,500 feet. Relatively high mountains and steep slopes have been formed in a major ultrabasic intrusion north of Ooblooyah Creek, in dolomite and limestone of the Ayles Formation, and in volcanic rocks of the M'Clintock Formation. Of the numerous small and intermediate ice caps, the largest is about 10 miles long. Most of these lie above an elevation of 1,000 feet, but in the north, some extend down to the sea. The most important valleys are those occupied by Taconite River, Ooblooyah Creek, and Egingwah Creek, all in the western part of the area. Vegetation is sparse and confined to valleys at low altitudes.

The north coast is fringed by ice shelves with their characteristic ridges and troughs. Ice in the inlets is smooth and partly disintegrates in late summer.

Previous Investigations

M'Clintock Inlet was discovered in 1876 by Pelham Aldrich, a member of the British Arctic Expedition of 1875–76 led by Sir George Nares. Aldrich, with a small party man-hauling a sledge, travelled from his ship, which was wintering east of the

MS. received May 1968.

present Alert weather station, along the north coast of Ellesmere Island to Alert Point. The same route was followed in 1906 by Peary, who proceeded to northern Axel Heiberg Island.

The first geological map and report describing this region was prepared by R. L. Christie (1957, 1964), a member of an expedition led by G. Hattersley-Smith. In 1954, that party explored the north coast of Ellesmere Island between Parr Bay (just southeast of Cape Aldrich) and the northwestern extremity of the island.

In the present area, Christie recognized three major geologic sequences: 1. a metamorphic basement complex, which he assigned to the Cape Columbia Group established by Blackadar (1954, 1960) and considered by him to be Lower Cambrian or older; 2. Ordovician sedimentary and volcanic rocks of the Franklinian Eugeosyncline assigned by Christie to two new reconnaissance units, the M'Clintock and Challenger Groups; 3. Pennsylvanian and Permian strata of the Sverdrup Basin resting unconformably on the older rocks. Because of the rapid pace of this expedition, Christie's observations were limited to coastal exposures.

Field Work

In the summers of 1965 and 1966 a team from the Geological Survey of Canada made reconnaissance studies in northeastern Ellesmere Island. This project, known as Operation Grant Land, was organized and directed by R. L. Christie (1966, 1967) and supported by fixed wing and rotary wing aircraft.

The writer was responsible for the study of the lower Paleozoic and (?) older unmetamorphosed rocks of the eugeosyncline; other major geological units of the north coast, such as the metamorphic basement complex assigned to T. O. Frisch, and the upper Paleozoic to Tertiary rocks of the Sverdrup Basin assigned to W. W. Nassichuk, were also briefly examined by the writer. In the summer of 1967 the writer concluded his studies with the support of the Continental Polar Shelf Project. During these three summers a total of 53 working days was spent in the area, making foot traverses from six light camps and one traverse by helicopter.

Definitions of terms used in this report to describe the size of carbonate crystals and the thickness of strata are given in Appendices 1 and 2 respectively.

Acknowledgments

The fossils were identified by M. S. Barss, M. J. Copeland, B. S. Norford, and R. Thorsteinsson, all of the Geological Survey of Canada; by the late W. A. Bell formerly of the survey, and by B. Mamet of the University of Montreal.

Several X-ray analyses were made by R. N. Delabio and several chemical analyses by S. Courville, both of the Geological Survey of Canada. Mrs. A. C. Semeon is responsible for some insoluble residue determinations, and P. Graham carried out some size analyses.

T. O. Frisch (then with University of California, Santa Barbara) accompanied the writer in the field in 1967, and also critically read those parts of the manuscript dealing with the igneous and metamorphic rocks.

The writer is indebted to L. K. Law of the Observatories Branch, N. Anderson of the Canadian Hydrographic Service, and E. F. Roots (Coordinator, Continental Polar Shelf Project) for transportation and hospitality in the field in 1967.

Table of Formations

SYSTEM	SERIES OR STAGE	GROUP	FORMATION	MEMBER	MAP-UNIT	LITHOLOGY	THICKNESS IN FEET
probably Pennsylvanian	Middle Pennsylvanian and/or younger				12	*Limestone breccia; minor limestone, conglomerate*	300 + (?)
					11	*Gypsum-anhydrite; minor sandstone, conglomerate, siltstone; some red beds*	0 - 580 ±
Pennsylvanian	Middle Pennsylvanian				10D	*Sandstone; minor limestone , siltstone, shale, gypsum-anhydrite, solution breccia; some red beds*	1,000 +
					10C	*Sandstone; minor siltstone, mudstone, conglomerate; some red beds*	550 +
					10B	*Shaly limestone, calcareous shale and mudstone; minor sandstone, conglomerate ; some red beds*	1,112 +
					10A	*Sandstone; minor conglomerate ; siltstone, shaly limestone, calcareous shale, pure limestone, dolomite*	750 +
angular unconformity							
Silurian	Ludlovian (?)				9C	*Sandstone; minor limestone, silty limestone, siltstone*	273 +
	lower Ludlovian and (?) upper Wenlockian		Marvin		9B	*Limestone; minor sandy limestone, calcareous sandstone*	600 +
	lower Ludlovian and / or Wenlockian				9A	*Sandstone, siltstone, shale*	400 +
not in contact							
Ordovician (?) and Silurian	Richmondian (?) Llandoverian and (?) Wenlockian		Imina		8	*Calcareous sandstone, siltstone; minor shaly limestone, limy shale, conglomerate*	760 +

Ordovician	Richmondian	Challenger	Zebra Cliffs	C	7C	*Shaly, silty, and dolomitic limestone; calcareous, dolomitic, and silty shale*	1,320 +
				B	7B	*Sandy, silty, argillaceous, and pure limestone; minor sandstone and siltstone; partly red*	1,800 + ?
				A	7A	*Dolomite, dolomitic limestone, limestone*	72
			Taconite River		6	*Sandstone, siltstone, conglomerate, shale, shaly and pure limestone*	950 + ?
			Ayles		5	*Dolomite, dolomitic limestone*	1,000 + ?
		M'Clintock		B	4	*Keratophyric flows; minor tuffaceous calcarenite, limestone*	290
	Lower Richmondian to Wildernessian			A		*Keratophyric flows and minor tuffs*	4,000 +
		Cape Discovery		D	3D	*Sandstone, minor conglomerate, siltstone; partly red; dolomite, volcanic flows*	1,500
				C	3C	*Calcareous siltstone (red), silty limestone*	1,050
	Wildernessian			B	3B	*Limestone, dolomite, in part sandy, silty, and argillaceous; minor keratophyric tuff*	300 + to 440 +
				A	3A	*Sandstone, conglomerate, impure limestone and dolomite, breccia*	0 to 223
angular unconformity							
Ordovician and / or older	possibly Lower to lower Middle Ordovician				2	*Keratophyric flows and tuffs; chert, argillaceous chert, slate; minor slaty impure limestone*	1,000 +
	contact relationships unknown						
					1	*Quartz-muscovite schist, quartz-muscovite-chlorite schist; minor marble*	

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STRATIGRAPHY

Three major sequences separated by angular unconformities are recognized in the M'Clintock Inlet area (*see* Table of Formations):

1. A pre-late Middle Ordovician sequence, possibly with an internal unconformity, composed of an older, metamorphic assemblage; and a younger, incompletely metamorphosed suite.

2. A late Middle Ordovician (Wildernessian) to Late Silurian (Ludlovian) sequence, divisible into seven formations and two unnamed map-units of formational rank.

3. A Pennsylvanian sequence divisible into three map-units of formational rank.

The most abundant rock types are pure and impure carbonates, keratophyric volcanic rocks, and relatively coarse grained, partly red weathering, clastic sediments; shale, chert, and evaporites are less abundant.

Late Middle Ordovician or Older

Map-unit 1

Lithology and Mode of Origin

Map-unit 1, comprising those rocks of the area that show complete regional metamorphism, has been examined by the writer at only a few localities.[1]

At the unnamed peninsula west of Bromley Island (Fig. 15, loc. 8), the unit consists of greenish weathering, quartz-muscovite-chlorite schist. Similar schist, but with less chlorite, is exposed about 2 miles west of the mouth of Ooblooyah Creek (loc. 1). Rusty weathering, quartz-muscovite-chlorite schist with carbonaceous matter is the predominant rock type at the head of M'Clintock Inlet. These rocks are in the greenschist facies of regional metamorphism (Fyfe and Turner, 1966), and probably represent original siltstone and shale. At the head of M'Clintock Inlet (locs. 2, 3), marble is associated with the clastic sediments. A typical specimen of this rock consists of medium- to coarse-grained, twinned calcite with a small amount of fine- to very fine grained quartz.

[1]A regional study of the metamorphic rocks on the north coast of Ellesmere Island by T. O. Frisch (1967) contains additional data on map-unit 1 in the M'Clintock area.

Contact Relationships, Age, and Correlation

At locality 1, map-unit 1 is unconformably overlain by Middle Pennsylvanian strata, and at locality 8, by Wildernessian beds of the Cape Discovery Formation. Therefore, the age of map-unit 1 cannot be younger than Middle Ordovician.

The contact relationships with map-unit 2 and the age of that unit are uncertain, but there is some evidence suggesting that map-unit 1 is older than map-unit 2 and that the latter is Early or early Middle Ordovician (*see below*).

The name Cape Columbia Group was given by Blackadar (1954) to metamorphic rocks between Cape Columbia and Cape Aldrich. A K-Ar age of 545 m.y. (Blackadar, 1960) suggests that the rocks of the type area recrystallized in Early Cambrian time or earlier. The rocks of map-unit 1 were assigned by Christie (1954) to the Cape Columbia Group because of their metamorphism. Whether map-unit 1 was metamorphosed by the same event that produced the Cape Columbia Complex, or by a younger Middle Ordovician orogeny remains uncertain (*see* pp. 61, 62).

Map-unit 2

Map-unit 2 (Fig. 1) comprises pre-late Middle Ordovician sedimentary and volcanic rocks that are distinctly less metamorphosed and probably younger than

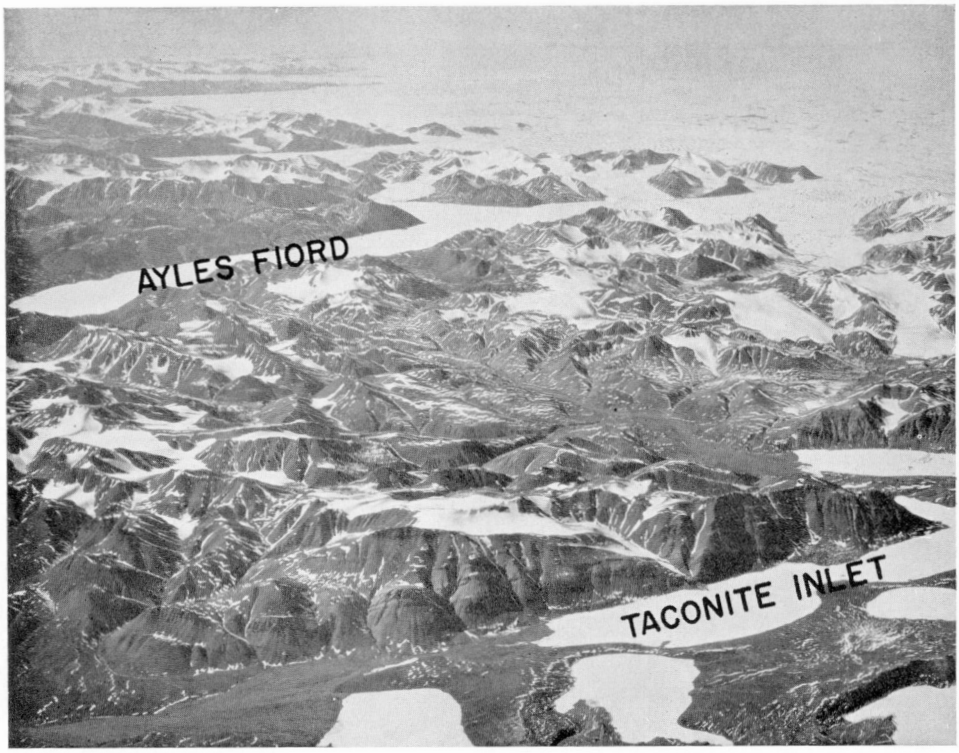


FIGURE 1. Oblique aerial view of map-unit 2 southwest of Taconite Inlet, westward. The structure is characterized by southwestward dipping low-angle faults and by sills forming conspicuous ledges. (RCAF 409L-231)

those of map-unit 1. Because of the intensely disturbed structure, the stratigraphy of the unit has not been worked out. Only one lithologic sub-unit has been distinguished so far: a volcanic assemblage on Bromley Island, informally designated map-unit 2a.

Lithology

Map-unit 2 consists mainly of volcanic rocks, chert, and limestone, in that order, with lesser amounts of admixed and interbedded argillaceous sediments.

Volcanic Rocks

The volcanic rocks are keratophyres of three main types: acidic flows and breccias, intermediate flows and breccias, and tuffs.

Acidic flows and breccias. These rocks weather from pale red to moderate red[1] and are aphanitic-porphyritic or aphanitic. The phenocrysts are mainly of K-feldspar (orthoclase and/or microcline) and, less commonly, of quartz, microperthite (Pls. I-5 and II-5), and sodic plagioclase, mainly albite. The groundmass consists of microcrystalline to cryptocrystalline aggregates of feldspar and quartz with submicroscopic phyllosilicates. Some rocks are relatively rich in "iron ore," mainly hematite, and certain flows have segregated into silica- or hematite-rich laminae so that they resemble cherty iron-formation or taconite. This impression is enhanced by sheared specimens that are coated with hematite of metallic lustre. However, the iron content of two typical specimens (5.12 and 5.9% Fe_2O_3 respectively) is too low to justify the terms iron-formation or taconite. Rusty weathering acidic volcanic rocks southeast of Bromley Island are rich in very finely crystalline pyrite.

The chemical and mineralogical composition of two characteristic specimens is given in Table I. These specimens are classified as acidic keratophyres because of their high silica content and sodic plagioclase.

Intermediate flows and breccias. The intermediate flow rocks weather pale red to pale brown, and commonly are aphanitic-porphyritic. The phenocrysts are mainly of albite and of chlorite pseudomorphous after pyroxene, amphibole, or biotite. One specimen contains remnants of biotite partly replaced by "iron ore" and chlorite. The groundmass is composed of sodic plagioclase, "iron ore," and semi-opaque, submicroscopic matter.

Tuffs and tuffaceous sediments. The tuffs and tuffaceous sediments are mostly laminated or thinly laminated (*see* Appendix 2 for terminology). They consist of acidic to intermediate pyroclastic materials, commonly with varying proportions of admixed or interbedded argillaceous and carbonaceous sediments, or microcrystalline calcite and dolomite. The pyroclastic material consists of feldspar, quartz, chlorite, altered chloritic shards, cryptocrystalline felsic aggregates, and "iron ore." All plagioclase crystals examined were sodic in composition. The colour of the strata

[1]Colours are named according to the chart by Goddard, 1963.

varies with their composition as follows: rocks rich in felsic materials are light grey; those rich in chlorite, greenish; those containing carbonates, yellowish; and those containing argillaceous and carbonaceous matter, light to dark grey. Most rocks have a slaty cleavage, and some have a schistosity. In the schistose rocks, the phyllosilicates have recrystallized to microcrystalline aggregates. Some relatively pure felsic rocks may be "welded tuffs."

Chert

The chert is pale to dark grey and weathers to shades of grey, or dusky yellow to moderate brown where authigenic pyrite is present. A thin section of a typical rock consists of laminae, about 0.3 to 1 mm thick, that differ in the concentration of carbonaceous impurities. Argillaceous matter, including muscovite, is mixed with the chert in varying proportions. Some beds are schistose, and the chert grains in them are stretched. In the specimens studied, the schistosity is nearly parallel with the bedding.

Limestones

The limestones examined are all slightly impure and schistose. Three specimens of phyllitic limestone studied in thin section consist mainly of microcrystalline carbonate grains that are tabular, subparallel with bedding, and range in grain size from about 5 to 50 microns. Vein-calcite in these rocks is coarser grained and prominently twinned. Impurities consist of silt-sized quartz, muscovite, chlorite, and carbonaceous matter. In one specimen, laminae of muscovite and chlorite form microscopic folds about 50 to 100 microns in half-wave length. Microcrystalline pyrite, which produces a yellowish stain on weathered surfaces, is scattered throughout the strata.

Sub-unit 2a

Most of Bromley Island is underlain by volcanic rocks, except for the southern part where phyllitic carbonates are exposed. At locality 7, on the east side of the island, about 1,000 feet of flows and tuffs is exposed. Similar volcanic rocks occur at localities 5 and 6. The stratigraphic position of sub-unit 2a is uncertain.

Contact Relationships

Map-unit 2 is unconformably overlain by the Cape Discovery Formation, the angular discordance ranging up to 90 degrees. Basic and ultrabasic dykes intrude the unit. The relationship with map-unit 1 is unknown; exposures west of Bromley Island are separated by outcrops of Ordovician rocks.

Metamorphism

Most rocks have a slaty cleavage, which is weakly defined in the volcanic flows and strongly defined in thinly stratified tuffs and sediments. In addition, some tuffs and sediments are schistose, the phyllosilicates, carbonates, quartz, and carbonaceous

matter in them having recrystallized in varying degrees. This schistosity, however, is probably confined to the vicinity of faults and shear zones.

The mineralogy of the volcanic flows is generally consistent with the greenschist facies, but may be the result of chemical alteration rather than metamorphism because volcanic rocks with the mineral assemblage of greenschists (keratophyres, spilites) are common in unmetamorphosed eugeosynclinal terranes.

Mode of Origin

The carbonates, cherts, and associated volcanic rocks were probably deposited in a marine environment. The authigenic pyrite and carbonaceous matter in limestone and slate indicate that the sediments of these beds were deposited in basins where reducing conditions existed below the sediment–sea water interface. Because of the association of chert with acidic volcanic rocks it is concluded that the silica in these sediments probably was originally of volcanic origin, although some of it may have passed through the tests of siliceous organisms, such as radiolarians. Radiolarian remains were not detected in the few thin sections of chert studied from map-unit 2, but they were seen in chert fragments of the Cape Discovery Formation obviously derived from map-unit 2 (Pl. I-1, 2).

Age and Correlation

Fossils have not been found in the sedimentary rocks of map-unit 2, and analyses of the strontium and rubidium content of the volcanic rocks indicate that these are not suited for isotopic age determinations. This unit cannot be younger than late Middle Ordovician, because it is unconformably overlain by Wildernessian strata of the Cape Discovery Formation.

Map-unit 2 is distinctly less metamorphosed than map-unit 1. Therefore, it represents either strata younger than the metamorphism of map-unit 1 or rocks older than that event that escaped thorough metamorphism because they were at higher crustal levels. In either case, map-unit 2 would be younger than map-unit 1. There is no evidence that the metamorphism in map-unit 1 dies out towards the outcrop area of map-unit 2, so that the possibility of map-unit 2 being equivalent to or older than map-unit 1 can be discarded.

The following relationships suggest that map-unit 2 may be Early to early Middle Ordovician. 1. Map-unit 2 is comparable to Arenigian and younger bedded cherts, graptolitic shales, and argillaceous limestones of the Hazen Plateau if one allows for typical facies changes from the magmatic belt of the Franklinian Geosyncline to the non-magmatic axial trough (Trettin, 1967, Fig. 1; 1968, map-unit 2). 2. Detritus, evidently derived from map-unit 2, appears first in Wildernessian beds of the Cape Discovery Formation. A thick, pre-Arenigian clastic sequence in the United States Range, on the other hand, which was probably derived from a source terrane that included the north coast of Ellesmere Island, is lacking in this material (Trettin,

1968, map-unit 1). 3. The volcanic rocks of map-unit 2 are similar to those of the unconformably overlying Cape Discovery Formation, and to lesser extent of the M'Clintock Formation. This suggests that the volcanic sequences above and below the unconformity are genetically related, and possibly of close age.

Late Middle and Late Ordovician

Cape Discovery Formation
(Map-unit 3)

A succession of limestone, sandstone, siltstone, dolomite, conglomerate, and subordinate amounts of volcanic rocks unconformably overlies map-units 1 and 2, and is overlain by the M'Clintock Formation of volcanic rocks. This sequence is here named Cape Discovery Formation after the northernmost point on the east coast of M'Clintock Inlet, where parts of it are prominently exposed. The cape was named by Pelham Aldrich of the British Arctic Expedition of 1875-76; H.M.S. *Discovery* was at that time wintering at Lady Franklin Bay, on the east coast of Ellesmere Island. The description given here is based on scattered exposures between the peninsula west of Bromley Island and Egingwah Bay. In this region four members, informally referred to as members A to D, are recognized.

Thickness and Lithology

Member A (map-unit 3A)

Member A consists of conglomerate and sandstone with a carbonate content, mainly dolomite, increasing in proportion progressively from base to top. Measured thicknesses range from a few feet to 223. The member has been observed only on the north end of the unnamed peninsula west of Bromley Island and at two localities on the island. The following type-section was measured at locality 8 (Figs. 2 and 15) at the unnamed peninsula.

Unit	Description	Thickness (feet)	Height above base (feet)
	Overlying beds: member B, Cape Discovery Formation		
2	Dolomite, sandy, and sandstone, dolomitic; minor dolomite and conglomerate; sandstones laminated; conglomerates laminated to thin bedded; clastic units mostly 2 to 3 feet thick, grade from conglomerate through sandstone up to dolomite, extend laterally for more than 50 feet, and show some large-scale cross-stratification at high angles	80	223
1	Basal breccia overlain by boulder-conglomerate with phenoclasts up to 3 feet; grades up to pebble-conglomerate and sandstone; poorly bedded unit	143	143
	Underlying beds: quartz-muscovite-chlorite schist of map-unit 1		

At locality 9 (Fig. 2) on the east side of Bromley Island the member is thinner, composed of finer sediments, and not so well exposed. The following section was measured there.

Unit	Description	Thickness (feet)	Height above base (feet)
	Overlying beds: member B, Cape Discovery Formation		
4	Limestone, medium light grey, greyish orange to pale brown-weathering, locally fossiliferous with brachiopods, bryozoans, echinoderms (GSC loc. 75417); contains dolomite, chert pebbles, sand, argillaceous and carbonaceous matter; beds about 2 inches thick	5	143
3	Covered interval, recessive	104	138
2	Conglomerate and breccia; phenoclasts mainly pebbles, but range up to 3 inches in diameter; phenoclasts are size-sorted; beds about a foot to 2.5 feet thick	4	34
1	Covered interval, recessive	30	30
	Underlying beds: volcanic rocks of map-unit 2		

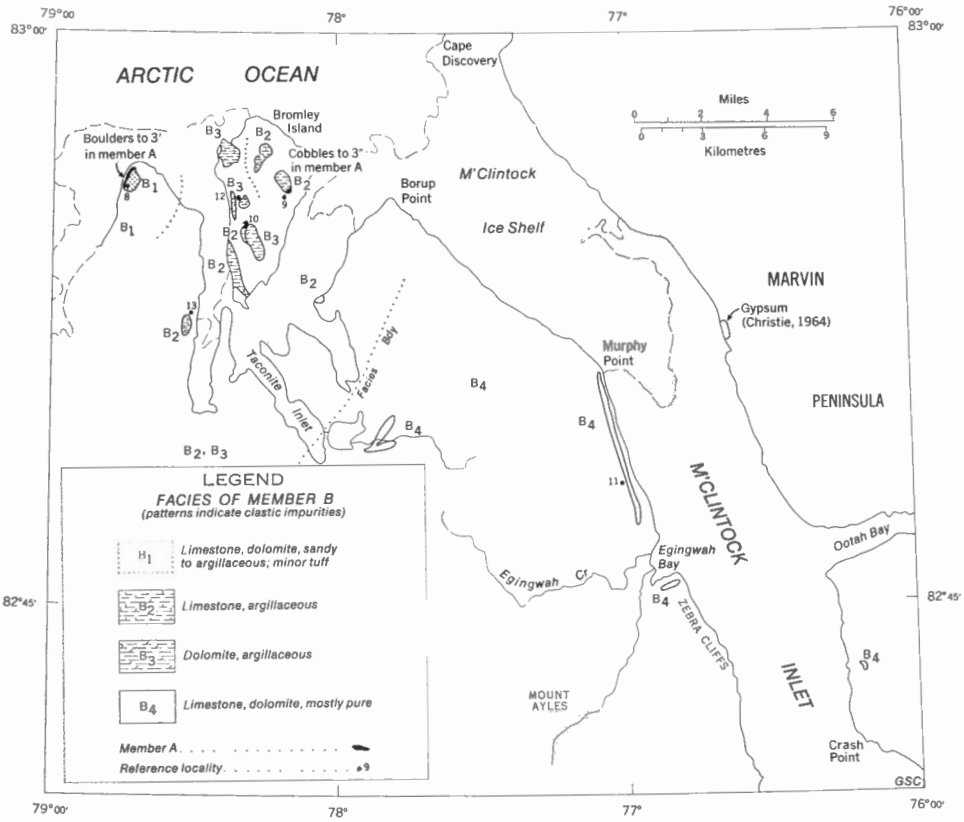


FIGURE 2. Cape Discovery Formation, members A and B, lithofacies.

At locality 10 (Fig. 2) on the island a few feet of laminated pebble-conglomerate and cherty and dolomitic limestone lies stratigraphically between volcanic rocks of map-unit 2 and member B of the Cape Discovery Formation.

The phenoclasts are mainly of chert or volcanic rock at all three localities. The chert is difficult to distinguish from cryptocrystalline felsic volcanic rocks. It is pure to argillaceous, and massive to schistose. Relatively clear, ellipsoidal nodules from about 0.10 to 0.13 mm in diameter, possibly of radiolarian origin, were observed in a few fragments.

