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STRATIGRAPHY OF THE PROTEROZOIC THULE GROUP, SOUTHEASTERN ELLESMERE ISLAND, ARCTIC ARCHIPELAGO

T. FRISCH
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STRATIGRAPHY OF THE PROTEROZOIC THULE GROUP, SOUTHEASTERN ELLESMERE ISLAND, ARCTIC ARCHIPELAGO

Abstract

The Thule Group comprises unmetamorphosed, gently dipping sedimentary and basaltic rocks unconformably overlying crystalline basement in chiefly two coastal areas of southeastern Ellesmere Island, namely Clarence Head-Cape Combermere and Goding Bay-Gale Point. The group is subdivided into six units, from bottom to top as follows:

unit I - sandstone and stromatolitic dolomite;
unit II - tholeiitic basalt sills and lavas and minor pyroclastics interbedded with red sandstone, siltstone and shale;
unit III - variegated sandstone, siltstone and shale, underlain by stromatolitic dolomite;
unit IV - white orthoquartzite;
unit V - variegated sandstone, siltstone and shale;
unit VI - mainly light weathering orthoquartzite.

The sediments were deposited in a shallow marine to terrestrial environment; the extrusive igneous rocks are terrestrial. The Thule Group is thickest at Goding Bay, where 1000 m of strata were measured in a section whose lower contact is not exposed and whose top is an erosion surface. The northern limit of Thule deposition lies between 78°32'N and 79°N. Whole-rock ^{40}K-^{40}Ar *ages of basalt from unit II indicate that the Thule Group is 1.0-1.2 Ga old.*

Résumé

Le groupe de Thule, composé de roches sédimentaires et basaltiques non métamorphisées, faiblement inclinées, déposées en discordance sur un socle rocheux cristallin, se retrouve surtout à deux endroits sur la côte sud-est de l'île Ellesmere, soit à la pointe Clarence et au cap Combermere et à la baie Goding et la pointe Gale. Il comprend les six unités suivantes, données en ordre ascendant:

unité I - grès et dolomie stromatolitique;
unité II - basalte tholéiitique, filons-couches, laves et quelques pyroclastites, avec des intercalations de grès rouge, de siltstone et de schiste argileux;
unité III - grès bariolé, siltstone et schiste argileux, avec dolomie stromatolitique sous-jacente;
unité IV - orthoquartzite blanche;
unité V - grès bariolé siltstone et schiste argileux;
unité VI - surtout orthoquartzite altérée de couleur pâle.

Le milieu de sédimentation varie d'un environnement marin peu profond à un environnement continental; les roches ignées extrusives sont d'origine continentale. Le groupe de Thule atteint son épaisseur maximale à la baie Goding, où 1 000 m de couches ont été mesurés dans un profil dont la surface de contact inférieure n'est pas exposée et le sommet constitue une surface d'érosion. La limite nord des sédiments du groupe se trouve entre 78°32'N et 79°N. La datation au K^{40}-Ar^{40} *du basalte de l'unité II indique que le groupe de Thule a été formé il y a environ 1,0 ou 1,2 Ga.*

INTRODUCTION

Forming splashes of colour in an otherwise bleak terrain, a distinctive sequence of unmetamorphosed sedimentary and basaltic rocks overlies the crystalline basement at several localities on the coast of southeastern Ellesmere Island, District of Franklin. These rocks are assigned, on the basis of similarity and proximity, to the Precambrian Thule Group of northwest Greenland (Dawes, 1976), 60-140 km to the east.

This report is concerned with the distribution, lithology, chronological order, depositional environment, and age of the Thule Group in Ellesmere Island. Correlations with Greenland and the tectonic significance of the rocks form the subject of a separate paper (Dawes et al., in press).

On Ellesmere Island, the bulk of the Thule Group outcrops in the following areas (Fig. 1), from south to north: Clarence Head-Cape Combermere, the peninsula between Goding Bay and Cadogan Inlet, and in the vicinity of Gale Point. A stratigraphic section was measured in each of these areas and the sections are referred to in this report as the Clarence Head, Goding Bay and Gale Point sections. They are shown graphically in Fig. 2 .

Field Work

The information contained in this report was obtained by the authors independently. Christie reconnoitred the coastal area of southeastern Ellesmere Island using dog sledges in the spring of 1960 (Christie, 1962a, b). He measured seven stratigraphic sections in the Thule Group using an altimeter and a height-of-eye levelling technique, corrected for the gentle dips of the strata.

Frisch studied the Thule Group during helicopter-supported 1:250 000 scale reconnaissance mapping of the Precambrian Shield of southeastern Ellesmere Island in 1977 (Frisch et al., 1978). He measured the Clarence Head, Goding Bay and Gale Point sections using a five-foot rule equipped with a clinometer and visited many other exposures that were not easily accessible to Christie. The three