Most volcanic fragments are acidic and have a microfelsitic or cherty texture. They are either massive, or brecciated and cemented by chlorite. Altered fragments consisting entirely of chlorite and "iron ore" are also common. Volcanic fragments of intermediate composition, consisting mainly of plagioclase microlites, chlorite, and "iron ore" are relatively rare, as are also fragments of dyke rock, composed chiefly of plagioclase. Only sodic plagioclase, i.e., albite or sodic oligoclase has been identified in these rocks.

The following rock types, in addition to chert and volcanic rock fragments, are common in the phenoclasts at locality 8: vein-quartz, quartz-muscovite-chlorite schist, phyllite, and coarse-grained altered rocks composed of intergrown carbonate and chlorite with interstitial "iron ore." The altered rocks are carbonatized ultrabasic or gabbroic rocks, fragmental volcanic rocks, or granulites.

The sand-sized material in the conglomerates, sandstones, and impure dolomites is composed mainly of chert, quartz, volcanic rock fragments, low-grade metamorphic rock fragments, and feldspar. Sodic plagioclase and microcline or orthoclase are present, but calcic plagioclase and sanidine have not been identified.

The detrital material is angular to rounded, and varies from predominantly poorly sorted to well sorted. Angular fragments of schist, similar to the underlying rocks of map-unit 1, are present in the basal strata at locality 8; angular, considerably fractured chert fragments, occur in the lowest exposed beds at locality 9. Some chert grains contain inclusion-free, rounded or ellipsoidal nodules that may represent radiolarian remains (Pl. I-1, 2).

Carbonate grains are mingled with the detrital material in the middle and upper parts of the member. At locality 8, the carbonate is mainly microcrystalline to finely crystalline, euhedral to subhedral dolomite. At locality 9, cryptocrystalline calcite and calcareous skeletal fragments are present in addition to microcrystalline dolomite.

Member B (map-unit 3B)

Member B, consisting mainly of limestone and dolomite, is characterized by variations in lithology and probably also in thickness. Complete sections have not been measured; minimum thicknesses of this member, established locally, are in excess of 300 and 450 feet respectively. Except for the few localities where member B is underlain by member A, it rests directly on map-units 1 and 2, and on the basic to ultrabasic intrusions cutting map-unit 2. Four lithofacies are distinguished (*see* Fig. 2).

Facies 1 (*map-unit* $3B_1$) represented only in the northern part of the unnamed peninsula west of Bromley Island, consists of limestone and dolomite with a con-

siderable amount of clastic impurities and some intercalated felsic volcanic rocks. Unlike the other three facies, facies 1 is difficult to distinguish on air photographs from map-units 1 and 2. The following incomplete section was measured at locality 8.

Unit	Description	Thickness (feet)	Height above base (feet)
	Fault contact		
3	Limestone, dark grey, greyish orange weathering, with fossils supported by cryptocrystalline to microcrystalline calcite; argillaceous, dolomitic, and partly sandy; thin-bedded; bedding vague; fracture cleavage	170	438
2	Acidic, probably keratophyric volcanic rocks, tuffaceous, partly welded; laminated to medium-bedded, with some large-scale cross-stratification at high angles	38	268
1	Dolomite, microcrystalline, medium grey; pale yellow, pale brown, and pale red weathering; calcareous, argillaceous, sandy, and pebbly; cephalopods, gastropods, trilobites, etc. (GSC loc. 75418) supported by cryptocrystalline to microcrystalline calcite; bedding vague, fracture cleavage	230	230
	Underlying beds: clastic and dolomitic sediments of member A		

Facies 2 (*map-unit* $3B_2$), exposed mainly on Bromley Island and southwest of it, consists of medium grey, slightly argillaceous limestone. The limestone weathers medium light grey to light olive-grey, is poorly bedded, sparsely fossiliferous, and cryptocrystalline to predominantly microcrystalline. It contains corals, gastropods, straight cephalopods, bryozoans, trilobites, and stromatoporoids that are supported by cryptocrystalline or microcrystalline calcite. Colonial corals are most abundant at localities 9 and 10. Locally, for example a short distance east of locality 12, at the base of the member, there are a few inches of medium light grey, greyish orange weathering, thinly laminated, slightly calcareous dolomite. Most dolomite crystals in these basal beds are 5 to 15 microns in diameter, but some range up to about 60 microns. The associated calcite is cryptocrystalline. This dolomite is more characteristic of facies 4 than facies 2, but could not be mapped separately because of its thinness.

Facies 3 (*map-unit* $3B_3$) consists of medium light grey, yellowish grey weathering, very finely crystalline to predominantly microcrystalline dolomite, which is bituminous, slightly argillaceous, and massive. Facies 3 locally interfingers with facies 2.

Facies 4 (*map-unit* $3B_4$) occurs mainly on the coast of M'Clintock Inlet. An incomplete reference section at locality 11, bounded at the base by a fault, is about 290 feet thick[1]. This facies is characterized by well-stratified,usually laminated limestones and dolomites that are almost devoid of fossils. Light grey, nearly pure limestone and

[1]Type sections have only been designated for those units of which a complete, well-exposed, and relatively undisturbed exposure is known. A reference section is given for those units of which only an incomplete, but otherwise satisfactory section is known. In the remaining units, the general area in which lithology, contact relationships, and minimum thickness were established serves as a substitute for the type section.

dolomite form the bulk of the member, but varicoloured, impure beds are also present: dark grey limestone and dolomite rich in carbonaceous matter occur in the lower part, and light green weathering, chloritic and argillaceous laminae, in the upper part. Birdseye dolomite (in the sense of Shinn, 1968, Fig. 7) was observed at various levels between Murphy Point and Egingwah Bay. At Murphy Point, veinlets of gypsum are present in dark grey, finely microcrystalline, bituminous dolomite near the base of the member.

Typical samples of pure limestone are composed of anhedral, finely microcrystalline calcite about 4 to 10 microns in diameter. One sample contains a few undetermined skeletal fragments, and another vaguely defined pellets about 0.1 to 0.2 mm in diameter. The dolomite specimens examined are composed of euhedral crystals, mainly about 5 to 30 microns in diameter.

A sample of birdseye rock consists of medium dark grey, wavy fragments of dolomite that are a few millimetres thick, up to several centimetres long, parallel to subparallel with bedding, and cemented by very light grey dolomite. The dark fragments consist of cloudy crystals of dolomite, about 5 to 10 microns in diameter, and the light coloured cement of clear dolomite crystals about 150 microns in diameter.

Argillaceous and chloritic specimens from the upper part of the member show recrystallization of the phyllosilicates to grain sizes of about 5 to 10 microns. The planes of schistosity form high angles with the bedding.

Gypsum on the east side of M'Clintock Inlet. A lens of gypsum, associated but not interbedded with volcanic rocks of the M'Clintock Formation, was mapped by Christie (1957, 1964) on the east side of M'Clintock Inlet opposite Murphy Point. The east side of the inlet north of Ootah Bay was not visited by the writer. Red beds, however, presumed to represent members C and D of the Cape Discovery Formation, and underlying carbonates presumed to represent member B, were seen from a distance at several localities between Cape Discovery and Ootah Bay. The gypsum mapped by Christie occurs within this discontinuous belt of outcrops of the Cape Discovery Formation, and probably forms part of it. There are, furthermore, some indications that the gypsum is related to facies 4 of member B. Veinlets of gypsum were observed in that unit at Murphy Point, and the entire unit seems to have been deposited in a shallow-marine to supratidal environment, closely related to the evaporitic environment (*see* Mode of origin).

Member C (map-unit 3C)

At the type section, locality 11, member C is about 1,050 feet thick, and consists of rhythmic alternations of thinly laminated to laminated silty limestone and calcareous siltstone (*see* Appendix 2). The limestone weathers light grey and the siltstone moderate red. Intraformational conglomerates are common in this unit. The red colour of the siltstone is due to hematite and to hematitic coatings on other minerals. The concentration of opaque material is fairly constant laterally, but varies vertically in a rhythmic fashion. In addition to the opaque material, the rocks contain silt-sized quartz and feldspar.

Member D (map-unit 3D)

At the type section, locality 11, member D contains about 1,500 feet of strata. It consists mainly of greenish red to moderate red, coarse- to predominantly fine grained sandstone with subordinate fine pebble-conglomerate and siltstone. Most of the unit is laminated, and some strata show current ripple-marks.

In the lower 300 feet of member D, a volcanic flow and varicoloured dolomites are associated with the clastic sediments; in the upper 100 feet, some impure greenish dolomite and reddish, silty limestone similar to the predominant rock type of member C are present.

The approximate volumetric composition, established by point count analysis, and some textural features of three typical samples of sandstone are given in Table III.

The volcanic fragments are mostly acidic and to a lesser extent intermediate in composition. Some felsic fragments are probably of pyroclastic origin. The feldspar, present as individual grains or in volcanic rock fragments, is sodic plagioclase, microcline or orthoclase, and microperthite. The sodic plagioclase is relatively clear, whereas the K-feldspar is sericitized. The quartz is generally clearer than is normal for metamorphic or plutonic quartz. This clearness, the common euhedral to subhedral habit, and the association with felsic volcanic fragments suggest that it is mainly of volcanic origin (Pl. I-4). The carbonate occurs partly as replacement of feldspar and volcanic fragments, and partly as individual, sand-sized crystals or microcrystalline aggregates. Both calcite and dolomite are represented. The opaque material weathers red, and is probably hematite. Because of the scarcity of clay matrix and the overall keratophyric composition, the sandstones are classified as keratophyric, volcanic arenites (*see* Gilbert, 1954).

The volcanic flow in the lower part of the member is similar to flow rocks in the basal part of the M'Clintock Formation (Table II). The dolomite is finely microcrystalline to finely crystalline and contains admixed or interlaminated silt-sized quartz, feldspar, volcanic fragments, and chlorite.

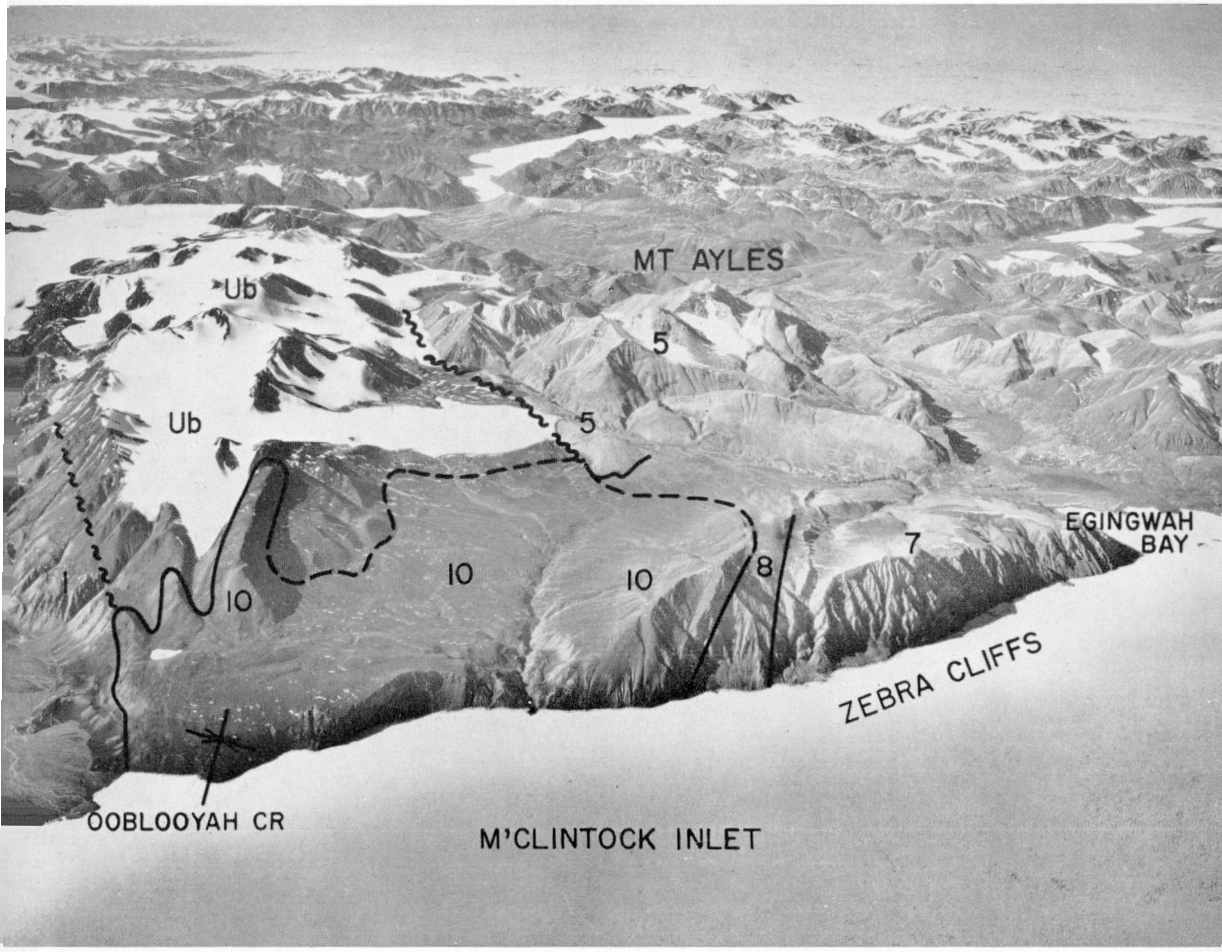
Contact Relationships

The Cape Discovery Formation rests with angular unconformity on map-units 1 and 2 and on the basic and ultrabasic intrusions cutting map-unit 2.

At locality 8, the structural discordance is not conspicuous, but there is a marked difference in metamorphism, the strata of map-unit 1 showing low grade regional metamorphism and the Cape Discovery Formation only a slaty cleavage. At locality 9, the angular discordance at the base of the Cape Discovery Formation ranges up to 90 degrees. At both localities the basal strata of the formation contain angular fragments of the immediately underlying rocks, which shows that the contact relationship is a normal stratigraphic one and not the result of faulting.

At locality 12, nearly horizontal dolomite of member B overlies steeply dipping basic to ultrabasic dykes that cut the volcanic rocks of map-unit 2 (Figs. 3 and 4).

The upper contact of the Cape Discovery Formation with the M'Clintock Formation is best exposed between Murphy Point and Egingwah Bay, and has been examined at locality 11. This contact is well defined and conformable.



Oblique aerial view of the west side of M'Clintock Inlet between Egingwah Bay and Ooblooyah Creek, westward. The Zebra Cliffs Formation (7) and the overlying Imina Formation (8) are exposed on the Zebra Cliffs in the right foreground. An ultrabasic intrusion underlies the relatively high mountain on the left. The ultrabasic rocks (Ub) are in fault contact on the left with pre-Wildernessian metamorphic rocks (1), and on the right, in the background, with light coloured carbonates of the Ayles Formation (5). Dark coloured Middle Pennsylvanian sediments (10) that rest unconformably on the metamorphic rocks, the ultrabasic intrusion, and the Imina Formation form a structural trough. (RCAF T404R-15)

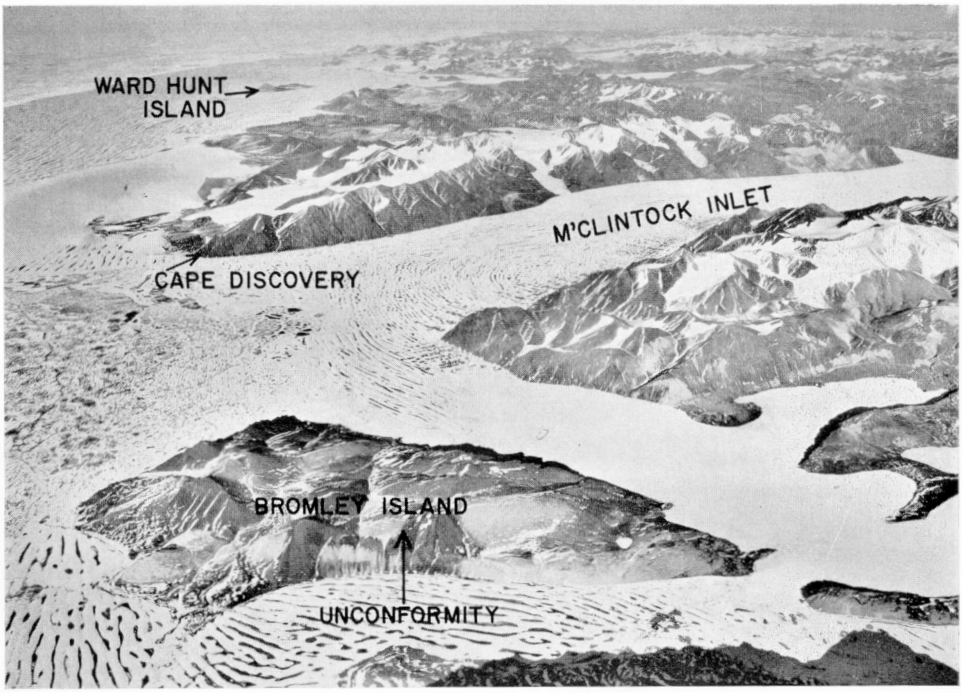


FIGURE 3. Oblique aerial view of Bromley Island, eastward. Note angular unconformity between underlying steeply dipping intrusions (dark) and overlying, nearly horizontal, dolomite of the Cape Discovery Formation. (RCAF T408L-2)

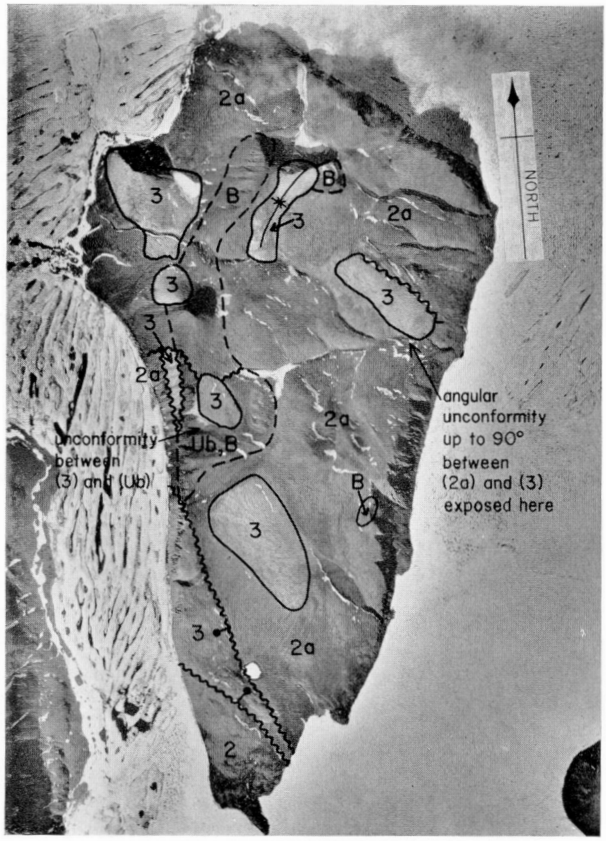


FIGURE 4

Vertical aerial view of Bromley Island. The numbers and symbols correspond with those of the geological map (Fig. 15). (Spartan A16 690-124)

Mode of Origin

Member A

The basal strata of this member probably represent a slightly reworked regolith; this is concluded from the angular shape of some fragments, and from their similarity with the underlying basement rocks. The uppermost beds, fossiliferous and rich in carbonates, are marine. The middle part of the member, characterized by conglomerates and large scale crossbedding, may represent fluviatile and deltaic environments transitional between those in which the basal and uppermost beds were laid down.

Variations in the size of the coarsest clasts indicate that the source of most sediments must have been a short distance to the west or northwest of locality 8, where boulders up to 3 feet in diameter occur (Fig. 2). The source terrane included cherts and keratophyres comparable to map-unit 2 and schists comparable to map-unit 1 with some intrusions and quartz veins.

The limited distribution of member A is probably due to deposition in erosional channels and other depressions of the Middle Ordovician land surface, and not to a disconformity between members A and B. This conclusion is based on the gradational nature of the contact and the probable Wildernessian age of both members.

Member B

Facies 1. During the deposition of this unit an upland source of clastic sediments persisted in the region west or northwest of locality 8 (*see* Fig. 2), but within the map-area detrital deposition was subordinate to carbonate formation. The fauna from locality 8, which includes trilobites and anthozoa, suggests a shelf environment.

Facies 2. Only a small proportion of argillaceous matter reached the depositional site of facies 2 which, judging from the coralline fauna (*see* GSC locs. 75419, 75420, and 69206), lay on a marine shelf. The absence of primary structures and of textures attributable to wave- or current-action indicates protected conditions, and the preservation of carbonaceous matter shows that reducing condition existed below the sediment–sea water interface. The microcrystalline texture is probably the result of recrystallization of an originally cryptocrystalline sediment (*see* Folk, 1959, 1962, 1965).

Facies 3. The massive dolomite of this facies probably formed by replacement of strata of facies 2 after their burial.

Facies 4. The lack of fossils and the laminated nature of the limestones and dolomites in this facies point to evaporitic coastal environments, e.g., lagoons, and supratidal flats. In such environments lime muds can form by direct precipitation (*see* Cloud, 1962) and dolomites by penecontemporaneous replacement (*see* Pray and Murray, 1965). The stratification was not appreciably disturbed either by burrowing organisms or by waves and currents.

Several possible modes of origin may be proposed for the laminated, planar type of birdseye structures observed. They closely resemble structures produced by artificial and natural drying of lime sediment, and are probably due to alternate

wetting and drying in the intertidal to supratidal environment (Shinn, 1968, p. 218, and Fig. 7). Another possible explanation is the removal and subsequent replacement by dolomite cement of originally interlaminated algal mats (Klovan, 1964) or evaporites.

Member C

Member C, which is laminated and unfossiliferous, probably originated in a very shallow and protected environment. It is similar to facies 4 of member B, but differs from that unit by the presence of silt and absence of dolomite. The silt probably indicates an uplift in the borderland to the north or northwest, movements that culminated during the deposition of member B. The rhythmic vertical changes in silt content may be related to rhythmic, possibly seasonal, climatic changes in the source area that resulted in increases and decreases of sediment transport. The breccias observed in this member are probably due to desiccation.

Member D

The association of cross-stratified clastic sediments with dolomite suggests near-shore deltaic environments of deposition. The red colour was probably inherited from the red weathering, keratophyric volcanic rocks of map-unit 2, which seem to have been the main source of the sediments.

Age and Correlation

Fossils from members A and B were identified by B. S. Norford as follows:

Member A

Locality 9 (Fig. 2). 3.7 miles northeast of the south tip of Bromley Island.

GSC loc. 75417
trimerellid brachiopod

Age: Middle Ordovician (probably Wilderness) to Late Silurian (Ludlow).

Locality 10. 2.3 miles north of south tip of Bromley Island.

GSC loc. 75416
rhynchonellid brachiopod

Age: probably Ordovician to Permian.

Member B

Locality 8. 0.8 mile southeast of unnamed cape just west of Bromley Island, about 140 feet above the base of the member.

GSC loc. 75418
bifoliate bryozoan
straight cephalopod
colonial coral
undetermined trilobite

Age: Middle Ordovician to Middle Devonian.

Locality 9 as described above.

GSC loc. 75419
echinoderm fragments
straight cephalopod
gastropod
undetermined corals

Age: Middle Ordovician to Permian.

Locality 10 as described above.

GSC loc. 75420

tetradiid and undetermined corals

Age: Middle Ordovician (Ashby) to Late Ordovician (Richmond).

Locality 13. Peninsula west of Bromley Island, west and southwest of south tip of Bromley Island; partly from outcrop, and partly from a continuous stream of debris of the same lithology (facies 2) extending from this locality for about 1½ miles to the north.

GSC loc. 69206

bryozoan
echinoderm debris
stromatoporoids
straight cephalopods
Maclurites sp.
Palaeophyllum sp.

Age: Ordovician, probably Barneveld or Wilderness.

In 1954, R. L. Christie (1964, p. 21) collected fossils from talus probably a little northwest of locality 8, which were identified by G. W. Sinclair as follows:

GSC loc. 24720

crinoid fragments
Anthozoa, genus indeterminate
Sowerbyella sp.
Liospira sp.
Illaenus sp.
Gonioceras sp.
Richardsonoceras sp.
Lophospira sp.

This collection was assigned by Sinclair to the Wildernessian stage. Christie, who was able to make only a very brief reconnaissance of the environs, supposed that the source beds were correlative with the Challenger Group of M'Clintock Inlet. The present mapping, however, shows that the fossils came from member A or B, most likely member B, of the Cape Discovery Formation.

The most diagnostic fossil in all these collections is *Gonioceras*, which suggests that member B is Wildernessian. The other identifications, though of less value, are not inconsistent with this assignment. The presence of a trimerellid brachiopod in member A shows that this unit, too, probably is not older than Wildernessian.

No fossils were found in members C and D. Their possible range is Wildernessian to Richmondian because they are overlain by the M'Clintock Formation, which contains Richmondian fossils in the upper part.

Members A and B are almost certainly correlative with strata on Judge Daly Promontory provisionally designated as Formation A (Norford, 1966); with the Bay Fiord Formation of central Ellesmere Island (Kerr, 1967); and probably also with member A of the Baillarge Formation of northwestern Baffin Island (Trettin, 1965). The first two are known to be of Wildernessian age; the last undoubtedly is of late Middle Ordovician age, and probably also Wildernessian. All three correlative units are composed mainly of impure carbonates deposited in near-shore and coastal

environments, with local evaporites present in the Bay Fiord Formation. Furthermore, member A of the Baillarge Formation, like the Cape Discovery Formation, is bounded at the base by a hiatus corresponding to the hiatus at the base of the Tippecanoe sequence of the stable interior of the North American continent (Sloss, 1963).

Formation A of Judge Daly Promontory, the Bay Fiord Formation, and member A of the Baillarge Formation are all overlain by massive limestones that are relatively pure and that contain mainly the so-called Red River fauna, although Norford states (op. cit.) that a slightly older fauna may be present in the lower part of Formation B on Judge Daly Promontory.

Neither these overlying limestones nor the Red River fauna are present in the M'Clintock Inlet area and, therefore, the correlation of members C and D is uncertain. It seems, however, that members C and D of the Cape Discovery Formation, because of their clastic content, are more closely related to the impure carbonates of Formation A on Judge Daly Promontory and to the Bay Fiord Formation than to the overlying pure carbonate units.

The volcanic rocks of the M'Clintock Formation, on the other hand, may be correlative with these slightly younger or overlying limestones. Therefore, the contact between the Cape Discovery and M'Clintock Formations is tentatively correlated with the contact between Formations A and B on Judge Daly Promontory (Norford, op. cit.), between the Bay Fiord and Thumb Mountain Formations on central Ellesmere Island (Kerr, op. cit.), and between members A and B of the Baillarge Formation. If this correlation is correct, then members C and D of the Cape Discovery Formations are also of Wildernessian age.

M'Clintock Formation
(Map-unit 4)

The name M'Clintock Group was given by Christie (1957, p. 12; 1964, p. 17) to an assemblage of mainly volcanic rocks with intercalated subordinate sediments best exposed on the coast of M'Clintock Inlet. The term "group" was used in a reconnaissance sense. As the M'Clintock Group cannot be divided into mappable sub-units, it is here re-defined as a formation. The M'Clintock Formation comprises the predominantly volcanic and associated subordinate sedimentary rocks that lie stratigraphically between the red beds of the Cape Discovery Formation and the carbonates of the Ayles Formation.

The lithology, contact relationships, minimum thickness, and age of the formation were established south and west of M'Clintock Inlet, between Borup Point and Egingwah Creek.

Locally two members are distinguished, informally referred to as members A and B.

Thickness and Lithology

Member A

Part of a section of member A at locality 14 comprises about 4,000 feet of strata. This section was not measured directly, but the thickness was inferred from photo

interpretation combined with structural observations from Bromley Island. The member consists mostly of flows and flow breccias, and lesser amounts of tuff. The rocks weather brownish grey with a shade of purple, reddish brown, or pale olive. The tuffaceous rocks are well stratified and partly laminated, but in the flow rocks bedding is difficult to discern. Some flows show pillow structure.

The flow rocks consist mainly of sodic plagioclase, chlorite, and "iron ore," and some also contain small proportions of K-feldspar, quartz, and clinopyroxene. The plagioclase occurring as phenocrysts is partly twinned and zoned, and ranges in composition from calcic oligoclase to sodic albite. Most pyroxene, and any amphibole and biotite that may have been present originally, have been replaced by chlorite and "iron ore;" only in one specimen are remnants of clinopyroxene preserved. In addition, the rocks are partly altered by carbonate, sericite, and epidote.

Both petrographic studies and the chemical analyses in Table II indicate that these rocks are keratophyres of intermediate composition, i.e., andesites with sodic plagioclase. According to Turner and Verhoogen (1960, p. 57), the intermediate volcanic rocks range in silica content from 52 to 66 per cent. Specimen 1 is near the acidic end of this spectrum, and specimen 2, which is more characteristic of the formation as a whole, is near the basic end.

Member B

Member B was observed only at locality 15, about 3 miles west of Egingwah Bay, just north of Egingwah Creek, where the following type section was measured on a south-facing slope.

Unit	Description	Thickness (feet)	Height above base (feet)
	Overlying beds: dolomite of Ayles Formation		
3	Calcarenite, tuffaceous, medium grey, light olive-grey weathering, very fine to coarse-grained, laminated, well sorted; composed of cryptocrystalline to microcrystalline, partly skeletal limestone fragments, and lesser proportions of chloritized shards	20	289
2	Volcanic flows, green and brown weathering, as in member A.....	253	269
1	Limestone, medium light grey, yellowish grey weathering, microcrystalline to cryptocrystalline; bedding generally poor, but fine, wavy laminations, possibly of algal origin present; containing a small proportion of sandy and silty impurities, and very sparse, matrix-supported fossils (GSC loc. 69207)..	16	16
	Underlying beds: volcanic flows of member A, partly with pillow structure		

Contact Relationships

The contact of the M'Clintock Formation with the overlying Ayles Formation is best exposed at locality 15, and that with the underlying Cape Discovery Formation is exposed at locality 16. Both appear to be sharp and conformable.

Mode of Origin

The limestone of member B, judging from its fauna, was deposited in a shelf environment. The pillow lavas and many breccias in member A suggest that it is subaqueous also, and a shallow, marine origin seems probable from its stratigraphic position between deltaic and shallow marine deposits.[1]

The preservation of some clinopyroxene shows that the formation, if metamorphosed at all, has not been completely metamorphosed; the sodic composition of the plagioclase and chloritic alteration of most mafic silicates, on the other hand, may be due to metasomatism rather than to metamorphism.

Age and Correlation

Fossils from member B at locality 15 were identified by B. S. Norford as follows:

GSC loc. 69207
stromatoporoids
?*Palaeofavosites* sp.
Age: Richmond to Silurian.

As the M'Clintock Formation is overlain by more than 5,000 feet of Richmondian strata, member B can hardly be younger than early Richmondian. Member A may range from late Wildernessian or Barneveldian to early Richmondian. The formation is probably correlative with the middle and upper parts of the Cornwallis Group designated as Thumb Mountain and Irene Bay Formations (Kerr, 1967), and the lowermost part of the Allen Bay and Cape Phillips Formations (Thorsteinsson, 1958).

Challenger Group

The name Challenger Group was given by Christie (1957, p. 13; 1964, p. 21) to "grey limestone and reddish sandstones, with minor conglomerate, feldspathic sandstone, and mudstone, and some altered basic volcanic rocks" exposed on the coasts of the upper part of M'Clintock Inlet. He considered this group to be younger than the M'Clintock Group, although the contact relationships were not established.

The term Challenger Group is here applied to all those strata of M'Clintock Inlet area that overlie the volcanic M'Clintock Formation and underlie the clastic Imina Formation. The Imina Formation was also named by Christie (1957, p. 16f.), but was not recognized in this area.

The Challenger Group is subdivided into three new formations; in ascending order, the names Ayles, Taconite River, and Zebra Cliffs are proposed.

Ayles Formation
(Map-unit 5)

Adam Ayles, a sailor of H.M.S. *Alert*, accompanied Pelham Aldrich in 1875 and 1876 on all his major sledge expeditions in northern Ellesmere Island. Ayles Fiord and a mountain 10 miles east-northeast of the head of that inlet were named in his

[1]It is possible, however, that the volcanics formed islands during times of rapid accumulation.

honour. The name Ayles Formation is proposed for the carbonate unit that lies stratigraphically between the volcanic M'Clintock Formation and the clastic Taconite River Formation. The lithology, contact relationships, age, and approximate thickness were established on Mount Ayles and in the vicinity of Egingwah Creek.

Thickness and Lithology

A section measured photogrammetrically on the southeast slope of Mount Ayles (Fig. 15, loc. 18) is about 1,000 feet thick. This section is bounded at the top by an erosion surface, but considered to be nearly complete. The formation has a minimum thickness of about 800 feet in a fault slice on the north slope of Mount Ayles (loc. 19).

The Ayles Formation consists mainly of calcareous dolomite and dolomitic limestone. From a distance, medium light grey, very resistant sets of strata tens of feet thick are seen to alternate regularly with slightly darker, more recessive sets of beds. Hand specimens of the dolomitic strata weather yellowish grey. The stratification has been almost obliterated, partly by dolomitization, and perhaps also by burrowing organisms; where preserved, it varies from laminated to thin bedded, and commonly shows shallow undulations a few inches to about a foot in wavelength.

The limestone is composed of microcrystalline, anhedral calcite. It is replaced, either massively or in a mottled fashion, by coarsely microcrystalline to medium crystalline, euhedral to subhedral dolomite with some calcite preserved in the interstices. The difference in the hue of the strata seems to be related to differences in the concentration of submicroscopic impurities contained mainly within the carbonate crystals. Only small amounts of silt- and sand-sized impurities, mainly quartz and muscovite, are present. Fossils are scarce, i.e., comprise considerably less than one per cent of the rock volume.

Contact Relationships

The boundaries of the Ayles Formation are distinct. The lower contact with the volcanic M'Clintock Formation has not been seen exposed, but is covered by only a few feet of talus at locality 15. The upper contact with the clastic Taconite River Formation is exposed at locality 23, where it is conformable.

Mode of Origin

The formation appears to have been deposited in clear water. The coralline fauna suggests a well-oxygenated shelf environment, perhaps between the zone of turbulence and wave base (*see* Wells, 1967).

Age and Correlation

Fossils from the Ayles Formation were identified by B. S. Norford as follows:

Locality 20. About 4 miles west of Egingwah Bay.

GSC loc. 69204

bryozoan

Tollina sp.

Age: Ordovician, probably Barneveld to Richmond.

Locality 21. 3.6 miles west of Egingwah Bay.
GSC loc. 69212
gastropod
stromatoporoid
Calapoecia 2 spp.
Catenipora sp.
Favosites sp.
Palaeofavosites sp.
Palaeophyllum sp.
Age: Ordovician, Richmond.

Locality 22. North of Egingwah Creek, 2.9 miles west of Egingwah Bay.
GSC loc. 69213
solitary coral
Catenipora sp.
Age: Ordovician, Barneveld to Richmond.

According to these identifications, the age of the Ayles Formation is Richmondian. It is correlative with lower parts of the Allen Bay and Cape Phillips Formations (Thorsteinsson, 1958, 1963).

Taconite River Formation
(Map-unit 6)

The name Taconite River Formation is here proposed for the Upper Ordovician clastic sediments of the M'Clintock Inlet region that lie stratigraphically between two carbonate units of Late Ordovician age; the Ayles Formation and the Zebra Cliffs Formation. The contact relationships, lithology, thickness, and age of the formation were established in the vicinity of Egingwah Creek.

Thickness

At locality 23, which is the only section known where both top and bottom are exposed, a thickness of 950 feet was measured. This section, however, is poorly exposed, and the thickness obtained may be unreliable because of structural complexities.

Lithology

Macroscopic. The Taconite River Formation consists of siltstone, sandstone, conglomerate, shale, and limestone, in decreasing order of abundance, and is characterized by many facies changes. Generally, the sediments become finer grained both upwards in the section and laterally to the southeast.

In the northern part of the area mapped, conglomerates with large phenoclasts are prominently exposed (Fig. 5). At locality 6, for example, a thrust plate of conglomerate about 50 feet thick contains boulders up to 2 feet in diameter. In the vicinity of Egingwah Creek and farther south conglomerates are less conspicuous, and most of the phenoclasts are less than 6 inches in diameter. At locality 23 the conglomerate is confined to the lower few hundred feet of the section, and this may be so everywhere.

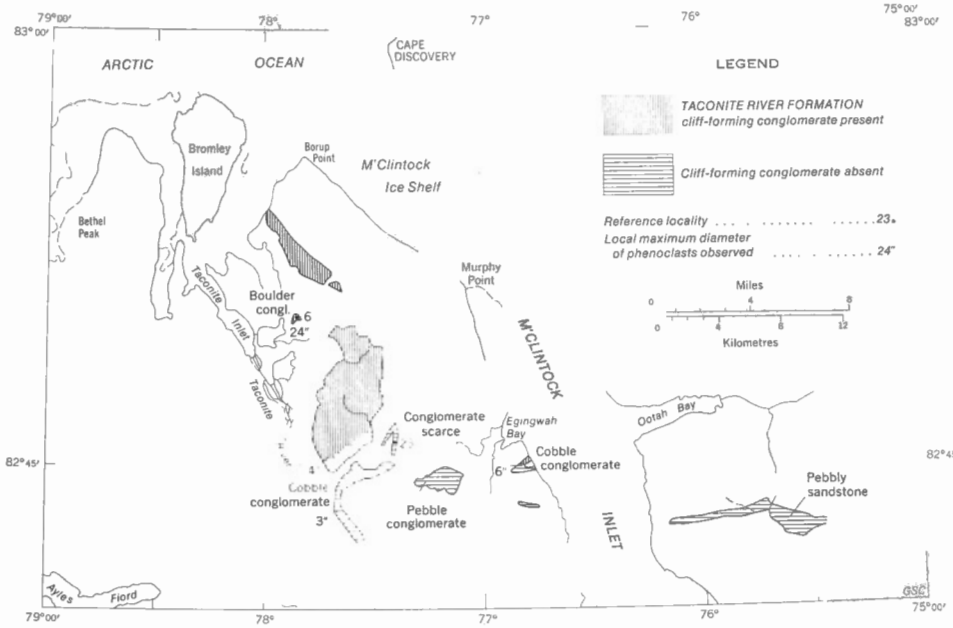


FIGURE 5. Taconite River Formation, lithofacies.

The sandstones are greyish green and range in grain size from very fine to very coarse. Red beds are common on the east side of M'Clintock Inlet, on Egingwah Creek, and south of it, but are rare north of that creek. Most of the sandstones are thin bedded to laminated, and some show casts of burrows made by sediment-feeding organisms. The siltstones are pale red, pale red weathering; light grey, greenish grey weathering; or medium light grey, olive-grey weathering. They are commonly extremely calcareous and in part thinly laminated. Dark grey, laminated shales are locally associated with the siltstones, but are generally poorly exposed. Most limestones are greenish grey, and contain impurities of clay and silt, but some are grey and relatively pure. An extensive, nearly pure limestone east of M'Clintock Inlet weathers conspicuously yellow.

Microscopic. The conglomerates, sandstones, and siltstones are composed mainly of carbonate, quartz, and chert, with lesser fractions of feldspar, volcanic and metamorphic rock fragments, chlorite, biotite, muscovite, and opaque materials. Their composition is variable, but lithic fragments predominate in the coarse-grained sandstones and conglomerates, whereas minerals are the more abundant constituents in the finer grained sediments.

The composition of six samples of sandstone is listed in Table IV.

Carbonate is the most abundant component. Most carbonate clasts are either individual, sand-sized grains of calcite, or cryptocrystalline to very finely crystalline limestone fragments. Dolomite crystals and aggregates, and schistose limestone or marble fragments are relatively rare.

Quartz, ranging from 1 to 53 per cent and averaging about 23 per cent of the rock volume, is second in abundance. It is present mainly in individual crystals, commonly with undulose extinction, and to lesser extent in aggregates of recrystallized chert and of vein quartz; a smaller amount of the grains are composed of metaquartzite.

Chert is relatively common only in coarse-grained sandstones, in which it ranges up to about 48 per cent. Part of the chert is unmetamorphosed, whereas another part is stretched and schistose. The chert contains varying amounts of argillaceous, carbonaceous, and carbonate impurities. Inclusion-free nodules, about 80 to 140 microns in diameter, were recognized within the chert fragments of one thin section; these nodules may represent radiolarian remains.

The feldspar content ranges between 2 and 9 per cent and averages about 4 per cent. Plagioclase, microperthite, and K-feldspar are represented; most of the plagioclase is albite.

Volcanic rock fragments are fairly abundant in the conglomerates and coarse-grained sandstones, but are rare to absent in the finer grained sediments. Most of the fragments identified were intermediate to acidic in composition, and their plagioclase was sodic. Some red-stained fragments resemble iron-rich felsic volcanic rocks of map-unit 2. Some chlorite may represent altered volcanic glass.

The metamorphic rock fragments, which range from about 11 per cent to trace amounts in the sandstones, are mainly of low metamorphic grade and consist of muscovite, chlorite, and quartz.

Muscovite, present in relatively coarse flakes, is conspicuous only in fine- to very fine grained sandstones, and in the siltstones. Biotite is present only in trace amounts.

The roundness of the clasts increases with increasing grain size, and varies from angular in the silt grade to subrounded in the very coarse sand grade. The sorting varies inversely with grain size. Coarse-grained sandstones commonly are poorly sorted, whereas fine- to very fine grained sandstones and siltstones commonly are well sorted. The type of cement present depends on the composition of the clasts: carbonate grains are cemented by calcite; quartz and chert by quartz; and red beds to some extent, apparently, by iron oxides. Some sandstones have a clay matrix.

According to Gilbert's (1954) classification, the sandstones are lithic arenites, and according to McBride (1963) litharenites.

A specimen of relatively pure, light grey, yellowish grey weathering limestone from east of M'Clintock Inlet consists of brachiopod, bryozoan, and echinoderm skeletal fragments enclosed in and supported by a cryptocrystalline calcite matrix.

Contact Relationships

The lower contact of the Taconite River Formation is well exposed at locality 23. There the relatively pure carbonate rocks of the Ayles Formation, and clastic and carbonate sediments of the Taconite River Formation are separated by about 4 feet of interlaminated limestone, shale, and siltstone. This contact is thus conform-

able and gradational; the transition beds are arbitrarily included in the Taconite River Formation.

The stratigraphic position of the Zebra Cliffs Formation above the Taconite River Formation is apparent from the succession of rock types in several folds, but the contact itself is generally concealed. This contact is tentatively considered to be conformable because indications of a nonconformity are lacking.

Mode of Origin

Sources of clastic sediments. The principal source of the clastic sediments of the Taconite River Formation was a partly metamorphosed, sedimentary and volcanic terrane comparable to map-units 1 and 2. The following types of fragments are characteristic of this suite:

quartz keratophyre (map-unit 2)
chert, schistose chert (map-unit 2)
schistose limestone (map-unit 2)
phyllite (map-unit 2)
quartz muscovite-chlorite schist (map-unit 1)
biotite (map-unit 1 ?)
muscovite, chlorite (map-units 1 and 2)
quartz (map-units 1 and 2).

Some chloritized, tuffaceous material resembles the volcanic material in the tuffaceous calcarenite of member B of the M'Clintock Formation.

It is inferred, because of the southward decrease in the size grade of the conglomerates (Fig. 5), that the source area lay to the north or northwest. A near source is indicated by the coarse grade of the northernmost conglomerates and by the variable composition of the sandstones.

Whereas some carbonate phenoclasts and medium to coarse sand grains may be terrigenous, the carbonate particles in the siltstones and very fine grained, calcareous sandstones were more likely derived from marine sediments. The bioclastic limestones of the Taconite River Formation itself are a suitable source for such materials.

Environments of deposition. The Taconite River Formation represents a variety of shallow-marine to non-marine environments. At least some limestones originated in moderately shallow water, shelf environments permitting coral growth. Thinly laminated dark to medium light grey shales and siltstones exposed in a syncline about a mile south of Egingwah Creek are characteristic of the pro-delta environment. The red sandstones and coarse conglomerates, on the other hand, may be partly of fluvial origin.

Age and Correlation

Fossils from the Taconite River Formation were identified by B. S. Norford as follows:

Locality 24. About 4.4 miles west of Egingwah Bay.

GSC loc. 69205
gastropod
cephalopod
Calapoecia sp.
Catenipora sp.

Age: Middle Ordovician to Early Silurian, probably Barneveld to Richmond.

The Taconite River Formation must be Richmondian because it lies stratigraphically between the Richmondian Ayles and Zebra Cliffs Formations. Therefore, it is correlative with lower parts of the Allen Bay and Cape Phillips Formations (Thorsteinsson, 1958).

Zebra Cliffs Formation
(Map-unit 7)

The name Zebra Cliffs Formation is here proposed for a thick succession of Upper Ordovician strata consisting mainly of pure and impure carbonates with interbedded, subordinate amounts of clastic sediments that lie stratigraphically between the clastic Taconite River and Imina Formations. The formation is named after the Zebra Cliffs, which are diagonally banded, dark and light grey precipices on the west coast of M'Clintock Inlet. The contact relationships, lithology, and thickness of the formation were established in the vicinity of the Zebra Cliffs. The formation is divided into three members, informally referred to as members A, B, and C.

Thickness and Lithology

Member A

Member A is about 72 feet thick near locality 23 and at locality 25 (type section); at locality 26, it is between 72 and 76 feet thick. Though relatively thin, it is a cliff-forming marker unit that can be readily identified in the field and on air photographs.

On the west side of M'Clintock Inlet, the member consists predominantly of calcareous dolomite which is partly brecciated, and contains stringers and lenses of chert. A typical sample from locality 25 is pale to dark yellowish brown on fresh surfaces and weathers pale yellowish brown. It is composed of microcrystalline to very finely crystalline dolomite with interstitial cryptocrystalline calcite. The rock is cut by veinlets of coarsely crystalline dolomite, and contains small lenses of chert and a little silt-sized quartz. A sparse coralline fauna (GSC loc. 69203) is present there.

On the east side of the inlet, the member consists of fossiliferous, locally brecciated limestones. Thin sections of two specimens from this area are made up mainly of ovoid pellets and/or intraclasts about 0.2 to 1 mm in diameter, which are composed of cloudy, cryptocrystalline calcite. Skeletal fragments of echinoderms and bryozoans are associated with the pellets. The matrix of the rock varies from finely microcrystalline and cloudy to medium crystalline and clear and seems to have recrystallized to various degrees. Lenses of chert are present in one of the specimens.

Member B

The total thickness of this member is unknown. An incomplete section at locality 27, measured by photogrammetric methods, comprises about 1,800 feet of strata.

The member consists of sandy, silty, argillaceous, and pure limestones that are commonly laminated to thin bedded, and well stratified. The alternation of light yellowish grey sets of strata with medium light grey to medium grey sets gives this unit a characteristic banded appearance. In the lower part of the member, a few tens of feet of red weathering sandstones and siltstones are intercalated with the carbonate rocks.

The member contains a rich and varied fauna of corals, bryozoans, gastropods, brachiopods, cephalopods, and ostracods, with relatively few graptolites. It is richer in fossils than any other pre-Pennsylvanian unit known in the area.

A typical, yellowish grey to olive-grey, yellowish weathering limestone contains about 10 per cent (by volume) of quartz, one per cent combined feldspar and muscovite, and 6 per cent broken brachiopod shells. The quartz ranges in grade from silt to fine sand. These impurities are embedded in a matrix of cryptocrystalline calcite with trace amounts of dolomite, and finely comminuted shell fragments.

A medium grey, medium to light grey weathering, thin-bedded calcareous siltstone contains about 79 per cent by weight of insoluble residues, mainly quartz, muscovite, feldspar, and clay-sized minerals; the soluble fraction consists of cryptocrystalline calcite. The intraclastic texture shows that the sediment was slightly reworked by currents.

A fine-grained, silty, pale red sandstone from the lower part of the member has the following approximate composition, established by statistical analysis of 200 points in a thin section:

	%
Quartz	31
Feldspar	22
Carbonate	16
Argillaceous, volcanic, and low grade metamorphic rock fragments, and possibly highly altered feldspar	16
Opaque materials	11
Chlorite, muscovite, clay minerals	4

The grains are subangular and moderately well sorted. They are partly cemented by carbonate and iron oxide and partly embedded in a matrix of chlorite, muscovite, and clay. Clay matrix makes up considerably less than 10 per cent of the rock volume and, therefore, the specimen is classified as a lithic arenite.

Member C

At locality 28 this member is at least 1,320 feet thick. The base is bounded by a fault but the section may be nearly complete. Member C is similar to member B, but is darker in colour, contains a larger proportion of argillaceous and carbonaceous matter as well as some dolomite, and has a graptolite fauna. It consists of shaly, silty,

and dolomitic limestones, and of calcareous, dolomitic, and silty shales. The upper 450 feet is more shaly than the lower part of the unit. In addition to graptolites, which are fairly common, the member contains some cephalopods and ostracods.

Calcite is the most abundant component of the rocks. In some strata it is cryptocrystalline and anhedral, and in others microcrystalline to finely crystalline, and subhedral. The microcrystalline to finely crystalline calcite includes remnants of cryptocrystalline material and seems to have formed by recrystallization. In this process, argillaceous and carbonaceous impurities have been concentrated in the crystal interstices. Dolomite is present only in some strata and forms varying, but mostly subordinate, amounts in these beds. The silt fraction consists mainly of quartz with subordinate feldspar, muscovite, and chlorite. In addition to minerals, the clay fraction contains carbonaceous matter. Authigenic pyrite is present in some beds. Locally, bituminous matter occurs in vugs.

Contact Relationships

The lower contact with the Taconite River Formation has not been seen, but the beds are probably conformable. The upper contact with the Imina Formation (discussed below) is probably also conformable.

Mode of Origin

Member B and the limestones of member A probably formed in shallow-water, marine environments below high-tide level; the dolomitic facies of member A is of similar or shallower origin. The absence of a benthonic fauna and the predominance of graptolites in member C suggest that this unit was deposited in considerably deeper waters. The presence of authigenic pyrite indicates reducing conditions below the sediment–sea water interface, and the preservation of much carbonaceous matter indicates that deposition of this material exceeded its destruction by oxidation. Although it does not necessarily follow that the sediments were laid down in a restricted basin, paleogeographic constructions demonstrate that graptolitic shales and carbonates commonly occupied relatively deep troughs.

The study of thin sections indicates that at least some limestones are calcisiltites, i.e., re-deposited clastic limestones of silt grade. This is concluded because of their granular texture and because of the presence of silicate clasts that are of approximately the same size as the carbonate grains. Petrographic analysis of clastic limestones of Ordovician and Silurian ages on the Hazen Plateau indicates that submarine redeposition favours the recrystallization of cryptocrystalline aggregates to microcrystalline and coarser textures.

Age and Correlation

The ostracods in the following collections were identified by M. J. Copeland, and the remaining fossils by B. S. Norford.

Member A

Locality 25. About 2.2 miles south of Egingwah Bay.
GSC loc. 69203
Troedssonites conspiratus (Troedsson)
Age: Ordovician, Richmond.

Locality 29. About 5.3 miles east-northeast of Crash Point.
GSC loc. 69211
Catenipora sp.
Calapoecia sp.
Palaeofavosites sp.
Age: Ordovician, Richmond.

Member B

Locality 30. About 5.7 miles northeast of Crash Point.
GSC loc. 69214
bryozoan
gastropod
orthid brachiopod
?*Diplograptus* sp.
Bollia sp.
Hallatia sp.
Age: Ordovician, probably Wilderness to Richmond.

Locality 31. 1.4 miles south of Egingwah Bay.
GSC loc. 69215
Catenipora sp.
Receptaculites sp.
Age: Ordovician, Barneveld to Richmond.

Locality 32. Top of Zebra Cliffs.
GSC loc. 69217
bryozoans
straight cephalopod
Favosites sp.
Age: Richmond to Middle Devonian.

Locality 33. 1.5 miles southeast of Egingwah Bay.
GSC loc. 69210
Calapoecia sp.
Catenipora sp.
Age: Middle Ordovician to Early Silurian, probably Barneveld to Richmond.

Locality 34. 1.3 miles south of Egingwah Bay; probably from member B of the Zebra Cliffs Formation, but possibly from the Taconite River Formation.
GSC loc. 69202
Rhynchotrema sp.
?*Sibiriolites* sp.
Age: Ordovician, Barneveld to Richmond.

Several collections were made by W. W. Nassichuk near the head of M'Clintock Inlet. These probably came from member B of the Zebra Cliffs Formation, but member A may be also represented.

Locality 37. Cliffs on the east side of the upper part of M'Clintock Inlet, about 3.5 miles southeast of south tip of small island.

GSC loc. C–6, elevation about 2,455 feet
echinoderm fragments
undetermined trilobite
straight cephalopods
undetermined brachiopods
?*Lithostrophia* sp.
Rafinesquina sp.
Calapoecia sp.
Catenipora 2 spp.

Age: Ordovician, Eden to Richmond.

GSC loc. C–7, 60 feet above base of section
echinoderm fragments
undetermined trilobite
straight cephalopod
gastropod
ostracod
undetermined brachiopods (6 spp.)
?*Austinella* sp.
?*Hesperorthis* sp.
Rafinesquina sp.
bryozoan
solitary coral
Calapoecia sp.
Catenipora sp.

Age: Ordovician, Eden to Richmond.

GSC loc. C–8, 690 feet above base of section
clam
bryozoan
solitary coral
undetermined brachiopods (2 spp.)
Rostricellula sp.

Age: probably Ordovician, Wilderness to Richmond.

GSC loc. C–9, 840 feet above base of section
clam
bryozoan
? straight cephalopod
Rostricellula sp.

Age: probably Ordovician, Wilderness to Richmond.

GSC loc. C–10, 1,090 feet above base of section
ostracod
brachiopod fragment
?*Sibiriolites* sp.

Age: probably Ordovician, Eden to Richmond.

Dr. Norford comments that collections C-8 and C-9 seem to be from the same assemblage and possibly from the same set of beds. This is consistent with the observation that at the head of M'Clintock Inlet the Zebra Cliffs Formation is imbricately thrust faulted.

The following fossils collected by R. L. Christie (1964, p. 22) and identified by G. W. Sinclair almost certainly came from member B of the Zebra Cliffs Formation.

GSC loc. 24721
Plasmopora lambei Schuchert
Columnaria n. sp. aff. *C. halysitoides* Troedsson
Palaeofavosites sp.
Calapoecia canadensis Billings
Halysites sp. aff. *H. feildeni* Etheridge
Syringopora n. sp.
Batostoma n. sp.
Rhinidictya sp.
Cyclospira cf. *C. vokesi* Roy
Hormotoma gracilis (Hall)
Lophospira spp.
Umbospira sp.
Holopea sp.
trilobite fragments
Leperditia sp.
Aparchites sp.
Krausella sp.
Conchoprimites sp.
scolecodonts
Age: Ordovician, Richmond.

Graptolites from member C were identified by B. S. Norford and R. Thorsteinsson as follows:

Locality 28. About 3.3 miles south-southeast of Egingwah Bay, and 0.5 mile west of M'Clintock Inlet; from the upper part of the member.

GSC loc. C–59
Climacograptus latus Elles and Wood
Age: Late Ordovician (Ashgill)

Locality 35. 2.4 miles south of Egingwah Bay, 1.6 miles west of M'Clintock Inlet; probably from the lower part of the member.

GSC loc. C–61
Climacograptus latus Elles and Wood
Orthograptus spp.
Age: Middle Ordovician to Late Ordovician, probably Late Ordovician (Ashgill)

Locality 36. East side of creek, about 1.9 miles southeast of Egingwah Bay, 2.6 miles west of M'Clintock Inlet.

GSC loc. C–60
Climacograptus latus Elles and Wood
Orthograptus sp.
Age: Middle Ordovician to Late Ordovician, probably Late Ordovician (Ashgill), possibly same fauna as that from locality 7–11.

These identifications indicate that the Zebra Cliffs Formation is Richmondian. The formation is correlative with lower parts of the Cape Phillips and Allen Bay Formations (Thorsteinsson, 1958).

Late Ordovician (?) and Silurian

Imina Formation
(Map-unit 8)

The name Imina Group was given by Christie (1957, p. 16) to a uniform sequence of fine- to medium-grained, compositionally immature sandstones (termed by him subgreywacke, greywacke, and argillaceous greywacke) exposed on the north coast of western Ellesmere Island, between Phillips Inlet and Cape Bourne, whose thickness, age, and contact relationships were unknown. Subsequent studies by the writer showed that the Imina is mainly of Llandoverian age (Trettin, 1964, 1969) although it may extend into the Late Ordovician and Early Wenlockian. The unit has been redefined as a formation (Trettin, 1969) as stratigraphic subdivision seems impossible. The beds on the west side of M'Clintock Inlet lying stratigraphically between the Zebra Cliffs Formation and a Middle Pennsylvanian conglomerate (map-unit 10A) are assigned to the Imina Formation because of their age and lithology.

Thickness and Lithology

At locality 38 (Fig. 15) the formation is about 760 feet thick, which is a minimum figure, because the unit there is truncated by an unconformity. It consists mainly of calcareous sandstone with lesser amounts of calcareous siltstone, limy shale, shaly limestone, and pebble-conglomerate. The sandstones and siltstones are coloured in shades of yellowish grey, light olive-grey, or greenish grey, and weather predominantly yellowish grey. Individual ledges of sandstones are exposed along the strike for a few hundred feet and are probably more extensive. These ledges, which are separated by poorly exposed shaly and calcareous intervals, represent typical turbidite sequences as described by Bouma (1962) and Walker (1967).

The standard sequence according to Bouma is:

e) pelitic interval
d) upper interval of parallel lamination
c) interval of current ripple lamination
b) lower interval of parallel lamination
a) graded interval.

Walker demonstrated that the lowest interval (a) or the two lowest intervals (a and b) may be missing in individual sequences, and that this defect is more common in turbidites which have travelled a long distance (distal turbidites) than in those which are close to their origin (proximal turbidites).

At M'Clintock Inlet interval (a) is well represented. In the strata examined it ranged in thickness from an inch to about 15 inches, whereas the other intervals were only up to a few inches thick. The graded interval ranged in grain size from coarse to fine, medium-grained sand being most abundant. The intervals showing parallel lamination, small-scale cross-stratification, and convolute lamination were fine- to very fine grained sandstone or coarse siltstone. Sole markings, such as grooves, ridges, and flute casts, are present at the base of some graded intervals, and some beds in the lower part of the section have abundant casts of burrows formed by sediment-feeding organisms. The pelitic interval is mainly represented by dark grey shaly limestone or calcareous shale.

The composition of seven characteristic specimens of sandstone is given in Table V. The main components of these sandstones are carbonate and quartz, with lesser fractions of feldspar, chert, volcanic rock fragments, mica, chlorite, and quartz-muscovite-chlorite schist.

The content of carbonate fragments ranges from 30 to 87 per cent and averages 48 per cent. The mode is 44 per cent. Several types of carbonate material can be distinguished, for example:

1. individual, sand-sized crystals of calcite, some with inclusions of cryptocrystalline calcite aggregates
2. cryptocrystalline and microcrystalline, partly recrystallized limestone fragments
3. a small amount of skeletal debris, including echinoderm columnals (Pl. II–6) and ostracod shells
4. a small proportion of microcrystalline dolomite.

The quartz content ranges from 9 to 52 per cent and averages 33 per cent. The mineral is present as single crystals; semi-composite aggregates probably derived from veins and recrystallized chert; and in composite aggregates representing metaquartzite. Some quartzite grains contain small proportions of muscovite; undulose extinction is common (Pl. I–6). Feldspar ranges from 1 to 13 per cent, averaging 7 per cent. Sodic plagioclase, microcline, and microperthite are the most common types (Pl. II–1, 2, 3, 4). Most samples contain less than 4 per cent of volcanic rock fragments, but one has 21 per cent. The fragments are mainly intermediate in composition and have sodic plagioclase.

The grain size of the sandstones varies from very fine to very coarse, fine- and medium-grained sediments perhaps being most common. The roundness of the sand-sized particles varies from predominantly subangular to subrounded.

The sand and coarse silt grains are embedded in a matrix composed of both carbonate and argillaceous materials. Quartz grains touching one another are cemented by silica. The rocks may be classified as calcareous greywackes but do not fit well into standard classifications of sandstone (e.g., Gilbert, 1954).

A conglomerate near the base of the formation consists mainly of limestone pebbles up to about 15 mm in diameter with lesser amounts of chert pebbles, crinoid fragments, and sand-sized quartz and feldspar in a matrix of detrital and precipitated calcite. The rock types represented by the fragments include microcrystalline pelletal and cherty limestone, and cryptocrystalline fossiliferous limestone. Some quartz grains are rounded to well rounded, and others euhedral, probably owing to authigenic growth.

Contact Relationships

The lower contact of the Imina Formation with the Zebra Cliffs Formation is structurally concordant and rather abrupt, there being little sand-sized material in the upper part of the Zebra Cliffs Formation. It is considered as conformable because both the underlying and the overlying sediments are of deep-water origin.

The upper contact of the Imina Formation with map-unit 10A is an angular unconformity.

Mode of Origin

The non-carbonate detritus in the Imina Formation can be assigned to two major groups of source rocks, as follows:

1. from metamorphic rocks comparable to map-unit 1: fragments of phyllite, muscovite, quartzite, and probably some quartz and chlorite
2. from cherty and volcanic strata comparable to parts of map-unit 2: chert, volcanic rock fragments, most feldspar, and probably some chlorite and quartz.

The carbonate fragments, on the other hand, seem to have originated on adjacent shelves. This is inferred from the presence of skeletal material which is absent from map-units 1 and 2.

The repetitive graded bedding suggests that the strata were mainly deposited by turbidity currents[1] in relatively deep water. A deep-water origin is confirmed by the presence of graptolites and the absence of benthonic fauna.

Age and Correlation

The basal beds of the Imina Formation, which conformably overlie late Richmondian beds of the Zebra Cliffs Formation, are of late Richmondian or early Llandoverian age.

Graptolites, collected a few hundred feet above the base of the formation were identified by B. S. Norford and R. Thorsteinsson as follows.

Locality 38. About 3.5 miles southeast of Egingwah Bay, 0.6 mile west of M'Clintock Inlet.
GSC loc. C–68
Monograptus aff. *M. priodon* (Bronn)
Age: Silurian, late Llandovery to Wenlock

The upper age limit of the formation cannot be determined precisely in the M'Clintock area, but has been determined in northwestern Ellesmere Island (Trettin, 1969) as late Llandoverian or early Wenlockian.

Silurian

Map-unit 9

Map-unit 9 comprises sediments of Wenlockian and/or Ludlovian age, exposed in a small area on the east side of M'Clintock Inlet. It is divided into three sub-units, a lower and an upper clastic unit referred to as map-units 9A and 9C, and a middle carbonate unit referred to as map-unit 9B or the Marvin Formation.

Map-unit 9A

Map-unit 9A has not been studied in detail because it is poorly exposed and difficult of access. The lower part consists of several hundred feet of greenish weathering siltstone and shale. These recessive strata are overlain by perhaps 300 or 400 feet

[1]The term turbidity current is here used for currents moving in consequence of the load they are carrying without reference to hydrodynamic mechanisms (Kuenen *in* Middleton, 1965, p. 217).

of greenish weathering sandstone with lesser amounts of interlaminated siltstone and shale. Ripple-marks are common, and relatively large echinoderm columnals are present locally.

The base of the unit is not exposed. It is conformably overlain by the Marvin Formation, and since the Marvin Formation is late Wenlockian and/or early Ludlovian, map-unit 9A must be of that age or older.

Map-unit 9A, similar in some respects, is distinguished from the Imina Formation by its greenish colour where weathered and by its larger content of chlorite. The Imina Formation is mainly Llandoverian, so the possible age range of map-unit 9A is late Llandoverian to early Ludlovian.

The silty and shaly lower part is comparable, and perhaps correlative, with silty and argillaceous rocks of Wenlockian to early Ludlovian age in northern Axel Heiberg and northwestern Ellesmere Islands designated as unit 2, Axel Heiberg Island, and unit 6, northwestern Ellesmere Island (Trettin, 1964), or as member A of the Lands Lokk Formation (Trettin, 1969).

Marvin Formation
(Map-unit 9B)

The name Marvin Formation, derived from Marvin Peninsula, is proposed for the carbonate rocks of Ludlovian and (?) late Wenlockian age east of Crash Point, M'Clintock Inlet, that are overlain and underlain by the clastic sediments referred to as map-units 9A and 9C.

Ross G. Marvin, a professor at the Columbia College of Civil Engineering, assisted Peary on his last two Polar expeditions. He was in charge of meteorological and tidal observations and helped to establish, by depth soundings, the existence of a continental shelf off the coast of Grant Land. Marvin drowned on April 10, 1909, 45 miles north of Cape Columbia, while returning from 86°38′N latitude in command of one of Peary's supporting parties. Several geographic features have been named in his honour: a submarine ridge in the Arctic Ocean, two small islands in Disraeli Fiord, and the peninsula between M'Clintock Inlet and Disraeli Fiord discussed here.

The type section is at locality 39, about 1.2 miles northeast of Crash Point. In the following description of the formation, however, data from this section have been supplemented by observations from other localities in the relatively small outcrop area east of Crash Point.

Thickness and Lithology

At locality 39 the formation consists of about 600 feet of fossiliferous, cryptocrystalline to microcrystalline limestone, with lesser amounts of sandy limestone and limy sandstone. Three informal sub-units are recognized.

Interval 0–224 feet. This interval consists of medium light grey, light grey to yellowish grey weathering, sparsely fossiliferous limestone. On air photographs and in the field, this sub-unit can readily be recognized by its relatively light colour and

steep profile. The fossils are supported by a microcrystalline to cryptocrystalline carbonate matrix. Pellets, about 40 to 120 microns in diameter, were noted in a thin section. The rocks are cut by numerous calcite veinlets.

Interval 224–436 feet. This interval is characterized by alternations of nearly pure, resistant limestone, with slightly impure, more recessive limestone. The unit is well stratified and commonly very thin bedded. The limestone is pale yellowish brown to pale brown and weathers pale brown. It is rich in skeletal fragments, which are commonly supported by a matrix ranging in grain size from coarsely microcrystalline to cryptocrystalline. The most abundant fossil is a large species of *Kirkidium*, but other smaller brachiopods, corals, bryozoans, and stromatoporoids are present as well as pellets of faecal or algal origin. Locally, stromatoporoids in growth position form lenses about a foot thick that extend several feet or more along the bedding.

Interval 436–600 feet. About two thirds of this sub-unit consists of pale brown, microcrystalline to cryptocrystalline, fossiliferous limestone, similar to the limestone of the underlying interval. These strata are thin to very thin bedded and some weather in nodular fashion.

The rest of the interval is composed of calcareous, fossiliferous sandstone and sandy limestone. In addition to the brachiopods, corals, bryozoans, and echinoderms that are present also in the other sub-units, this interval contains oncolites, up to 22 mm in diameter (Fig. 6). These spheroids commonly have a core of skeletal material, for example a crinoid columnal or bryozoan fragment, which is surrounded by concentric, partly eroded, undulating laminae. The spheroids are embedded in a matrix of carbonate, quartz, and muscovite. The sandstones are similar to those of map-unit 9C, and will be discussed with them.

FIGURE 6. Oncolites in matrix of very fine grained, highly calcareous sandstone of the Marvin Formation. The oncolites consist of irregular, wavy carbonate encrustations of algal origin on skeletal fragments derived from echinoderms, corals, and stromatoporoids. Length of specimen 11.3 cm, diameter of longest oncolite 2.4 cm.

Contact Relationships

The lower contact of the formation is abrupt but conformable. The upper contact is conformable and gradational, and the upper boundary is arbitrarily placed where sandstone becomes more abundant than limestone.

Mode of Origin

The absence of dolomite and the presence of a rich and varied fauna suggest that the Marvin Formation was deposited in a marine shelf environment probably below the intertidal zone. Lack of strong currents or waves capable of winnowing is indicated by the ubiquitous carbonate mud matrix. This conclusion is supported also by the presence of exclusively tabular stromatoporoids. These, according to Klovan (1964), occur in turbulent as well as quiet waters, but are more common in the latter environment. Some movement of the water, however, is indicated by the oncolites. Although oncolites may be of both organic and inorganic origin, the present types are suggestive of an algal origin (*see* Dunham, 1965). These spheroids, which must have rolled around on the sea-floor, may occur at any depth of water down to the shelf edge (McMaster and Conover, 1966).

Age and Correlation

Fossil collections from the Marvin Formation were identified by B. S. Norford as follows:

Locality 40 (Fig. 15). From the basal beds 1.2 miles northeast of Crash Point.
GSC loc. 75421
echinoderm fragments
undetermined trilobite
rhynchonellid and undetermined brachiopods
?*Atrypella* sp.
?*Kirkidium* sp.
?*Howellella* sp.

Locality 40. From interval 224 to 436 feet.
GSC loc. 75422
Kirkidium sp.

Locality 41. From interval 436 to 600 feet about 0.3 mile east of M'Clintock Inlet.
GSC loc. 69208
fossil debris, including echinoderms, gastropods, and bryozoans
solitary coral
Kirkidium sp.
Cystihalysites sp.
Halysites sp.
Fossopora sp.
Syringopora sp.
?*Tryplasma* sp.

Norford states in his report that these collections probably belong to the *Atrypella* fauna, which is both early Ludlovian and late Wenlockian, and is widespread in the Arctic regions (*see* Thorsteinsson, 1958, p. 74).

The Marvin Formation is similar to, and probably correlative with, a limestone southwest of Clements Markham Inlet, from which R. L. Christie (1964, p. 28) collected the index fossil *Atrypella phoca* and the writer collected *Kirkidium* sp. and other forms.

It is interesting to note that limestone lenses also occur in volcanic rocks of probable early Ludlovian age, on Emma Fiord, northwestern Ellesmere Island (Trettin, 1964, p. 14; 1969, p. 40).

On air photographs, limestones on the east side of the upper part of M'Clintock Inlet appeared similar to those of interval 0–224 feet of the Marvin Formation, although in the field they could not be distinguished from overlying thrust sheets of the Zebra Cliffs Formation (*see* Fig. 7). Fossils collected from these rocks were identified by B. S. Norford as follows:

Locality 42. About 1.7 miles southeast of the south tip of the small island that marks the entrance to the upper part of M'Clintock Inlet.

GSC loc. C–69

ostracods
gastropod
orthic brachiopod
fragments of trilobites and bryozoans
?*Receptaculites* sp.
heliolitid coral
?*Cystihalysites* sp.

Age: probably Silurian

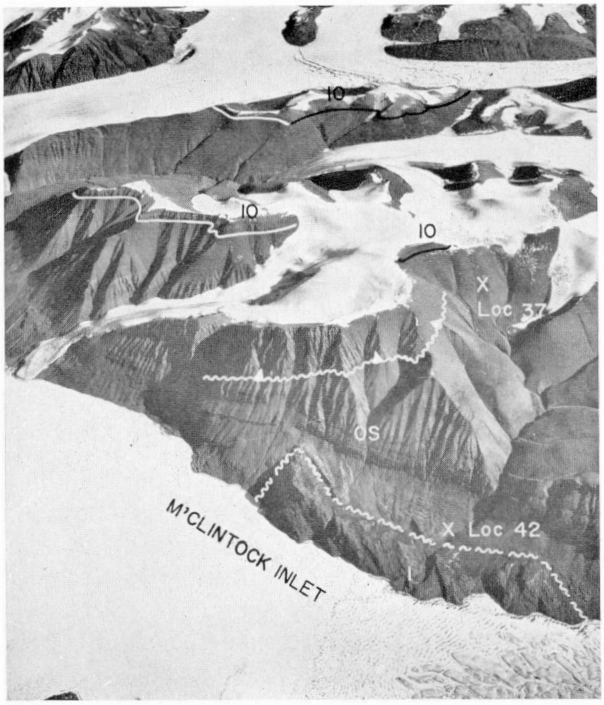


FIGURE 7

Oblique aerial view of cliffs on the west side of the upper part of M'Clintock Inlet, eastward. Metamorphic rocks (1) are overlain by Ordovician and (?) Silurian carbonates (OS), in turn overlain by Middle Pennsylvanian strata (10). Silurian (?) fossils suggestive of the Marvin Formation were found at locality 42, and Richmondian fossils suggestive of the Zebra Cliffs Formation at locality 37. A single major thrust fault is shown, but others must be present. (RCAF T404L-20)

The possibility that these strata are Ordovician cannot be ruled out because *Receptaculites* is fairly common in the Zebra Cliffs Formation and was collected from it in the same general area. If, however, these strata are not Ordovician but definitely Silurian, they are most likely of Ludlovian age and correlative with the Marvin Formation, because, as far as known, the Lower and Middle Silurian rocks of northern Ellesmere Island are clastic.

Map-unit 9C

Thickness and Lithology

A complete section of this map-unit, which is bounded at the top by the present land surface, is not preserved. At locality 39 the minimum thickness of the unit is 273 feet. It consists mainly of pale olive or yellowish grey, fine-grained, laminated lithic arenite. Interbedded with this sandstone are several ledge-forming limestone beds. The limestones are partly pure and partly impure, and some contain fossils that are supported by a microcrystalline to cryptocrystalline matrix.

The stratigraphic section at locality 39 follows.

Unit	Description	Thickness (feet)	Height above base (feet)
	Top of section: erosion surface		
7	Lithic arenite, pale olive, pale olive to yellowish grey weathering, laminated, mostly fine grained; minor granule-conglomerate	80	273
6	Limestone, pale yellowish brown, pale brown weathering, poorly stratified, laminated, crinoidal, fossils are supported by microcrystalline to cryptocrystalline matrix; clastic impurities; ledge-forming unit	6	193
5	Lithic arenite, pale olive, olive-grey weathering, mostly fine grained, laminated, with conical to hemispherical depressions up to about 1 cm in diameter	116	187
4	Limestone, light to medium grey, microcrystalline to cryptocrystalline; lower part thin bedded, upper part unbedded	7	71
3	Lithic arenite, yellowish grey, yellowish grey weathering, mostly fine grained, laminated	17	64
2	Siltstone, light olive-grey, light olive-grey to yellowish grey weathering, rich in microcrystalline calcite, with minor dolomite; pelletal; laminated; grading downward to limestone, cryptocrystalline, with worm borings (?), skeletal matter, and clastic impurities; beds 1–2 feet thick; ledge-forming unit	3	47
1	Lithic arenite, as in unit 3	44	44
	Underlying beds: Marvin Formation		

The composition of each of four typical sandstone specimens is listed in Table VI. The quartz occurs partly as individual crystals and partly as fused, metamorphic aggregates (Pl. I–3). Some grains have inclusions of muscovite and chlorite. The feldspars identified were K-feldspar including microcline, and sodic plagioclase. A

large proportion of the grains are untwinned. Muscovite and chlorite are the most abundant phyllosilicates; biotite is less common (Pl. I–7). These minerals occur as individual crystals, in fragments of phyllite, or together with quartz in fragments of schist. The carbonate is partly calcite and partly dolomite. It occurs mainly as cryptocrystalline to microcrystalline aggregates, or as individual, sand-sized crystals.

Most grains are angular to subangular. The sorting varies from good to poor and is mostly intermediate. The cement consists of quartz and calcite.

Mode of Origin

The presence of crinoid ossicles and pellets suggests that the limestones were deposited in a relatively shallow shelf environment, and a similar environment is probable for the associated sandstones. The carbonate in the sandstones is probably of contemporaneous marine rather than of terrigenous origin. The main sources of the clastic sediments were low grade metamorphic rocks comparable to the Cape Columbia Complex.

Because of the poor rounding and compositional immaturity of the clastic materials, it is concluded that they are first-cycle sediments that were rapidly buried.

Age and Correlation

Diagnostic fossils have not been found in map-unit 9C. Because of its stratigraphic position immediately above the Marvin Formation, it is concluded that map-unit 9C is probably of Ludlovian age. The unit is comparable in lithology to and perhaps correlative with a Ludlovian sandstone–siltstone unit on Emma Fiord, northwestern Ellesmere Island (unit 7 of Trettin, 1964; or member C, Lands Lokk Formation, Trettin, 1969).

Pennsylvanian and Permian

Map-unit 10

On the coasts of M'Clintock Inlet the Silurian and older rocks are unconformably overlain by a succession of clastic sediments including red beds and carbonates, with minor amounts of evaporites in the upper part. This sequence was investigated in an area of a few square miles east of Crash Point. Four informal divisions referred to as map-units 10A to 10D were distinguished.

Lithology and Thickness of Sub-units

Map-unit 10A

At locality 43 about 1.6 miles northeast of Crash Point sub-unit 10A is about 750 feet thick. This section is bounded at the base by a fault, but may be nearly complete because an apparently complete section on the west coast of M'Clintock

Inlet is of comparable thickness. The unit has the following composition based on a visual estimate at this locality:

	%
Sandstone with minor siltstone	65
Conglomerate	25
Shaly limestone and calcareous shale	5
Limestone and dolomite	5

Most sandstones and conglomerates weather pale olive. Individual ledges of sandstone and conglomerate interbedded with more recessive rock types can be traced laterally at least for a few thousand feet, but within these ledges facies changes from sandstone to conglomerate occur over short distances. Some conglomerates extend laterally for a few hundred feet and are a few feet thick; others are a few feet in strike-length and a few inches thick, and these are generally lenticular. The sandstones and conglomerates are commonly cross-stratified, and the following types of current- and wave-made primary structures were observed:

—planar foresets, one foot or a few feet thick;

—large scoop-shaped troughs, up to about 30 feet long, with maximum dips up to 30 degrees on the blunt, upstream end;

—small scoops, a few inches to about 2 feet long;

—series of homoclines with rounded shoulders, that step down in the direction of current flow;

—ripple-marks;

—parallel alignment of plant stems.

Most phenoclasts are pebble-sized and range up to about 3 inches in diameter, but some are cobble- or boulder-sized and range up to 1½ feet in diameter. The conglomerates have a sandy matrix. The sandstones, described below in more detail, are classified as lithic and volcanic arenites. The shaly limestones and calcareous shales are dark grey, laminated to thin bedded, and fissile. They are relatively rich in organic matter, which consists mainly of finely comminuted carbonaceous matter with some stems and relatively few leaves.

Two types of relatively pure carbonate rocks were distinguished: limestones composed of hemispherical to ellipsoidal stromatolites (domal stromatolites according to Aitken, 1967) one to several inches in diameter; and yellowish brown weathering, very thin bedded to thin-bedded, calcareous dolomites and limestones.

Map-unit 10B

At locality 44 about 3.2 miles east of Crash Point this subdivision is about 1,100 feet thick, and is composed mainly of impure limestone and related calcareous shales and mudstones, some of which are rich in carbonaceous matter. The organic content of equivalent strata west of M'Clintock Inlet appears to be lower. Present in smaller amounts are fine-grained, quartz-rich, laminated sandstones, some weathering red. Medium- to very coarse grained lithic arenites and pebble-conglomerates occur in the upper part of the sub-unit.

A summary of the section at locality 44 follows.

Unit	Description	Thickness (feet)	Height above base (feet)
	Overlying strata: ledge-forming, green and red weathering sandstone and conglomerate of unit 10C		
4	Impure limestone, concretionary limy shale; at base of unit three ledge-forming sandstones; a pebble-conglomerate about 24 feet above base	164	1,112
3	Impure limestone, concretionary limy shale	236	948
2	Impure limestone, concretionary limy shale, red mudstone	584	712
1	Red siltstone and sandstone; sandstone very fine to medium-grained, laminated to thinly laminated	128	128
	Underlying strata: sandstone of unit 10A		

Map-unit 10C

A complete section of this sub-unit is not exposed in the area examined. In a fault block about 1.3 miles northeast of Crash Point it has a minimum thickness of about 550 feet. About two-thirds of the sub-unit there consists of red-brown weathering, mostly fine- to very fine grained laminated sandstone and minor siltstone and mudstone. Nearly one-third is composed of medium- to coarse-grained sandstone and fine pebble-conglomerate; the weathering colour of this fraction is mainly greenish grey and to a lesser extent reddish brown. The rest is made up of laminated calcareous siltstone and light grey mudstone. Both straight and linguoid ripple-marks are common.

Map-unit 10D

A complete, undisturbed section of this sub-unit is not exposed in the area investigated. A lower part, exposed on a ridge about half a mile northeast of Crash Point, comprises about 1,000 feet of strata. The overlying part appears to represent another thousand feet or more of beds, but may be repetition by faulting of lower beds.

The most abundant rock is sandstone; limestone, siltstone, shale, and gypsum and anhydrite are less common.

The sandstones are pale red, pale grey, pale brown, or olive-grey, and most of them are very fine to fine-grained, but vary to very coarse grained. They are commonly laminated, and some strata show ripple-marks and small scoop-shaped troughs. The beds are a few hundred feet or more in strike-length. Associated with the sandstones are smaller amounts of siltstone displaying similar colours and bedding characteristics.

The limestones are dark grey, thin bedded, and contain varying amounts of clay, silt, or sand. An evaporite solution-breccia, about 24 feet thick, is composed mainly of limestone fragments, with less dolomite, and minor chert. The fragments are up to a foot long, angular or round, and unsorted.

The gypsum and anhydrite occur in units a few feet to about 10 feet thick, and are locally extremely contorted.

Microscopic Petrography

Sandstones and conglomerates. These two rock types are composed of both lithic clasts and minerals; the former predominate in the conglomerates and coarse-grained sandstones, and the latter in the fine- and very fine grained sandstones (Table VII). The lithic clasts were derived mainly from volcanic rocks, carbonates, metamorphic rocks, and chert in decreasing order of importance. Two types of volcanic fragments may be distinguished: intermediate to felsic fragments commonly with sodic plagioclase (quartz keratophyres); and fragments of uncertain composition altered to chlorite. A considerable amount of the volcanic material, particularly of the second type, may be pyroclastic. Most carbonate clasts are microcrystalline to cryptocrystalline limestone or pelletal limestone, some are dolomitic limestone, and others individual calcite crystals. The metamorphic fragments are mainly phyllite, quartz-muscovite schist, and phyllitic shale. Some chert is schistose. Grains of chert with ellipsoidal nodules of possible radiolarian origin are common.

The predominant clastic mineral is quartz; chlorite, muscovite, and feldspar are present in lesser amounts, and tourmaline and zircon in trace amounts.[1] Sodic plagioclase is the most common feldspar. The chlorite occurs partly in rounded, microcrystalline aggregates that optically resemble glauconite. X-ray analyses of two specimens by R. N. Delabio, however, indicate that these aggregates are composed of chamosite, a septechlorite.

Most fragments are subangular to subrounded, but some quartz grains are rounded or possess an original rounded outline beneath a siliceous overgrowth.

The sorting is variable: very fine grained, laminated sandstones commonly being well sorted; and coarse-grained, pebbly sandstones being poorly sorted.

Matrix and cement vary with the composition of the rocks. Sediments rich in quartz are partly cemented by quartz, those rich in carbonate clasts by calcite, and red beds apparently in part by iron oxides. In addition, the sandstones contain variable amounts of clay matrix which, however, rarely exceeds 10 per cent. In sandstones rich in volcanic material the clay matrix cannot be distinguished from the margins of altered chloritic fragments.

Impure limestone and calcareous shale. The soluble fraction consists of microcrystalline and cryptocrystalline calcite, and the insoluble part consists mainly of clay-sized material with a small amount of silt. The clay-sized fraction includes both minerals and carbonaceous matter. A specimen from unit 10A had 18 per cent by weight of insoluble residue, and two specimens from unit 10B contained 21 and 89 per cent respectively.

Carbonates. Stromatolitic ellipsoids in map-unit 10A are composed of undulating laminae of cryptocrystalline calcite with varying proportions of clay and asso-

[1]Minerals, including tourmaline and zircon, were identified in thin sections; no heavy mineral separations have been made.

ciated carbonaceous matter. Layers relatively rich in these impurities are dark yellowish brown, whereas relatively pure laminae are a greyish orange. Microscopic examination reveals that the undulations represent complex combinations of *Collenia* and *Cryptozoon*-type structures. Individual stacks of hemispheroids (following the terminology of Logan, *et al.*, 1964) are about one to a few millimetres in diameter. The space between these stacks is filled with oölites, some with quartz nuclei, and minor amounts of quartz, feldspar, and chlorite in an abundant matrix of microcrystalline to very finely crystalline calcite.

A sample of dark grey, greyish orange-weathering dolomite collected from strata probably equivalent to map-units 10A or 10B consists of euhedral to subhedral microcrystalline dolomite crystals (range about 4 to 40 microns, average diameter about 20) surrounded by cryptocrystalline anhedral calcite with varying but smaller amounts of clay-sized minerals and carbonaceous matter. Soft-sediment deformation is visible in a hand specimen.

A typical specimen of dark grey, medium dark grey weathering limestone from map-unit 10C consists of pellets about 0.1 mm in diameter, as well as poorly preserved organic structures that may represent foraminifera and algae, in a matrix of cryptocrystalline to finely crystalline calcite. Another specimen of medium dark grey, medium grey weathering limestone is composed of crystals that range in size from about 9 to 45 microns and have inclusions of less than 5 microns. This rock contains foraminifera (*see below*).

Evaporites and solution breccia. In thin section, an evaporitic rock appears as alternating layers about 0.2 to 6 mm thick, composed mainly of euhedral anhydrite and subhedral to anhedral gypsum. The crystals range approximately from 5 to 300 microns, and are commonly about 50 microns long. Some gypsum is oriented perpendicularly to the stratification. Small amounts of submicroscopic impurities, probably organic matter and clay, are associated with the calcium sulphates.

A typical specimen of evaporite solution-breccia consists of fragments of various types of limestone with minor amounts of chert in a matrix of cryptocrystalline calcite. The fragments, ranging up to about 13 mm in diameter, vary considerably in size and shape. The limestone fragments are mainly pure but partly dolomitic. Some are pelletal; others contain crinoid columnals and possibly foraminifera. The original rock probably consisted of a variety of limestone types with interstratified evaporites.

Contact Relationships

External contacts. Map-unit 10 overlies the Silurian and older rocks with angular unconformity. On the west coast of M'Clintock Inlet the unit rests, from north to south, on the Lower Silurian Imina Formation, on an ultrabasic intrusion, and on low-grade metamorphic basement rocks. Contacts with Silurian and older rocks on the east side of the inlet appear to be faulted.

The contacts between map-units 10 and 11 are, for the most part, faults. A conformable contact, however, between fossiliferous limestone of map-unit 10D and gypsum–anhydrite of map-unit 11 is exposed at locality 50, about 7 miles southeast of Crash Point.

Internal contacts. The four sub-units are concordant and, with the exception of the basal contact of unit 10B, the internal contacts are gradational. The latter boundary is marked by a rather abrupt decrease in the grade of the clastic sediments and by the sudden appearance of red beds, but evidence of intervening erosion has not been obtained.

Mode of Origin

Sources of clastic sediments. The petrography of the clastic sediments indicates that they were probably derived from lower Paleozoic and older rocks, but the possibility of contributions from Devonian and Carboniferous strata cannot be dismissed. The fragments observed may be assigned to the following probable sources.

Pre-Middle Ordovician basement—phyllite, phyllitic rocks
—quartz-muscovite schist
—schistose chert
—coarse muscovite
—quartz keratophyre and related volcanic fragments
—some carbonate fragments
—some chlorite, feldspar, quartz, etc.

Ordovician and Silurian strata—some carbonate fragments, particularly fossiliferous limestones
—some volcanic material (M'Clintock Formation?)
—some quartz, particularly rounded grains
—some chlorite, feldspar, etc.

Devonian strata are not known to be preserved in northern Ellesmere Island and, therefore, their possible contribution cannot be assessed. Late Mississippian clastic sediments have been reported from Nansen Sound area and Clements Markham Inlet (Kerr and Trettin, 1962), and strata comparable to these may have contributed some quartz, etc. The local character of these deposits suggests that they may have been widely eroded prior to Pennsylvanian sedimentation.

Paleocurrent directions. The azimuths of fourteen axes of scoop-shaped troughs in sub-unit 10A were measured near locality 43 (Figs. 8 and 15). This group of determinations has the following statistical parameters.

Mean	144° azimuth
Range	103 to 223° azimuth, i.e., 120°
Standard deviation	29.5°
Confidence limits of mean	(p = 0.05): ± 14°

The predominant current direction at this locality thus is from northwest to southeast.

Three readings were taken from the basal part of unit 10D, about 1.6 miles northeast of Crash Point. Two represent lineations, and one represents the axis of a minor scoop-shaped trough. The results are as follows.

Mean	226° azimuth
Range	201–254, i.e., 53°

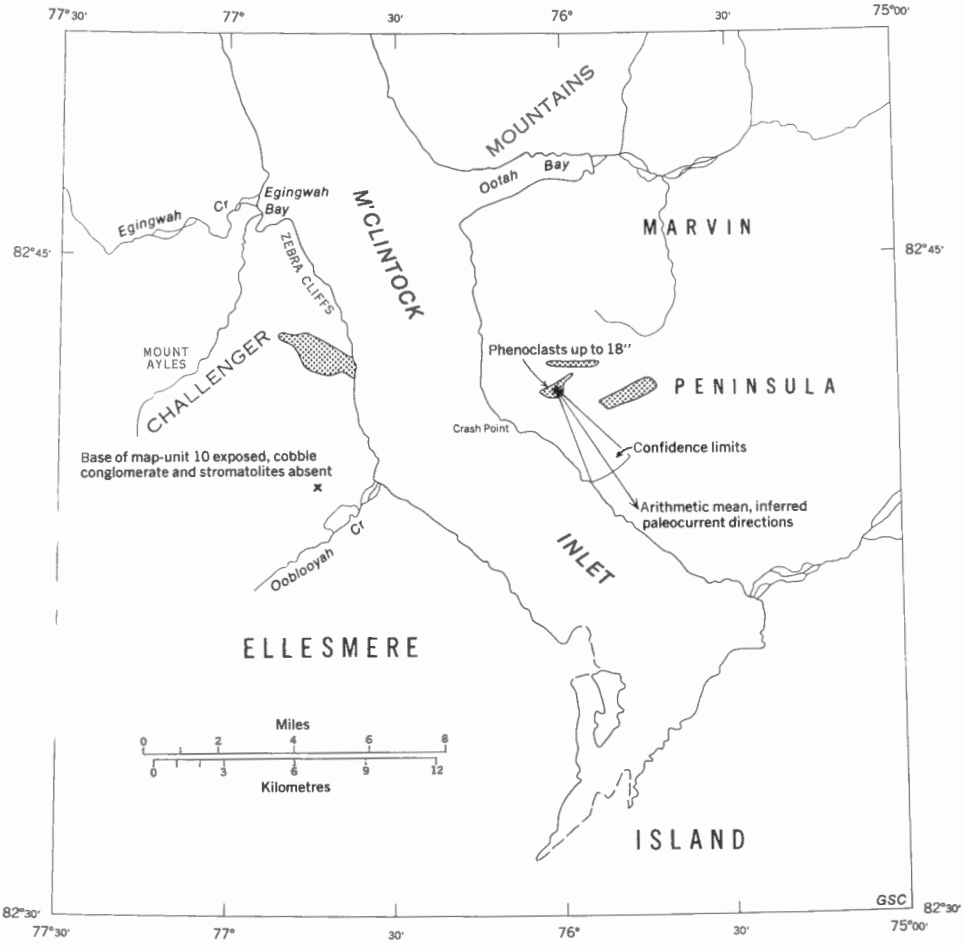


FIGURE 8. Map-unit 10A, outcrop areas and inferred paleocurrent directions.

Environments of deposition. It is inferred from the relatively coarse grade of most clastic sediments that they were deposited not far from their source area in the north or northwest. The immature and heterogeneous composition of the sediments supports this conclusion, and further indicates relatively rapid deposition without much re-working and mixing.

The sandstones of unit 10A that are characterized by large-scale crossbedding at high angles must have been deposited by relatively swift, competent currents, probably in fluviatile or estuarine channels. The small-scale crossbedding in the other units also indicates current activity, but in a lower flow regime (*see* Harms and Fahnestock, 1965). Intermittent exposure in an oxidizing, perhaps subaerial, environment is suggested by the red colour of a large part of these sediments.

The following inferences about the environments of deposition of map-unit 10 are based on the ecology of its faunas and floras; complete lists of these fossils follow under *Age and Correlation.*

M. J. Copeland states that the ostracods identified by him from shaly limestones and calcareous shales of map-units 10A and 10B are common in Pennsylvanian coal measures and hence suggestive of non-marine or brackish conditions, although ostracods of the same type have also been found in marine facies. Of the spores reported by M. S. Barss from shaly limestones and limy shales of map-unit 10A, *Calamospora* and *Lycospora* are characteristic of coal seams where they occur approximately *in situ*; *Florinites*, on the other hand, is most abundant as transported material in marine shales, although it also occurs in coal seams and non-marine shales (Neves, 1958). Mamet comments that the foraminifera and red algae which he identified in the uppermost limestones of map-unit 10D are common in sediments of shallow water facies, for example in cyclothems. Although stromatolites occur in some modern inland lakes, the domal types present in map-unit 10A are most common in tidal environments characterized by low turbulence (Aitken, 1967).

In summary, map-unit 10 represents shallow-marine, brackish, and perhaps also non-marine, fluvial environments; unequivocal evidence for open marine environments is lacking.

Age and Correlation

Macroflora. Plant fossils from map-unit 10 were identified by W. A. Bell as follows.

MAP-UNIT 10A

Locality 43. 1.6 miles northeast of Crash Point.

GSC loc. 7476

A single leafy shoot like that from GSC loc. 7473, somewhat better preserved. Cannot be reliably identified, but *Lepidodendron wortheni* very possible. This sample has a species of ostracod (both valves preserved in some instances) several times larger than those of GSC locs. 7470 and 7472.

GSC loc. 7477

Calamites sp.
Impossible to identify owing to poor preservation. Presumably some of the ribs at least alternate at the nodes, so that species does not seem to be an *Asterocalamites* which is confined to Mississippian.

GSC loc. 7478

Lepidodendron wortheni Lesquereux
The species, so far as known, is restricted elsewhere to middle and upper parts of Pennsylvanian formations of equivalent ages. The specimen is best preserved of the lycopods present in all the collections submitted from M'Clintock Fiord area.

MAP-UNIT 10B

Locality 45. About 2.3 miles east-northeast of Crash Point; drift, probably close to source.

GSC loc. 7470

Lepidophloios laricinus Steinberg
Lepidophyllum sp.
an unidentified branching seaweed (?)
Apparently a Pennsylvanian age is more probable than a Mississippian age (*see* remarks for GSC loc. 7469). In addition to megaplant remains, there are scattered paleoniscid fish bones and scales and rare minute ostracods.

Locality 46. About 1.8 miles northeast of Crash Point.

GSC loc. 7472

Lepidostrobophyllum sp.

Lepidophyllum sp.

Such leaves are useless for refined age interpretation. Associated with the leaves are abundant minute ostracods like those occurring at GSC loc. 7470, and several paleoniscid fish scales occur as well.

GSC loc. 7473

A very poorly preserved fragment of a leafy lycopod shoot, too obscure for generic identification, but may well be *Lepidodendron wortheni* Lesquereux. The rock also contains rare paleoniscid fish scales and minute ostracoda like those mentioned above.

UNDIVIDED MAP-UNIT 10

Although the stratigraphic position of the collections described below is not certain, they are probably from beds equivalent to map-units 10A, 10B or both.

Locality 47. About 0.5 mile west of M'Clintock Inlet, and 2.3 miles northwest of the mouth of Ooblooyah Creek.

GSC loc. 7469

Lepidophloios laricinus? Steinberg

The preservation of leaf-cushions is so poor in these specimens that it is not certain whether the form is conspecific with *L. laricinus* rather than with *L. scoticus*. If actually *laricinus*, and such identification is favoured, an Upper Carboniferous age is considered more probable. The presently known occurrences elsewhere of *laricinus* are in Upper Carboniferous or Pennsylvanian deposits, and *scoticus* in Lower Carboniferous or Mississippian.

Locality 48. About 4.1 miles east-southeast of Crash Point.

GSC loc. 7471

Lepidophloios laricinus Steinberg

The specific identification of this specimen is considered sufficiently reliable to omit a question mark. So far as present time ranges are concerned, the species strongly suggest a Pennsylvanian age.

Summary

Dr. Bell gave the following summary of his findings: "If correctly identified both *Lepidophloios laricinus* and *Lepidodendron wortheni* strongly favour a Pennsylvanian age, particularly a Westphalian stage. However, in dealing with such a small florule from a distant region, one is not justified in assuming that these two species had the same time ranges there that they are known to have in North America and Europe. Spore analyses should yield a much more comprehensive and reliable evidence."

Spores from map-unit 10A. Only one specimen yielded spores. These were identified by M. S. Barss as follows.

Locality 43 (*see above*).

GSC loc. 7475

Calamospora sp.
Lophotriletes sp.
Reticulatisporites sp.
Apiculatisporis sp.
Lycospora spp.
?*Laevigatosporites* sp.
Florinites sp.

Mr. Barss comments: "Specific identifications were not attempted because of the preservation of the spores. The most abundant spores were *Lycospora* and *Florinites*. The presence of *Florinites* in the sample indicates a Pennsylvanian age. This genus, to my knowledge, does not occur below the Pennsylvanian, but can range into the Permian. However, with such an abundance of *Lycospora* it is not likely that the possibility of a Permian age need be considered."

Ostracods from map-units 10A and 10B. Ostracods from locality 43, map-unit 10A, GSC loc. 7476; locality 45, map-unit 10B, GSC loc. 7470; and locality 46, map-unit 10B, GSC locs. 7472 and 7473 were examined by M. J. Copeland who comments as follows. "The ostracod specimens are poorly preserved, but may be identified generically as *Carbonita* sp., a widely ranging Pennsylvanian genus. *No more precise age determination is possible*, but the general shape of the specimens is most reminiscent of those from strata of Westphalian C and D age in the Maritime Provinces or, in general, Middle Pennsylvanian."

Foraminifera from map-unit 10D. Pale yellowish brown, cryptocrystalline limestone with echinoderm columnals forming the uppermost beds of map-unit 10D at locality 50, about 7 miles southeast of Crash Point, and half a mile north of M'Clintock Inlet yielded fusulinids, which were identified by R. Thorsteinsson as follows:

GSC loc. C–5

Profusinella sp.
Pseudostaffella sp.
Wedekindellina sp.

Age: Moscovian in terms of the European type section; Middle Pennsylvanian in the American standard section.

B. Mamet, who examined a thin section of this rock noted the following other foraminifera:

Ammovertellinae
Bradyinidae
Earlandiidae
Climacammina sp. of the group *C. moelleri* Reitlinger
trilayered *Globivalvulinella* sp.
Palaeotextulariidae
Tuberitina sp.

Mamet comments that these forms are not zonally significant, but that they indicate a Moscovian age. The presence of abundant red algae (Rhodophycophyta) confirms inferences made about the environment of deposition (*see above*).

Summary

Map-unit 10D is Moscovian, and map-units 10A to 10C are probably also Middle Pennsylvanian.

Notes on Correlation

Shaly limestones, and multicoloured clastic sediments including conglomerate, partly red coloured sandstone, and red and green siltstone similar to map-unit 10 were observed by the writer at Piper Pass, about 11 miles south of the head of Clements Markham Inlet. The type area of the Sail Harbour Group (Blackadar, 1954) lies on strike with this locality, about 18 to 43 miles to the northeast. The Sail Harbour Group was described by Blackadar as consisting of black shale, slate, and argillaceous limestone, sediments that are common both at Piper Pass and in sub-unit 10B on M'Clintock Inlet.

According to Blackadar (op. cit.), the Sail Harbour Group is Permian or older because it seems to underlie red beds of the Guide Hill Group, which in turn are overlain by Pennsylvanian or Permian limestones of the Feilden Group. On the other hand, the Sail Harbour seemed to be younger than the Cape Rawson Group because it is less deformed.

There are, then, two reasons for suggesting that map-unit 10 is at least partly correlative with the Sail Harbour Group: (1) Both represent the oldest known post-Silurian sediments in the respective areas; (2) the Sail Harbour Group is lithologically similar to parts of map-unit 10.

Map-unit 11

Distribution, Thickness, and Lithology

Map-unit 11 is represented by two facies; a predominant evaporite facies, and a subordinate clastic facies.

Evaporite facies (*map-unit* 11_1). This facies, consisting of gypsum and anhydrite, underlies much of the area south and west of Crash Point (Fig. 9). The beds are generally contorted, and the contortions are probably due to expansion concomitant with the hydration of the original anhydrite. Within the area mapped, pronounced changes in thickness are apparent. At locality 49, the unit is about 500 to 600 feet; at locality 50, about 30 feet; at locality 51, about 10 feet; and east of 51 it is not represented. The evaporites form two complex anticlines, the top of which coincides approximately with the present land surface because the overlying beds of map-unit 12 have been stripped by erosion.

These variations in thickness may be due to various factors or processes:

(1) environmental factors, resulting in original differences in thickness;
(2) flowage of gypsum–anhydrite from the flanks of the anticlines to their crests;
(3) differential solution by subsurface waters, a process that would also account for the brecciation in overlying strata of map-unit 12;
(4) local faulting.

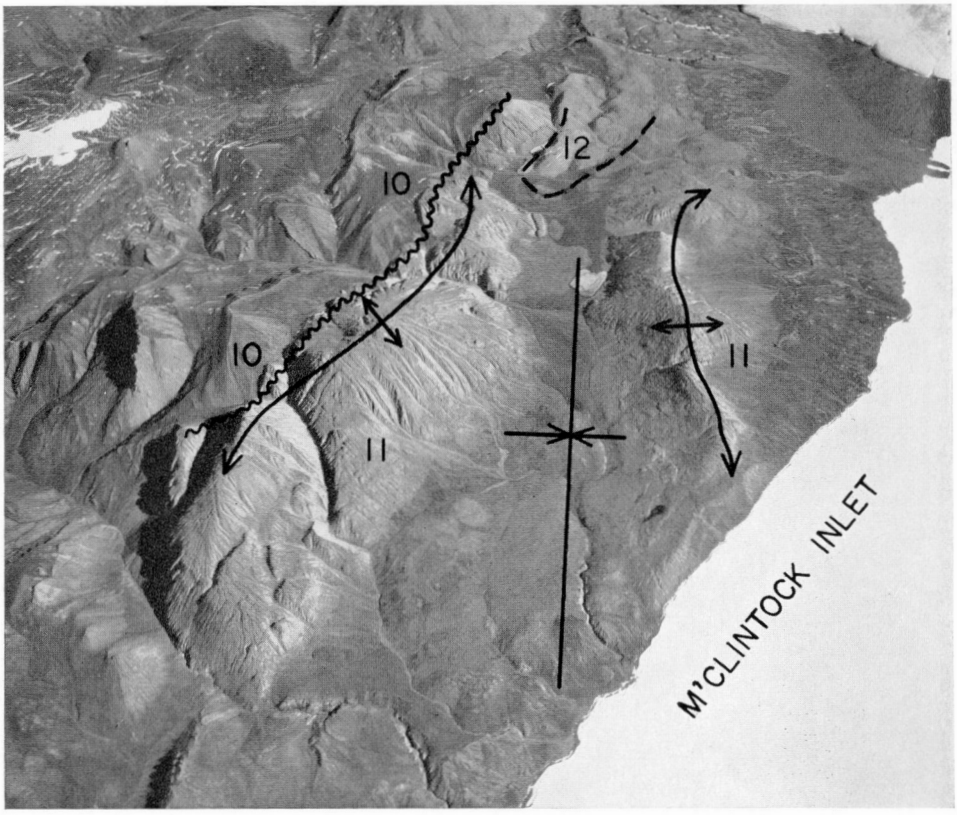


FIGURE 9 Oblique aerial view of east side of M'Clintock Inlet, southeast of Crash Point. Pennsylvanian gypsum–anhydrite (11) forms a broad syncline flanked by two anticlines. The evaporites rest with fault contact on Middle Pennsylvanian clastic and carbonate sediments (10), and are overlain by limestone breccia (12). The syncline marks the axis of a major structural trough. (RCAF T404L-17)

Clastic facies (*map-unit* 11_2). This facies has been seen only at locality 49, about a mile east of Crash Point. It is a narrow body of partly red weathering sandstone, pebble-conglomerate, and siltstone which probably represents a channel fill.

Contact Relationships, Age, and Correlation

At locality 50 the evaporites conformably overlie limestone of map-unit 10D, which contains Middle Pennsylvanian fusulinids. Map-unit 11 therefore is Middle Pennsylvanian or younger.

Map-unit 12

Distribution, Thickness, and Lithology

Outcrops of map-unit 12 are confined to the southeastern extremity of the area mapped and are bounded at the top by the present-day erosion surface. Estimated thickness of strata at locality 52 is 300 feet.

The lower few tens of feet consists of medium light grey, light grey to medium grey weathering limestone that is predominantly finely microcrystalline but ranges in grain size up to finely crystalline. At locality 52 this limestone is partly brecciated and poorly bedded. At locality 53 it is thinly laminated, and individual lamina or sets of laminae form irregular folds from one to about 10 mm in half-wave length.

The overlying strata are conspicuous due to their yellow-weathering. Most of these are calcareous breccias composed of fragments of silty and sandy limestone or calcareous sandstone. The limestone fragments are finely microcrystalline, and the carbonate crystals contain extremely fine, dust-like inclusions. In some specimens the fragments are discrete but in others they are only vaguely distinguishable from the matrix, which consists of coarsely microcrystalline to medium crystalline, clear calcite.

A small part of the unit consists of unbrecciated, yellowish grey to greyish orange weathering, very thin bedded, poorly bedded, microcrystalline limestone.

In the upper part of the unit, there are local boulder-conglomerates with a calcareous matrix.

Mode of Origin

The laminated, crenulated strata in the lower part of the unit are probably of algal origin and represent intertidal environments. The conglomerate beds in the upper part, judging from their shape in cross-section and from the presence of boulders in them, probably represent channels of competent streams that derived their sediments from nearby sources. The limestones and breccias cut by these conglomerates must, therefore, be of fresh or brackish water origin. From the angular nature of the fragments in the breccias it is concluded that they probably formed in place. The brecciation may have been caused by the solution of underlying evaporites, by desiccation, or by both processes.

Contact Relationship and Age

North of locality 52, unit 12 rests conformably on unit 11. Fossils have not been found in map-unit 12. The unit, however, is the youngest in a conformable sequence overlying map-unit 10D, which contains Middle Pennsylvanian fusulinids; a Middle Pennsylvanian or younger age can thus be assigned to it.

Map-unit 13

This unit, which is confined to the southeastern part of the map-area, was examined briefly. It forms a west-plunging anticline that is bounded both on the north and the south by faults; its base is not exposed. The lower and middle parts consist of poorly bedded, partly cherty, fossiliferous limestone containing bryozoans, large brachiopods, and corals. The conglomerate and breccia are composed mainly of clasts of carbonate and chert, but also contain transported fossils. Fossils have not been collected. The unit is different in lithology from map-units 10 to 12 and probably younger. Regional studies by W. W. Nassichuk (pers. com.) indicate that it is not younger than Permian.

Map-unit 14

This unit is represented by an isolated fault block, probably a gravity slide, about 5 miles east-southeast of Crash Point. The block consists of several hundred feet of strata, mainly limestone and dolomite, with interbedded evaporites in the lower part. The limestone in the upper part is rich in brachiopods and other fossils. Fusulinids collected from these strata by W. W. Nassichuk were identified by R. Thorsteinsson as follows:

Locality 63.
GSC loc. C–382

Schubertella cf. *S. kingi* Dunbar and Skinner
Schwagerina sp.

Age: Early Permian

INTRUSIVE ROCKS

Numerous intrusions in the area mapped differ in size, composition, and state of alteration. Most are relatively small and dyke-like, but one is a stock, tens of square miles in extent. The composition of these intrusions ranges from ultrabasic to acidic, and the state of alteration from complete replacement by chlorite, serpentine, albite, etc., to nearly unaltered. All intrusions are younger than map-unit 2, which is Middle Ordovician or older. Beds of Wildernessian age overlie some intrusions but are cut by others. One post-Wildernessian body has yielded an Early Devonian isotope age. The rocks known or suspected to be pre-Wildernessian are more highly altered than the younger ones. In the following description, the rocks are grouped according to composition, state of alteration, and age, in that order.

Altered Ultrabasic and Basic Intrusions

North of Ooblooyah Creek. An intrusion composed of olive-green weathering, massive ultrabasic rocks underlies a large area at the southeastern periphery of the region studied. The exposed part of this intrusion is roughly elliptical in plan, nearly 13 miles long and 4 miles wide. Its outlines were mapped by the writer in the course of a brief helicopter traverse in 1965 and by photo interpretation, and the lithology was briefly examined in the northeasternmost part of the exposures.[1]

Most rocks in the northeastern part of the pluton are completely altered to minerals of the chlorite and serpentine groups. At locality 55, however, comparatively well preserved, coarse-grained wehrlite is exposed. A thin section of a representative specimen consists mainly of clinopyroxene classified as salite (Deer, Howie, and Zussman, 1963, vol. 2, pp. 1, 132) on the basis of the following measurements:

$$n_y = 1.705 \pm 0.004$$

$$2v = 59 \pm 2^\circ \text{ (1 det.)}$$

About a third of the thin section consists of chlorite and serpentine, partly pseudomorphous after olivine. Nearly 10 per cent is weakly pleochroic tremolite-actinolite, and about one per cent or less, relatively fine grained, brownish red biotite or phlogopite.

On the east and southwest, the pluton is unconformably overlain by Pennsylvanian strata of map-unit 10. The northern contact with the Ayles and M'Clintock Formations and the southwestern contact with map-unit 1 appear to be faulted.

[1]A more detailed study based on field work in 1966 has recently been completed by T. O. Frisch (1967).

The ultrabasic pluton is intruded by small bodies of quartz diorite and related rocks (*see below*), probably Early Devonian. It is probably genetically related either to the quartz diorite intruding it, or to the ultrabasic rocks on Bromley Island. In the first case the plutonic rocks would most likely be of Early Devonian age, and in the second, Early or Middle Ordovician age.

Bromley Island. The most common intrusive rocks on Bromley Island are altered diabase dykes consisting of albite, partly chloritized clinopyroxene, and "iron ore." The texture is ophitic or sub-ophitic. The proportion of mafic minerals and hence the darkness of the rocks varies. The intrusions are considerably altered to chlorite and sericite, and to a lesser extent to talc and prehnite.

Less common are ultrabasic dykes, which are exposed mainly in the central western parts of the island. A typical specimen of serpentinized peridotite from locality 54 consists mainly of serpentine, about 10 per cent clinopyroxene, and about one per cent of combined tremolite–actinolite, phlogopite or biotite, and "ore." Some serpentine is characterized by "mesh structure," and probably has replaced olivine. The crystallographic orientation of the clinopyroxene is uniform throughout a thin section, forming a poikilitic texture. Mica and tremolite–actinolite, being normally less than 0.2 mm in crystal length, are much finer grained than the pyroxene and original olivine. The biotite or phlogopite is intensely red in the maximum absorption position, which suggests that the mineral is richer in TiO_2 than in Fe^{++} (Deer, Howie, and Zussman, 1963, pp. 49, 71).

The ultrabasic and basic dykes intrude mainly acidic tuffs of map-unit 2. At several localities they are unconformably overlain by member B of the Cape Discovery Formation, the contact being exposed at locality 12 (Fig. 2).

On the extreme west side of the central part of the island, the ultrabasic rocks are in fault contact with a slice of member B of the Cape Discovery Formation.

The possible age range of the dykes is limited by the age of the overlying strata which is late Middle Ordovician, and of the intruded rocks which is possibly Early or early Middle Ordovician. If the latter assignment is correct, then the dykes must be of Middle Ordovician age.

Unaltered Basic Intrusion

Bromley Island. Whereas most intrusions cut map-unit 2 and probably pre-date the Cape Discovery Formation, a single diabase dyke at locality 56 intrudes the Middle Ordovician carbonates. A specimen of the dyke is sub-ophitic in texture and consists mainly of plagioclase laths and clinopyroxene, with lesser amounts of biotite and "iron ore," and some alteration products such as chlorite and talc. The plagioclase in this rock is zoned and ranges in composition approximately from sodic andesine to calcic labradorite. The zoning, range of composition, and lack of alteration of the feldspar contrasts with that of the pre-Cape Discovery intrusions on Bromley Island.

Altered Basic to Intermediate Intrusions

Southeast of Egingwah Bay. Dykes intruding map-unit 2 in the small outcrop area southeast of Egingwah Bay (loc. 58) range in composition from intermediate to basic and contain sodic plagioclase.

A specimen of altered diabase consists of clinopyroxene and albite in sub-ophitic texture with chlorite and subordinate "iron ore." A specimen of altered diorite is composed mainly of hornblende and albite with minor amounts of tremolite–actinolite, clinopyroxene, epidote, chlorite, carbonate, and opaque minerals. Reddish brown apatite is a relatively abundant and coarse-grained accessory. The albite, showing complete twinning and some undulatory extinction, appears to have been metasomatized; the hornblende is little altered.

Intrusions of this type were not seen in the overlying strata of the Cape Discovery Formation, which suggests that the intrusions may be of pre-late Middle Ordovician age.

Southwest of Taconite Inlet. Numerous sills are present in map-unit 2 southwest of Taconite Inlet.

A specimen from locality 59 examined in thin section consists mainly of feldspar with lesser fractions of chlorite, clinopyroxene, biotite, "iron ore," and probably prehnite. Most feldspar is albite, but a minor quantity is microperthite. The clinopyroxene is extensively replaced by chlorite. Two types of biotite are recognized. The first, which is considerably chloritized and comparable in grain-size to the feldspar and pyroxene, is probably an original constituent of the rock. The second, which is much finer grained, yellowish brown, and replaces all other minerals, probably represents a later alteration.

From the altered state of these intrusions and from their absence in the Cape Discovery Formation and younger units on Taconite Inlet, it is concluded that they are possibly of pre-Wildernessian age.

Unaltered Intermediate to Acidic Intrusions

Peninsula west of Bromley Island. A dioritic dyke cutting members A and B of the Cape Discovery Formation was observed on the peninsula west of Bromley Island at locality 57 (Fig. 15), and other intrusions of this type are probably present. A specimen examined in thin section consists mainly of feldspar, clinopyroxene, and chloritized biotite with less than one per cent of quartz, "iron ore," and accessories. The plagioclase is zoned approximately from sodic andesine to sodic labradorite. K-feldspar forms less than a third of the total feldspar, and some grains contain myrmekitic and graphic intergrowths of quartz.

The intrusion is late Middle Ordovician or younger, and may be related to the Early Devonian quartz diorites described below.

North of Ooblooyah Creek. Four small quartz dioritic intrusions were discovered by the writer in the eastern part of the ultrabasic mass north of Ooblooyah Creek in 1965, and a fifth was found by T. O. Frisch in the central part of that stock in 1966.

The pluton at locality 62 is of irregular shape, whereas those at localities 60 and 61 are tabular. The granitic rocks at locality 60 shown on the map as a single outcrop are, in fact, several sheets that are separated by serpentinite. Although these intrusions are dyke-like in form, their hypidiomorphic-granular texture appears more closely related to plutonic than to hypabyssal rocks.

The approximate mineral composition and classification of six specimens is shown in Table VIII. Although the rocks are given different names because of differences in the composition of the feldspar and proportion of quartz, they are mineralogically related.

The plagioclase ranges in composition from pure albite to intermediate andesine, and is generally zoned, normal zoning being predominant. Most plagioclase, except for the albite, is altered to white mica and epidote.

The K-feldspar commonly shows pericline twinning, and is probably mainly microcline. Some grains contain perthitic albite, and others myrmekitic quartz. The K-feldspar is relatively unaltered.

The hornblende is mainly unaltered, but replaced at the margins by tremolite–actinolite. It is pleochroic showing the following absorption colours: z: dark green with a shade of blue; y: dark green; x: light green with a shade of red-brown.

The biotite has inclusions of zircon, rutile, and apatite. It is nearly unaltered in the specimens from locality 60, partly to completely chloritized in the specimens from locality 61, and partly replaced by "ore" in those from 62. In the maximum absorption position, it is dark red-brown with a shade of olive.

The tremolite–actinolite is light green to colourless, and grows in felted aggregates from the margins of the hornblende crystals. It is commonly intergrown with the quartz, and to minor extent with the feldspar.

A K-Ar age determination on hornblende (GSC No. 1296) from locality 60 yielded an apparent age of 390 ± 20 m.y.[1] There are three reasons supporting this determination as the approximate age of emplacement: (1) from the state of the plagioclase it is inferred that the rock has not been metamorphosed; (2) the specimen came from a small high-level plug that probably cooled fairly rapidly; (3) within the confidence limits stated, the determination coincides with several other recent age determinations from northeastern Ellesmere Island (Frisch, 1967), especially with a K-Ar age of 390 m.y. (Frisch, pers. com.) from a zoned basic–ultrabasic body at Cape Fanshawe Martin. According to the most recent time scales (Friend and House, 1964; Bottino and Fullagar, 1966) the apparent age and its confidence limits are Early Devonian.

[1] $K = 0.57\%$; $Ar^{40}/K^{40} = 0.0254$; radiogenic argon 90%.

STRUCTURAL GEOLOGY AND TECTONICS

Times of Structural Deformation

Orogenic movements are inferred for the late Proterozoic to Early Cambrian interval, the Middle Ordovician (?), the Late Silurian to Middle Pennsylvanian interval, and the middle (?) Tertiary.

Late Proterozoic – Early Cambrian Orogeny

The data suggesting a late Proterozoic to Early Cambrian period of diastrophism may be summarized as follows:

1. Folding and metamorphism occurred in northeastern and northern Greenland in the late Proterozoic (Haller, 1961; Haller and Kulp, 1962). The resulting orogen, which is known as the Carolinidian, trends towards northernmost Ellesmere Island and the Cape Columbia metamorphic complex may be its continuation, as suggested by Haller (op. cit.).

2. Biotite from a gneiss in the type area of the Cape Columbia Group yielded an apparent age of 545 m.y. (Blackadar, 1960). This determination, which according to the latest time scale is Early Cambrian (Cowie, 1964), at best gives an upper limit for the metamorphism, because K-Ar ages from metamorphic terranes, as those from deep-seated plutons, are commonly too young. This is generally attributed to the slow cooling of deeply buried parts of the orogen. The cooling would be accelerated, however, by tectonic uplift that normally follows folding and metamorphism, and the date obtained may be close to that later event.

3. Prior to the Arenigian, probably mainly in the Cambrian, more than 3,000 feet of sandstone, siltstone, conglomerate, and shale was deposited at the present site of the United States Range and on northern Axel Heiberg Island. The mineralogy of these strata indicates that they were derived from metamorphic and plutonic source rocks. The coarse grade of the sediments suggests that the source terrane was close, and the facies relationships and directional structures suggest that it lay to the northwest (Trettin, 1968). Thus, these sediments indicate that prior to the Ordovician a metamorphic – plutonic complex was elevated in the region now occupied by the Cape Columbia Complex.

These three points make a reasonable case for a late Proterozoic – Early Cambrian orogeny on the north coast of Ellesmere Island. It remains uncertain, however, whether the strata of map-unit 1, originally assigned to the Cape Columbia Group, were metamorphosed during that orogeny or during an inferred Middle Ordovician event discussed below.

Middle Ordovician (?) Orogeny

An angular unconformity at the base of the late Middle Ordovician and (?) younger Cape Discovery Formation is evidence of an orogeny prior to the late Middle Ordovician. If the underlying beds of map-unit 2 are Early or early Middle Ordovician as suggested above, then this event must have occurred approximately in Middle Ordovician time.[1] If, however, map-unit 2 represents a less metamorphosed part of the Cape Columbia Complex, then this angular unconformity is related to the Early Cambrian or Proterozoic orogeny discussed below, or to an unknown event between Early Cambrian and Middle Ordovician times.

Late Silurian to Middle Pennsylvanian Movements

A marked angular unconformity lies at the base of the Carboniferous strata throughout the Arctic islands. This unconformity is present in the M'Clintock Inlet region, where the youngest dated unit beneath it is Late Silurian (Ludlovian) and the oldest unit above it is Middle Pennsylvanian.

Three orogenies are known to have occurred in other parts of the Arctic islands during the Late Silurian – Middle Pennsylvanian interval.

1. Late Silurian and (?) Early Devonian earth movements occurred in northern Axel Heiberg Island (Trettin, 1967) and were approximately contemporaneous with the Caledonian main orogeny of east Greenland (Haller and Kulp, 1962). Related movements in the region of Boothia Uplift and Cornwallis Fold Belt are restricted to the Early Devonian (Kerr and Christie, 1965).

There is some inconclusive evidence that the M'Clintock region may have been affected by the Caledonian movements: (a) The apparent age of 390 ± 20 m.y. from the quartz diorite north of Ooblooyah Creek and several other determinations from the region between Cape Fanshawe Martin and Cape Aldrich (Frisch, 1967) coincide, within the confidence limits stated, with Caledonian (*sensu stricto*) isotope ages from east Greenland (Haller and Kulp, 1962). On the other hand, if the quartz diorite north of Ooblooyah Creek is genetically related to the ultrabasic pluton which it intrudes, then the 390 m.y. age determination may represent a time of crustal extension rather than compression. (b) The Caledonian structures in northern Axel Heiberg Island and the Boothia–Cornwallis region trend northerly to northwesterly and cut across westerly to southwesterly trends of adjacent terrain unaffected by Caledonian diastrophism. Intersecting northerly and westerly trends also occur in the M'Clintock region.

2. The final orogeny of the eugeosyncline in northern Axel Heiberg Island climaxed in late Middle to Late Devonian time (Trettin, 1967).

3. The final orogeny of the miogeosyncline followed that of the eugeosyncline and probably occurred in the latest Devonian and/or Mississippian.

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[1]Biotite from a gneiss in the Cape Columbia – Cape Aldrich area yielded an analytical age of 445 ± 18 m.y. (Frisch, 1967). This age may indicate a reheating of the Cape Columbia Complex in the Ordovician.

Tertiary Orogeny

The Carboniferous and younger strata, as well as the underlying rocks, were folded and faulted by an orogeny that probably occurred in the Tertiary (Thorsteinsson and Tozer, 1960). On the Hazen Plateau, the youngest strata involved are Oligocene or Miocene (*map-unit 15C* of Christie, 1964; *see* Trettin, 1968, Fig. 1).

Structural Features and Their Ages

Styles of Folding

The rocks of map-unit 1 and the sedimentary and tuffaceous strata of map-unit 2 have a pronounced schistosity or axial plane cleavage. The geometry of the folds formed by these rocks has not been studied in the present area, but prevailing structural theory (e.g., Whitten, 1966) recognizes that rocks with such schistosity or cleavage generally form "similar folds" or "slip folds," produced by differential slippage on planes that are subparallel or parallel with the axial planes of the folds. These structures are Middle Ordovician and/or older as they occur only in pre-Wildernessian units.

The folds in the volcanic flows of map-unit 2 and in the Middle Ordovician to Pennsylvanian strata, on the other hand, are "concentric folds" and originated by flexure combined with differential slippage along bedding planes. This is inferred from a few cross-sections exposed on the coasts of M'Clintock Inlet, and from the general absence of a well-developed axial plane cleavage. The concentric folds are formed in Middle Ordovician or older to Permian rocks and are Middle Ordovician (?), Late Silurian to Middle Pennsylvanian, and Tertiary in age. The Tertiary folds are commonly broad and open.

Trends and Plunges

The area mapped is characterized by two sets of fold axes that lie approximately at right angles: one southerly and the other easterly.

Southwesterly to southeasterly trending folds predominate in the northwestern and central western parts of the area. From airphoto interpretation it appears that these trends also characterize the adjacent area to the west. The folds north of Egingwah Creek plunge gently in southerly directions; south of the creek, the axes are approximately horizontal. In the eastern and southern parts of the area, the folds trend mainly east-west and plunge gently in both directions.

Easterly and southerly trending strata intersect abruptly on the northeastern slope of Mount Ayles where their contacts are faulted, and about 8 miles southwest of the head of Ayles Fiord (Figs. 10 and 13). The change in trend is gradual at the southwest side of Mount Ayles, where the fold axes swing around from southerly to easterly directions.

Both easterly and southerly trends were established in the M'Clintock region prior to the late Middle Ordovician. The pre-Wildernessian age of the southerly trends is apparent on Bromley Island, where south-trending dykes are unconformably overlain

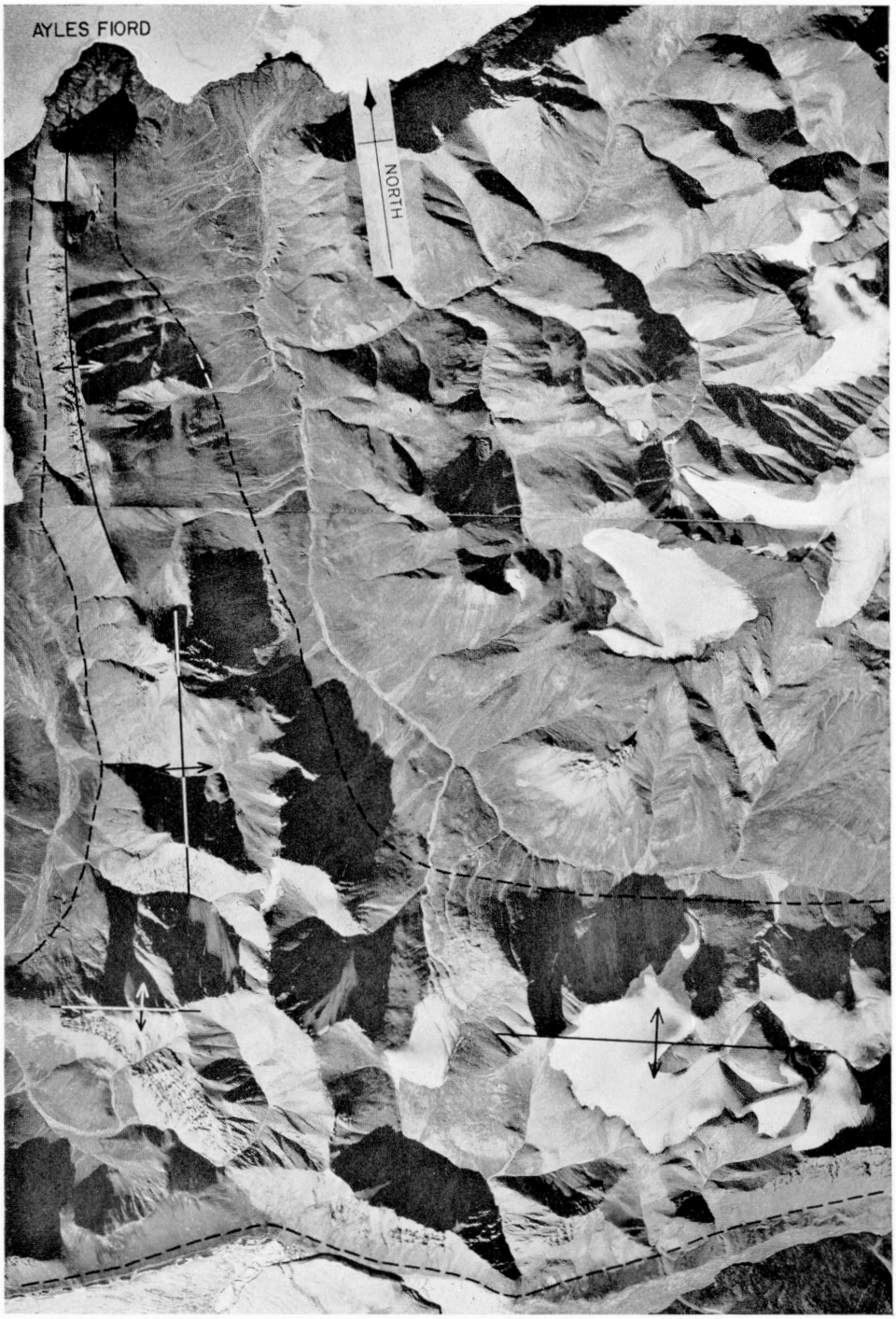

FIGURE 10. Vertical aerial view of the region south of the head of Ayles Fiord shows intersection of southerly and easterly trends. The folds are formed in carbonates of Middle Ordovician age or older. (Spartan A16690-116, 117)

by nearly horizontal beds of the Cape Discovery Formation: the pre-Wildernessian age of the easterly trends is apparent on the small island near the head of M'Clintock Inlet where metamorphic rocks of map-unit 1 have an easterly striking gneissosity.

Taconite River Fault Zone

The Taconite River fault zone is a south-trending complex zone of faulting parallel with Taconite River. Faults of this zone separate pre-Wildernessian strata on the west from late Middle and Upper Ordovician strata on the east.

Numerous thrust (?) faults that form low angles with bedding surfaces are present southeast and east of Bromley Island and in the vicinity of Taconite Inlet. Southwest of Taconite Inlet the faults are confined to map-unit 2 (Fig. 15), but north and east of the inlet slices of map-unit 2 are intercalated with slices of the Cape Discovery and Taconite River Formations. Southwest of Taconite Inlet the fault planes dip mainly southwest, which suggests tectonic transport to the northeast; northeast of the inlet they are folded and dip in various directions.

A high-angle reverse fault separates map-unit 2 from the Taconite River Formation east of Taconite River. The fault seems to be a thrust, but could also be an originally east-dipping normal fault rotated northeastward so that it now dips west, because folds north of Egingwah Creek are overturned in that direction.

About 7 miles south of the head of Taconite Inlet, an anticline formed in the Ayles Formation is truncated by a complex fault that probably had both strike-slip and dip-slip (terminology from Dennis, 1967) movement. Dextral strike-slip is inferred from the S-shape of the anticlinal axis, which suggests southward drag on the east side. Dip-slip with relative uplift of the western block is inferred from the absence of the Ayles Formation west of the fault where only Middle Ordovician and older rocks and some Pennsylvanian outliers are exposed.

Structural Trough between Zebra Cliffs and Ooblooyah Creek

A complex, east-west trending structural trough, mostly bounded by faults, is present on both sides of M'Clintock Inlet between Zebra Cliffs and Ooblooyah Creek. This structure involves mainly Pennsylvanian rocks and is probably of Tertiary age.

On the east side of the inlet this trough may be divided in three structural zones, characterized from north to south as follows: (1) Northwest of Crash Point, there is a belt of normal faulting. Two complex minor grabens are present, but the overall result of the faulting is a down-stepping from north to south. (2) East and southeast of Crash Point, the normal faulting passes into chaotic folding and faulting mainly in map-unit 10. Coaly shales of map-unit 10 are there overlain by an isolated, relatively small fault block of map-unit 14. The fault contact between map-units 10 and 14 cuts across the stratification of map-unit 14, but is subparallel with the stratification of map-unit 10. No other explanation seems possible than that this "rootless" block attained its present position by gravitational sliding. In the area immediately to the north the fault blocks step down from north to south so it is suggested that

the block slid in that direction. Evidence obtained by a brief reconnaissance suggested that other gravity slides may be present in this zone, and that coaly shales of map-unit 10 generally form the footwalls of these structures. (3) The zone of chaotic folding and faulting is bordered on the south by two anticlines with an intervening syncline (Fig. 9), formed mainly in the evaporites of map-unit 11. The syncline, which is broad and open, marks the axis of the structural trough. South of the third zone, the base of the Pennsylvanian succession rises from below sea-level to altitudes of more than 3,000 feet. This rise cannot be explained entirely by the northerly dip; a major fault may be present in the drift-covered area about 8 miles southeast of Crash Point.

The structure on the west side of the inlet, where a major graben borders the ultrabasic pluton on the north, is diagrammatically represented in cross-section A-A′ (Fig. 15).

Structural High Northwest of Ooblooyah Creek

The ultrabasic pluton northwest of Ooblooyah Creek forms a structural high that is bounded by faults on the north, south, and west. The northern contact, which was examined closely, is a normal fault. Middle Pennsylvanian strata that unconformably overlie the pluton on the east and southwest dip away from it at low to intermediate angles (*see* Frontispiece). This structural setting suggests that most upward movement occurred prior to the Middle Pennsylvanian, although some occurred at a later time, probably during the Tertiary orogeny.

Low-angle Faults at the Head of M'Clintock Inlet

Around the upper part of M'Clintock Inlet, lower Paleozoic carbonates overlie metamorphic rocks of map-unit 1. The contact between these two units is exposed on the west side of the inlet, near locality 3, where it is a south-dipping fault that forms low angles with the stratification of the carbonates. The carbonates, which are transected by many thrust faults (Fig. 7) represent mainly member B of the Ayles Formation (*see* Ayles Formation, age and correlation), but probably also the Marvin Formation (*see* Marvin Formation). The faulting probably occurred prior to the Middle Pennsylvanian because in this region Middle Pennsylvanian red beds rest unconformably on both the lower Paleozoic carbonates and map-unit 1. They are not preserved in the vicinity of the fault itself, but probably overlaid it prior to their removal by Pleistocene or Recent erosion.

Significance of Intersecting Trends

The presence of two sets of structural trends which are nearly perpendicular to each other is an unusual feature that requires an interpretation.

Easterly Trends

The easterly structural trends conform with the predominant structural grain of northern Ellesmere Island. They are aligned with gneissic trends in the Cape

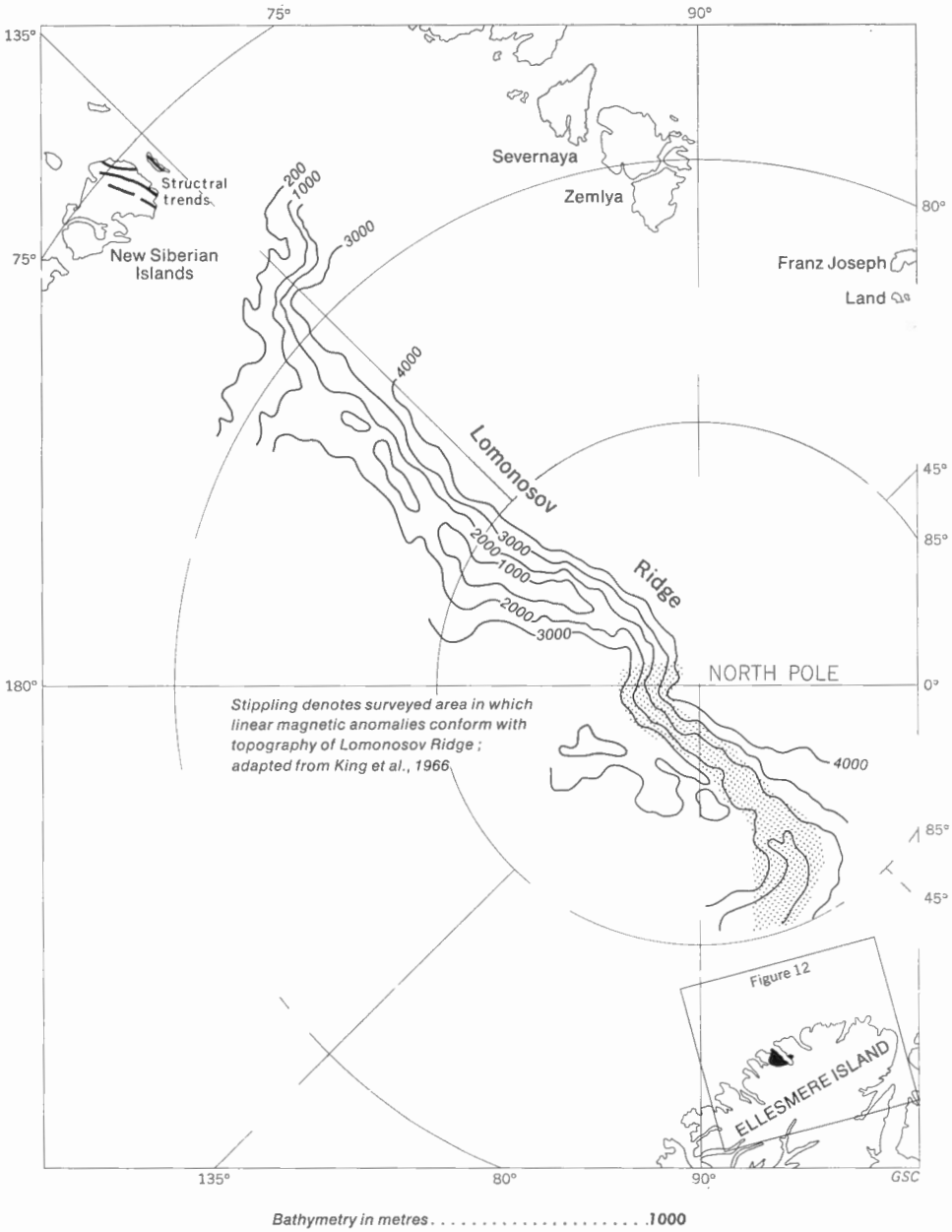

FIGURE 11. Index map of the Arctic Ocean, showing Lomonosov Ridge. Structural trends in New Siberian Islands and bathymetry adapted from Byrne and Fuller, 1960.

Columbia area (*see* Christie, 1964, Geological Map), and they are subparallel with Tertiary thrusts at the head of Tanquary Fiord, due south of the M'Clintock area (Fig. 12). These trends reflect the orientation of the stress field that dominated the structural history of the northern Ellesmere Island throughout the geological record.

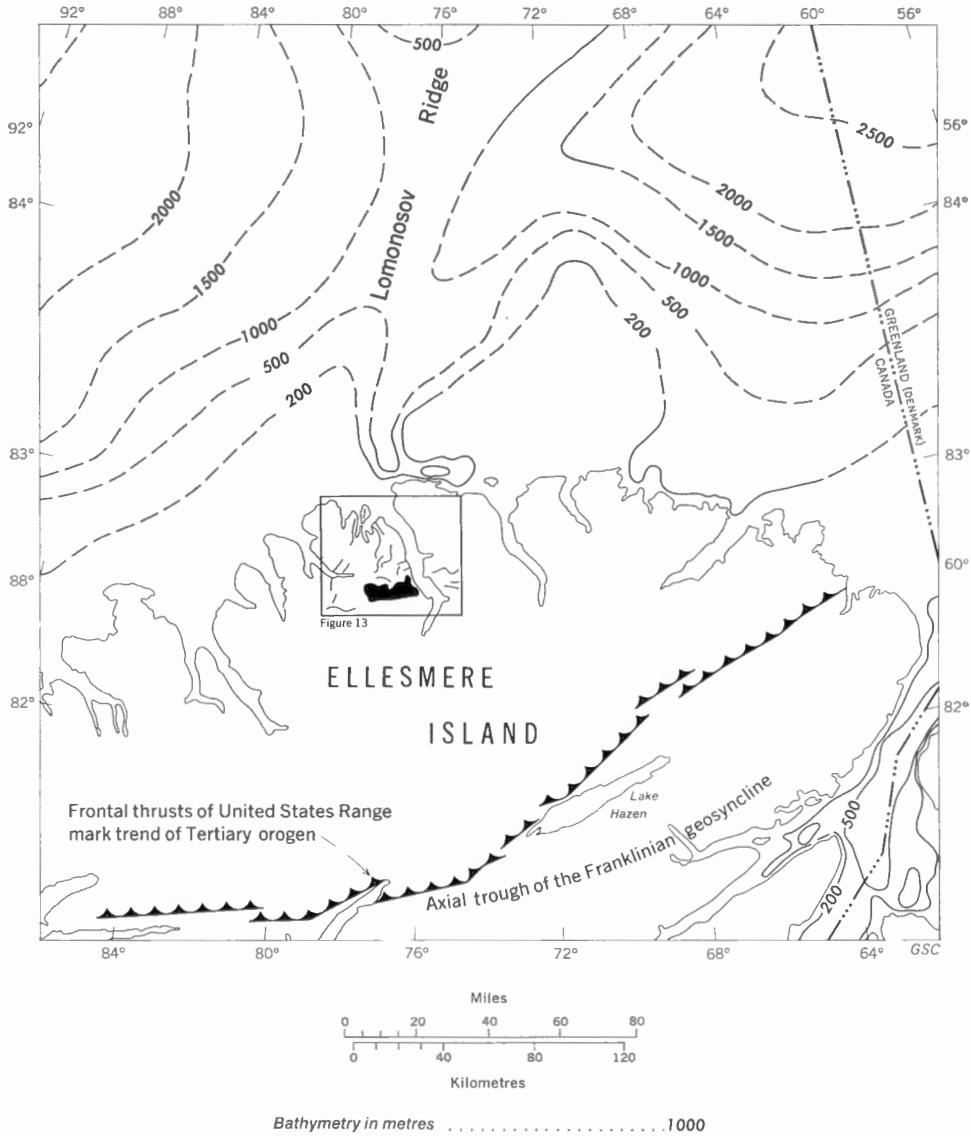

FIGURE 12. Index map of northern Ellesmere Island, showing southern extremity of Lomonosov Ridge and structural features on land. Bathymetry from Canadian Hydrographic Service, 1967.

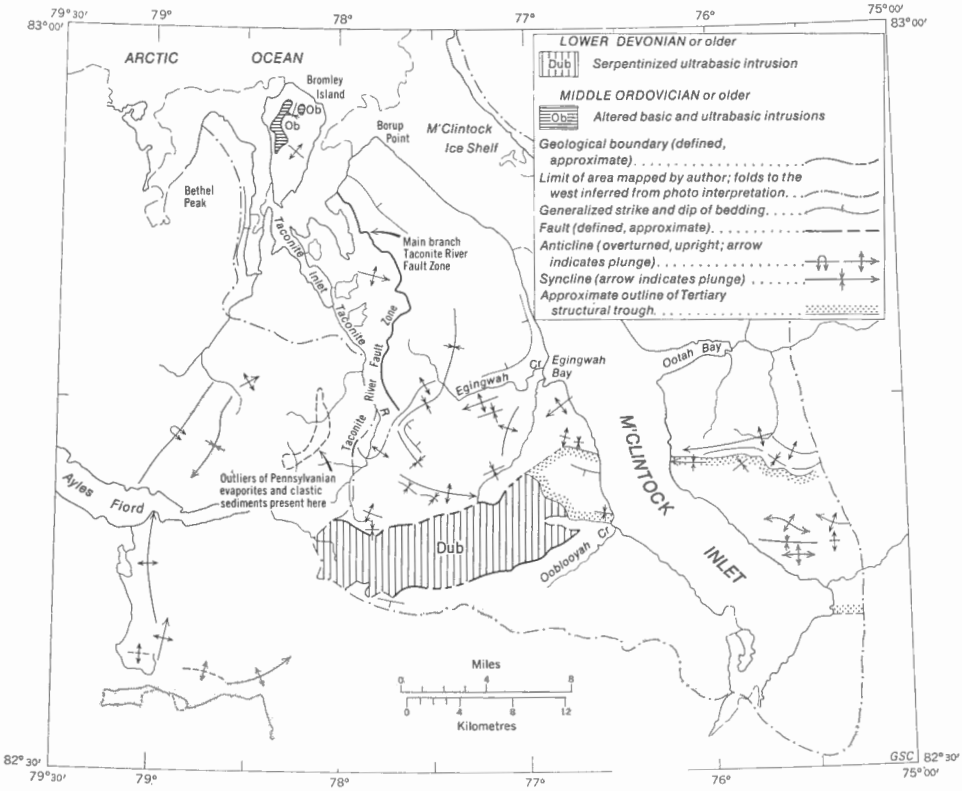

FIGURE 13. Structural trends and major basic and ultrabasic intrusions.

Relationships of Southerly Trending Structures with Lomonosov Ridge

The south-trending structures line up with the extreme southeastern flank of the Lomonosov Ridge (Figs. 12, 13). This probably is not accidental, but suggests some kind of structural continuity, a view supported by three lines of evidence.

1. Morphological studies by Dietz and Shumway (1961) indicated that the Lomonosov Ridge was not constructed by volcanic processes but by structural deformation. The overall topographic simplicity, slope convexity, and slight asymmetry of the ridge suggested to these authors that it represents a large fault block or overturned geanticline.

2. Aeromagnetic studies of the North American half of the ridge showed that the region between about 85° latitude and the Pole is characterized by isolated linear magnetic anomalies that conform with the topographic trend of the ridge (Fig. 11). These anomalies probably represent the structural trend of vertical or inclined sheets of volcanics or rocks of similar magnetic susceptibility (King, *et al.*, 1966).[1]

[1]It has been pointed out to the writer—by an unknown reviewer of a manuscript dealing with the Lomonosov Ridge—that these inferences are based on widely spaced flights, and that more detailed studies would be necessary to prove the parallelism of magnetic anomalies and topography.

3. The structural trends in the New Siberian Islands, as those in the M'Clintock area, line up with the Lomonosov Ridge (*see* Fig. 11).

The following summary of evidence presented in the preceding chapters indicates that areas continuous with the Lomonosov Ridge were elevated relative to areas on the east during two Paleozoic orogenies.

1. The clastic sediments in members A and B of the Cape Discovery Formation were derived from a nearby westerly or northwesterly upland source (Fig. 2) which occupied the present site of the Lomonosov Ridge on the continental shelf.

2. During the Late Silurian – Middle Pennsylvanian interval, the terrain west of the Taconite River fault zone was elevated relative to the terrain on the east.

The Lomonosov Ridge as a physiographic feature, however, dies out on the coast of Ellesmere Island, and there is no evidence of a relative uplift of the south-trending belt in post-Middle Pennsylvanian time. This implies either that the present Lomonosov Ridge dates back to Middle Pennsylvanian or earlier time, or that the movements which produced it were younger and were confined to the ocean. Profound changes have occurred in the lands around the Arctic Ocean since Pennsylvanian time, and the Arctic Ocean itself has been affected by Cenozoic rifting (Johnson and Heezen, 1967); therefore, the second alternative is probable. The movements that elevated the present Lomonosov Ridge relative to the ocean basins on either side, however, were probably guided by pre-existing bedding attitudes and ancient zones of weakness (such as the Taconite River fault zone) that extend to the land and account for the alignment of the structures on land with the bathymetric contours and magnetic anomalies in the ocean.[1]

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[1]The Russian geologists have generally held that the Lomonosov Ridge is underlain by continental crust and that some form of structural connection exists between Siberia and northern Ellesmere Island, although the specific tectonic interpretations have varied widely. The present consensus is probably expressed *in* Atlasov, I. P., Egiazarov, B. Kh., Dibner, V. D., Romanich, B. S., Zimkin, A. V., Vakar, V. A., Demenitskaya, R. M., Levin, D. V., Karasik, A. M., Hakkel, Ya. Ya., and Litvin, V. M.: Tectonic map of the Arctic and Subarctic; Communications Scientifiques présentées à la Commission de la Carte Géologique du Monde, pp. 121–128. Paris, 1966. The Lomonosov Ridge, previously considered a Mesozoic fold belt, is here pictured as part of an extensive "early Caledonian" orogenic system that also includes the Caledonian fold belts of Cornwallis Island and northern Axel Heiberg Island. The Caledonian *s.s.* isotope ages reported by Frisch (1967) and the present writer from northern Ellesmere Island are compatible with this view, as are the inferred Middle Ordovician movements in the M'Clintock Inlet area.

The leading Russian geophysical experts on the Arctic Ocean have recently proposed that the Lomonosov Ridge has a "subcontinental" crust, i.e., a relatively thin continental crust composed mainly of the "granitic" layer, the sedimentary layer being thin or absent (Demenitskaya, R. M., Karasik, A. M., Kiselev, Ju. G., Litvinenko, I. V., and Ushakov, S. A.: The transition zone between the Eurasian continent and the Arctic Ocean; *Can. J. Earth Sci.*, vol. 5, pp. 1125–1129). This hypothesis is not incompatible with the conclusion, reached in the present study, that the Lomonosov Ridge, or a part of it, was elevated repeatedly in the early and middle Paleozoic. These uplifts seem to have resulted in relatively deep erosion and in the exposure at the surface of metamorphic rocks. The subsequent record of the Lomonosov region, however, is unknown; the possibility, for example, that upper Paleozoic to Tertiary sediments accumulated there cannot be dismissed.

North American views have been more varied. N. A. Ostenso, the leading North American geophysical investigator of this region stated in 1966: "... Soviet investigators argue that the Lomonosov Ridge is a sedimentary structure folded during Mesozoic time; ... bathymetric profiles across the Alpha Cordillera suggest that it is a horsted section of the oceanic crust ... Magnetic data supports both these theories" (The structure of the Arctic Ocean Basin; *New York Acad. Sci.*, Ser. II, vol. 28, pp. 975–980, *see* p. 978).

The Zone of Structural Intersection; a Site of Repeated Crustal Extension

Two major features mark the zone in which southerly and easterly trends intersect; the Early Devonian or older ultrabasic pluton, and the structural trough described above. The pluton was probably emplaced along a deep-reaching tension fracture, and the trough, which locally forms a graben (*see above*), is also indicative of crustal extension. Another ultrabasic pluton similar to the Ooblooyah Creek body was discovered by T. O. Frisch east of M'Clintock Inlet and the present map-area in 1967 (Frisch, 1967).

Some Paleogeographic and Tectonic Inferences from the Middle Ordovician to Late Silurian Tectonic Record

Rate of Subsidence

During the Wildernessian to Ludlovian interval, which is not completely represented, more than 14,600 feet of strata was deposited, and during the Wildernessian to Richmondian part alone, more than 12,600 feet. These figures indicate high rate of subsidence and deposition, i.e., truly geosynclinal conditions.

Paleobathymetry

The inferred depositional environments show a considerable range in depth. These may be assigned (Fig. 14, "Bathymetry") to four levels, as follows: (1) non-marine environments represented by a regolith and by fluvial sediments; (2) shallow-water marine environments represented by unfossiliferous carbonates typical of evaporitic assemblages, and by interbedded red beds and carbonates; (3) shelf environments characterized by carbonates with benthonic faunas; (4) environments below shelf edge represented by argillaceous carbonates with graptolites and by turbidites.

The resulting curve of depth of water versus stratigraphic position and time shows that shallow marine and shelf conditions prevailed. There were, however, two episodes of non-marine deposition coinciding with uplifts in the source area: the first in the Wildernessian and the second in the Richmondian; and there was one episode of deep submergence in the Richmondian and Llandoverian.

Clastic Sedimentation

Uplifts of the Source Area and Changes in its Composition

Episodes during which the source area was high are inferred from sandstones and conglomerates in the stratigraphic column of the M'Clintock area (Fig. 14, solid lines), and also from impure carbonates (dotted line) that are probably shelf equivalents of near-shore and non-marine clastic sediments.

The composition of the source region, shown in the last column of Fig. 14, was deduced in the following manner from the 22 point count analyses given in Tables III to VI. The carbonate fraction of these specimens is considered to have been derived from contemporaneous marine sediments. The silicate fraction was assigned

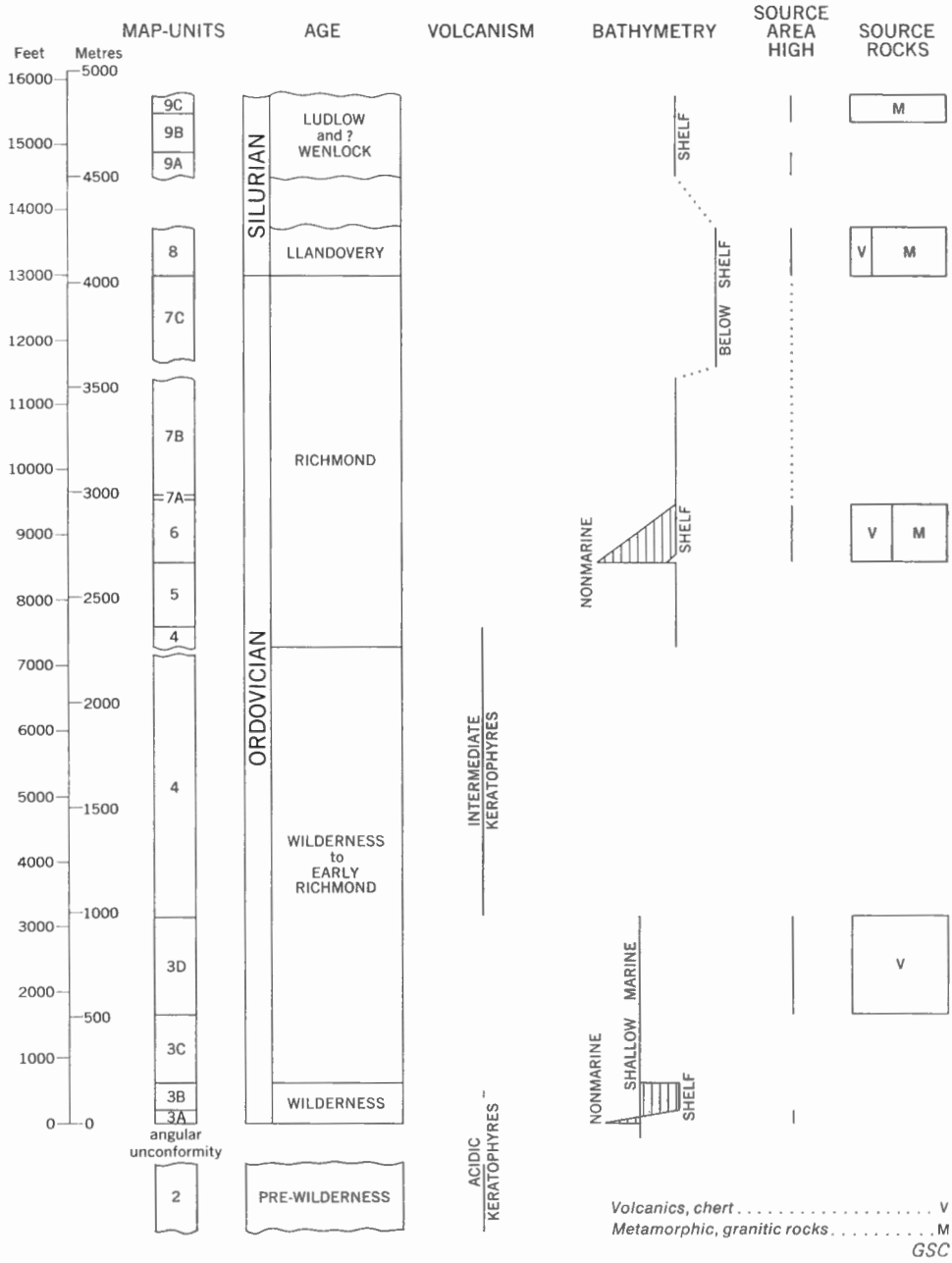


FIGURE 14. Chart illustrating tectonic inferences from the Ordovician–Silurian stratigraphic record.

to two genetic groups; one, characterized by volcanic rock fragments, chlorite and chert, is comparable to map-unit 2; the other, characterized by muscovite and fragments of phyllite and schist, is referable to map-unit 1. Quartz and feldspar, which are less diagnostic, were assigned to these two groups according to their volcanic or non-volcanic characteristics, and according to the relative abundances of the more diagnostic fragments. The results obtained are not numerically significant, but they demonstrate that in the course of late Middle Ordovician to Late Silurian time metamorphic and plutonic rocks became gradually more widely exposed in the source area. This suggests that the older suite of rocks became progressively denuded in the source area as a result of repeated uplifts. (*See* Pls. I and II.)

Location of Source Area

Lithofacies and paleocurrent studies lead to the conclusion that the Middle Ordovician to Late Silurian clastic sediments were derived from terrains in the region now occupied by the Arctic Ocean. In several cases the coarseness of the debris suggests a nearby source. The Wildernessian strata probably came from an ancestral Lomonosov Ridge, but other units probably had more easterly sources.

The provenance of some Ordovician and Silurian units is briefly reviewed below.

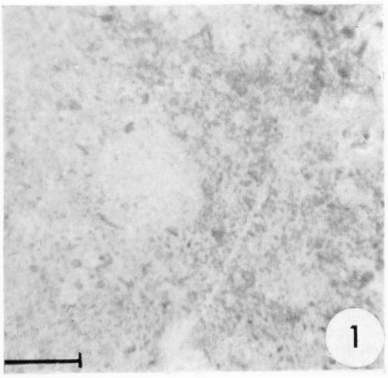
The source of the clastic sediments in members A and B of the Cape Discovery Formation probably lay a short distance west or northwest of the unnamed cape west of Bromley Island, where coarse boulder–conglomerate occurs in the basal strata of the formation (Fig. 2).

Boulder– and cobble–conglomerates of the Taconite River Formation are mostly confined to the area between Egingwah Creek and Borup Point (Fig. 2). The largest clasts seen, boulders up to 2 feet in diameter, occur in the northernmost outcrops examined, which suggests that their source was nearby and lay to the north or northwest.

The Imina Formation is too poorly exposed in the M'Clintock region for satisfactory paleocurrent studies. An extensive study of sole markings on turbidites of the Hazen Plateau (Trettin, 1968), however, suggests that the sediments there were derived from northwesterly sources. The average direction of transverse transportation inferred from 625 readings at eight stations between Alert and Tanquary Fiord is 146 degrees (reference meridian 76°W). In the M'Clintock region, this average direction is approximately parallel with the west coast of M'Clintock Inlet between Murphy Point and Zebra Cliffs. It is remarkably close to the mean paleocurrent direction of map-unit 10A at locality 43, determined as 144° ± 140 on the basis of 14 readings.

Volcanism

Volcanic rocks are restricted to map-unit 2, the Cape Discovery Formation, and the M'Clintock Formation—all units that are stratigraphically close to the sub-Wildernessian unconformity (Fig. 14); this suggests that the volcanism was the result of crustal instability preceding and following the inferred Middle Ordovician (?) orogeny. It is possible that the volcanism was a surface expression of contemporaneous granitic intrusion at depth because the rocks are acidic to intermediate in composition.



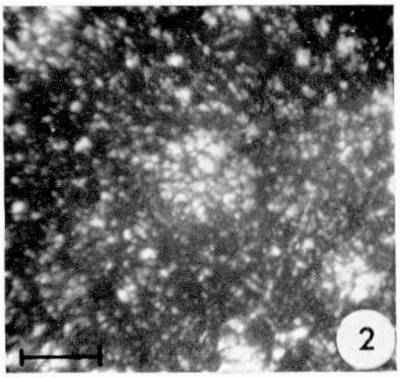
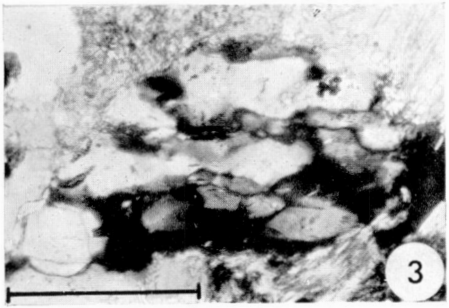
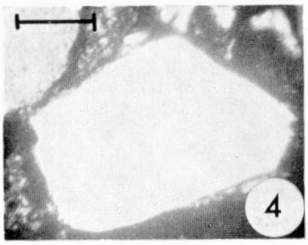
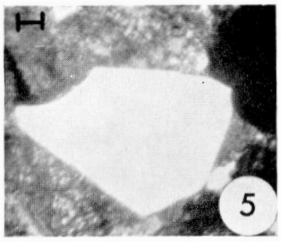


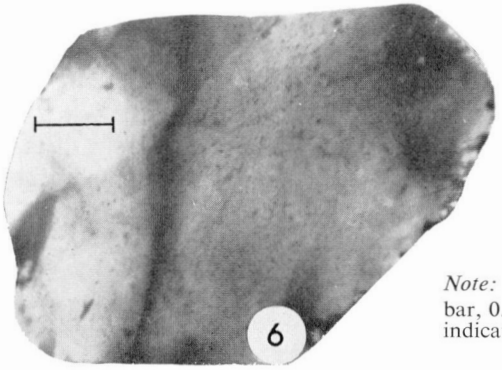
PLATE I

Photomicrographs of clastic particles and their presumed sources: quartz, quartzite, cherts, mica.



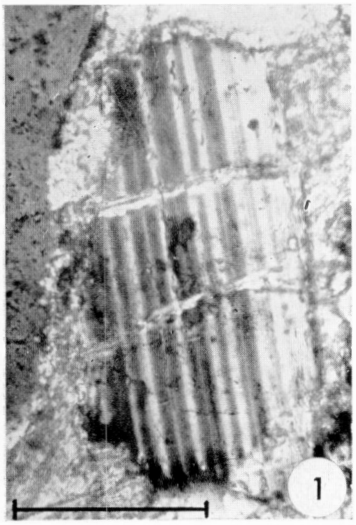






Note:
bar, 0.1 mm long, indicates scale.

1. Part of detrital chert grain showing inclusion-free spheroidal nodules that are possibly of radiolarian origin; pebble-conglomerate at the base of the Cape Discovery Formation, member A; ordinary light. (HPT-68-L3)
2. The same grain under crossed nicol prisms. (HPT-68-L4)
3. Detrital grain of schistose quartzite; map-unit 9C; nicol prisms crossed. (HPT-68-L7A)
4. Detrital quartz grain. Euhedral habit, clearness, and association with acidic volcanic rock fragments suggest that the quartz is of volcanic origin; Cape Discovery Formation, member D; nicol prisms crossed. (HPT-68-L16)
5. Microphenocryst of quartz in acidic keratophyre of map-unit 2V. Acidic keratophyres of pre-Wildernessian age were probably the source of the volcanic quartz in the Ordovician and Silurian sandstones. Nicol prisms crossed. (HPT-68-L11)
6. Detrital quartz grain showing undulose extinction; Imina Formation; nicol prisms crossed. (HPT-68-L11)
7. Detrital muscovite and biotite; map-unit 9C; ordinary light. (HPT-68-L5C)



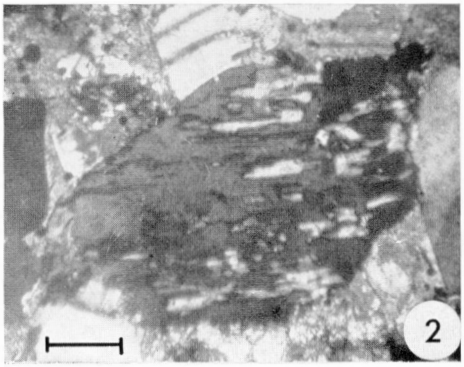
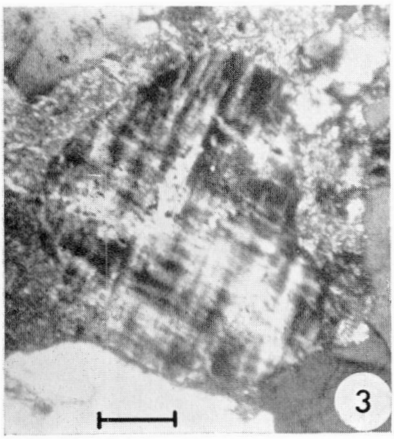
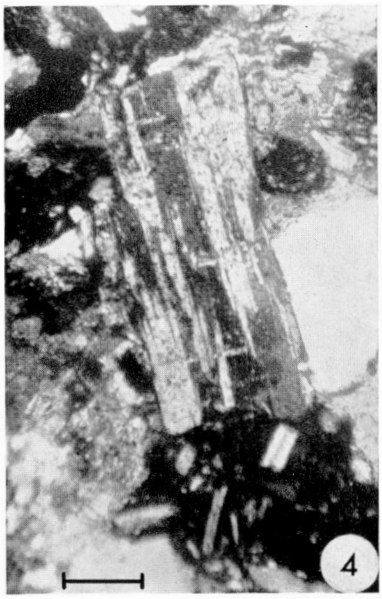


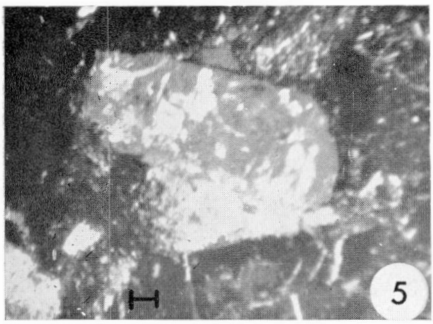
PLATE II

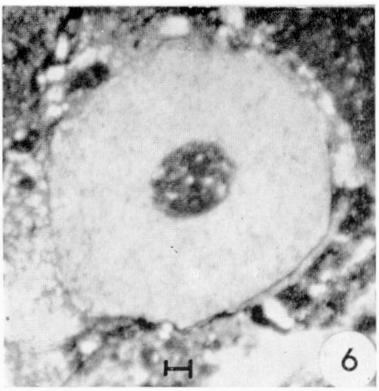
Photomicrographs of clastic particles and their presumed sources; feldspar, volcanic rock fragment, carbonate.

Note: bar, 0.1 mm long, indicates scale.









1. Detrital albite showing 001 cleavage and negative extinction; Imina Formation; nicol prisms crossed. (HPT-68 -L8A)
2. Detrital microperthite; Imina Formation; nicol prisms crossed. (HPT-68-L9)
3. Detrital microcline; Imina Formation; nicol prisms crossed. (HPT-68-L27)
4. Detrital albite showing "chess board" twinning, and volcanic rock fragment of intermediate composition; Imina Formation; nicol prisms crossed. (HPT-68-L10)
5. Microperthite microphenocryst in keratophyre breccia of map-unit 2A. Acidic to intermediate keratophyres of pre-Wildernessian age are the probable source of most feldspar in the Ordovician and Silurian sandstones. Nicol prisms crossed. (HPT-68-L36)
6. Echinoderm columnal in pebble-conglomerate of the Imina Formation; ordinary light. (HPT-68-L24)

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APPENDICES

APPENDIX 1: Terms Used to Indicate the Size Ranges of Carbonate Crystals

The grades distinguished correspond to the Wentworth scale, and the nomenclature used has been adapted from Leighton and Pendexter (1962) and Drummond (1963). In this nomenclature, carbonate grains of sand size are described in terms of sand grades (i.e. as fine, medium, coarse, etc.), those of silt size are termed microcrystalline, and those of clay size, cryptocrystalline. Although the so-called cryptocrystalline grains are visible in thin section under the highest power objective, the term cryptocrystalline seems justified as optical tests cannot be made on these crystals.

2–1 mm	very coarsely crystalline
1–0.5 mm	coarsely crystalline
0.5–0.25 mm	medium crystalline
0.25–0.12 mm	finely crystalline
0.12–0.06 mm	very finely crystalline
0.06–0.004 mm	microcrystalline
0.06–0.03 mm	coarsely microcrystalline
0.03–0.004 mm	finely microcrystalline
0.004 mm or less	cryptocrystalline

APPENDIX 2: Terms Used to Indicate the Thickness of Strata (*after McKee and Weir, 1953*)

Thickness greater than 120 cm	very thick bedded
120–60 cm	thick bedded
60–5 cm	thin bedded
5–1 cm	very thin bedded
1 cm–2 mm	laminated
2 mm or less	thinly laminated

APPENDIX 3: Chemical Analyses
(by S. Courville)

Accuracy

J. A. Maxwell, head of the Analytical Chemistry Section of the Geological Survey, states that the confidence limits of the rapid method chemical analyses are as follows:

(a) *determined simultaneously by X-ray fluorescence spectroscopy*

	1 standard deviation	
SiO_2(30–75%)	±1.2% in the reported value	
(81%)	±1.2%	"
Al_2O_3 (up to 20%)	±0.7%	"
Total Fe as		
Fe_2O_3 (up to 15%)	±0.5%	"
CaO (up to 40%)	±0.3%	"
MgO (up to 40%)	±1.0%	"
K_2O (up to 5%)	±0.1%	"
TiO_2 (up to 2%)	±0.05%	"
MnO (up to 1%)	±0.02%	"

(b) *determined separately by chemical methods*

	2 standard deviations	
FeO (up to 15%)	±0.2% in the reported value	
Na_2O (up to 10%)	±0.15%	"
P_2O_5 (up to 1%)	±0.04%	"
CO_2	±0.1%	"
H_2O (total)	±0.1%	"

TABLE I *Map-unit 2. Chemical composition of volcanic flow rocks (2 specimens)*

Current No. Analysis No. Field No.	Spec. 1 66-35-860 Tm-65-220b	Spec. 2 66-35-861 Tm-65-H-21
	%	%
SiO_2	81.0	69.9
TiO_2	0.26	0.56
Al_2O_3	7.1	10.1
Fe_2O_3	1.5	5.9
FeO	0.9	1.1
MnO	0.08	0.26
MgO	0.9	3.4
CaO	0.3	1.5
Na_2O	1.6	3.3
K_2O	5.9	1.9
H_2O	0.9	2.3
P_2O_5	0.03	0.07
CO_2	0.5	0.9
	101.0	101.2

Specimen 1. From locality 4 (Fig. 15).
Macroscopic: a greyish red to moderate red weathering, aphanitic–porphyritic rock with phenocrysts up to about 3 mm.
Microscopic: the phenocrysts are K-feldspar (sanidine not represented), microperthite, and sodic plagioclase. The groundmass is microfelsitic, and shows some argillic and calcareous alteration.

Specimen 2. From locality 6.
Macroscopic: a pale and light grey, laminated, aphanitic rock.
Microscopic: a cryptocrystalline, felsitic groundmass contains microphenocrysts of quartz and feldspar up to about 120 microns in size, and "iron ore." In the pale red layers, the groundmass is masked by iron oxide coating. Most feldspar is sodic plagioclase, but some K-feldspar may be present.

TABLE II | *M'Clintock Formation. Chemical composition of volcanic flow rocks (2 specimens)*

Current No.	1	2
Analysis No.	66-35-863	66-35-862
Field No.	Tm-65-F-61	Tm-65-2c-1
	%	%
SiO_2	64.3	56.4
TiO_2	0.88	0.72
Al_2O_3	14.6	17.5
Fe_2O_3	3.2	3.8
FeO	2.1	3.4
MnO	0.10	0.09
MgO	2.2	4.4
CaO	1.9	0.8
Na_2O	6.5	3.2
K_2O	0.1	5.1
H_2O	1.8	3.5
P_2O_5	0.25	0.23
CO_2	1.1	0.1
	99.3	99.0

Specimen 1. From the basal strata of member A at locality 16.
Macroscopic: a pale red to greyish red weathering, aphanitic-porphyritic flow rock.
Microscopic: phenocrysts of feldspar, chlorite, and "iron ore." Most feldspar is sodic plagioclase, zoned from calcic oligoclase to sodic albite, which is much sericitized, and has inclusions of apatite. Chlorite and "iron ore" are pseudomorphous after pyroxene or amphibole, and possibly after biotite. The groundmass consists of feldspar, mainly microlites of sodic plagioclase, chlorite, "iron ore," and minor amounts of quartz.

Specimen 2. From member A at locality 17.
Macroscopic: a pale brown weathering, aphanitic-porphyritic flow breccia.
Microscopic: most phenocrysts are of feldspar and a few of chlorite. The feldspar is mainly sodic plagioclase, and is partly skeletal. Some grains are zoned from oligoclase to albite. Only a minor fraction of K-feldspar was detected, which partly mantles the plagioclase. The groundmass consists of feldspar, chlorite, and cryptocrystalline phyllosilicates, and is altered to minor extent by carbonate.

APPENDIX 4: Petrographic Analyses

Accuracy of Point Count Results

The standard deviation of the point count results is given by the following formula (van der Plas and Tobi, 1965):

$$\sigma = \sqrt{\frac{p\,(100-p)}{n}}$$

where p equals the real content of the mineral in per cent by volume and n the total number of points counted.

This means that the estimate will lie between $+\sigma$ and $-\sigma$ in 68 out of 100 cases, and between $+2\sigma$ and -2σ in 95 out of 100. In the following table the values of 2σ, and thus the confidence limits at the 95 per cent confidence level, are listed for various values of p and n.

These confidence limits, however, apply only under the following conditions:

1. The distance between the points analyzed must be larger than the largest mineral grains. The point distance used is 0.36 mm; so this condition is not fulfilled in the case of some medium-grained and all coarser grained sandstones and igneous intrusions.

2. The types of fragments counted must be distributed randomly throughout the section. This is generally so, with the exception of a few laminated sandstones, in which the opaque minerals are concentrated in thin layers.

3. The identification of the minerals must be correct. Generally, the operator's error is insignificant; however, the following pairs of fragments were difficult to distinguish and are subject to significant errors: chert and microfelsite; highly altered feldspar and argillaceous rock fragments; and, to lesser extent, quartz and untwinned, metamorphic feldspar (Table VI). Where argillaceous material is associated with carbonate, it is generally masked by the carbonate because of the much higher birefringence of calcite and dolomite. In this case, only analysis by acid leaching gives a reliable estimate of carbonate.

Values of 2σ

p	n=200	n=300	n=400	n=500	n=600
%	%	%	%	%	%
2; 98	1.98	1.62	1.40	1.25	1.14
5; 95	3.1	2.5	2.0	1.9	1.8
10; 90	4.2	3.5	3.0	2.7	2.4
15; 85	5.0	4.1	3.6	3.2	2.9
20; 80	5.7	4.6	4.0	3.6	3.3
25; 75	6.1	5.0	4.3	3.9	3.5
30; 70	6.5	5.3	4.6	4.1	3.7
40; 60	6.9	5.7	4.9	4.4	4.0
50	7.1	5.8	5.0	4.5	4.1

TABLE III | *Cape Discovery Formation, Member D—Composition and textural features of sandstones (3 specimens)*

Composition based on analysis of about 300 points per section
Locality: 3-4

Field No.	Tm-65-F-43	Tm-65-F-42	Tm-65-F-51
Volcanic rock fragments	46%	40%	33%
Feldspar	18	35	36
Quartz	3	11	22
Chert and/or microfelsite	tr	1	1
Muscovite, chlorite	1	tr	tr
Carbonate	1	—	8
Opaque matter	31	13	tr
Rounding	pebbles, coarse sand: rounded to sub-rounded; very fine to medium-grained sand: subrounded to subangular	subrounded	subrounded to subangular
Sorting	mainly good, but coarse sand and conglomerate are bimodal	good	fair
Grade	conglomerate, coarse sandstone, inter-laminated with very fine grained sandstone	fine-grained sandstone	medium-grained sandstone
Cement, matrix	iron oxide and (?) quartz	quartz	muscovite, chlorite
Colour	greyish red to moderate red 5R 4/2–5R 5/4	greyish red to moderate red 5R 4/2–5R 5/4	light olive-grey 5Y 5/2

TABLE IV *Taconite River Formation—Composition of sandstones (6 specimens)*

Composition based on analysis of about 300 points per section

Field No.	Tm 65-8b-2	Tm 65-A-10	Tm 65-243b	Tm 65-243d	Tm 65-A-3	Tm 65-A-4
Carbonate and masked argillaceous matter	43%	3%	46%	9%	65%	85%
Quartz	1	37	23	53	14	10
Chert	22	48	3	2	tr	tr
Feldspar	2	3	6	4	9	3
Volcanic rock fragments	18	5	11	5	—	—
Chlorite, altered tuff	9	1		3	3	tr
Muscovite	—	tr	8	2	4	2
Phyllite	4	1		7		—
Schist	—			4	2	—
Opaque matter	1	2	3	11	3	tr
Grade	very coarse grained, pebbly	medium- to coarse-grained, pebbly	fine- to medium-grained	fine-grained	very fine to fine-grained	very fine grained, silty

TABLE V A | *Imina Formation—Composition of sandstones (7 specimens)*

Composition based on analysis of about 300 points per section

Field No.	Tm 67-G-1	Tm 67-G-2	Tm 65-10e	Tm 67-G-4	Tm 67-G-3	Tm65-G-31	Tm 65-230
Carbonate and masked argillaceous matter	87%	44%	41%	30%	44%	44%	46%
Quartz	10	9	42	52	42	42	32
Feldspar	1	13	8	6	6	6	10
Microfelsite and chert undifferentiated		6	4	2	tr	3	2
Chert		4	2	7	4	2	tr
Volcanic rock fragments	2	21	2	3	2	2	2
Chlorite		3	tr*	tr	tr	1	4
Muscovite, phyllite; minor quartz-muscovite-chlorite schist		tr	tr*	tr	2	tr	3
Biotite	—	tr	—	—	tr	—	tr
Opaque	tr	tr	tr*	tr	tr	tr	1
Grade	medium-grained	medium-grained	fine- to medium-grained	medium-grained	fine-grained	fine-grained	very fine to fine-grained

*trace amounts add up to 1%

TABLE V B | *Imina Formation—Grain size parameters and carbonate content of sandstones (5 and 4 specimens respectively)*

Grain size parameters based on maximum diameter of about 100 grains of quartz, chert, feldspar, or volcanic rock fragments in thin section. Grains were selected on the basis of a grid system. The thin section parameters have not been converted to sieve equivalents.

Carbonate content established by insoluble residue analysis. Confidence limits express one half of the difference between duplicate analysis.

Percentage of masked materials obtained by subtraction of results of insoluble residue analysis from results of point count analysis.

Field No.	Mean grain size (ø)	Standard deviation	Skewness	% Carbonate	% Masked materials
Tm 65-10e	1.97±0.14	0.85	0.43		
Tm 67-G4	1.73±0.15	0.89	0.21	30.1±0.4	0
Tm 67-G3	2.19±0.11	0.68	0.03	33.7±1.7	10
Tm 65-G31	2.54±0.12	0.75	0.02	35.4±0.4	9
Tm 65-230f	3.07±0.11	0.68	0.21	34.8*	11

*one analysis only

TABLE VI | *Marvin Formation and Map-unit 9C—Composition of sandstones (4 specimens)*

Composition based on analysis of about 600 points per section

Field No.	Tm 65-238c	Tm 66-305a-D1	Tm 66-305a-E1	Tm 66-304-F3
Unit	Marvin Fm., Member C	Map-unit 9c: section at b; unit 1	Map-unit 9c: section at b; unit 2	Map-unit 9c: section at b; unit 3
Quartz	42%	56%	52%	53%
Muscovite, chlorite, biotite; phyllite, schist	28	18	33	29
Carbonate and masked argillaceous matter	21	14	6	10
Feldspar	7	9	7	8
Chert	tr	tr	tr	—
Opaque matter	2	3	2	tr
Grade	fine-grained	fine-grained	fine-grained	fine-grained

TABLE VII | *Map-unit 10—Composition of sandstones (6 specimens)*

Composition based on analysis of 200 to 300 points per section

Field No.	Tm 65-17a	Tm 65-C2	Tm 65-16a-4	Tm 65-34a	Tm 65-20a	Tm 65-222c
Map-unit	10A	10B	10B	10C	10C	10D
Quartz, quartzite	16%	66%	76%	37%	32%	80%
Volcanic rock fragments, chlorite	57	11	1	2	39	
Carbonate and masked argillaceous matter	6	17	13	26	2	
Metamorphics, muscovite	tr	2	5	15	4	20
Chert	11	tr	tr	6	13	
Feldspar	7	2	2	2	7	
Opaque matter	3	2	3	12[1]	3	
Grade red	coarse- to very coarse grained, pebbly	very fine grained	very fine grained	medium-grained	medium-grained	very fine grained

[1]This is a specimen of 'red bed'; much of the opaque material is an iron oxide coating on the sand grains.

TABLE VIII *Quartz dioritic intrusions north of Ooblooyah Creek; mode, composition of plagioclase, and classification (6 specimens)*

Composition based on analysis of about 300 points per section.
Composition of plagioclase inferred from extinction angle x′ versus 010 in sections normal to a. Classification after Brown, 1952.

Locality	60	60	61	61	62	62
Field No.	Tm 65-206a-1	206a-2	222a-1	222a-2	227g-1	227g-2
Feldspar	80%	77%	68%	78%	71%	72%
Ratio K-fsp/ plagioclase	0.3	0.2	0.1	0.2	0.2	0.2
Composition plagioclase	An_{20}-An_{28}	An_{27}-An_{37}	An_{28}-An_{37}	An_{27}-An_{38}	An_{0}-An_{9}	
Quartz	4%	8%	23%	14%	22.5%	21
Hornblende	7	6	3	2%		
Biotite	0.5	1	0.5	chloritized	0.5	1
Chlorite	—	—	1.5	3%	—	—
Actinolite	8.5	8	—	—	4	4
Epidote	—	—	1	1	—	—
Carbonate	—	—	1	—	—	—
Opaque	—	—	2	2	2	2
Classification	Syenodiorite	Diorite	Quartz diorite	Quartz diorite	Albite granite	Albite granite

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151 Precambrian geology of Boothia Peninsula, Somerset Island, and Prince of Wales Island, District of Franklin, *by* R. G. Blackadar, $2.25 (M42–151)

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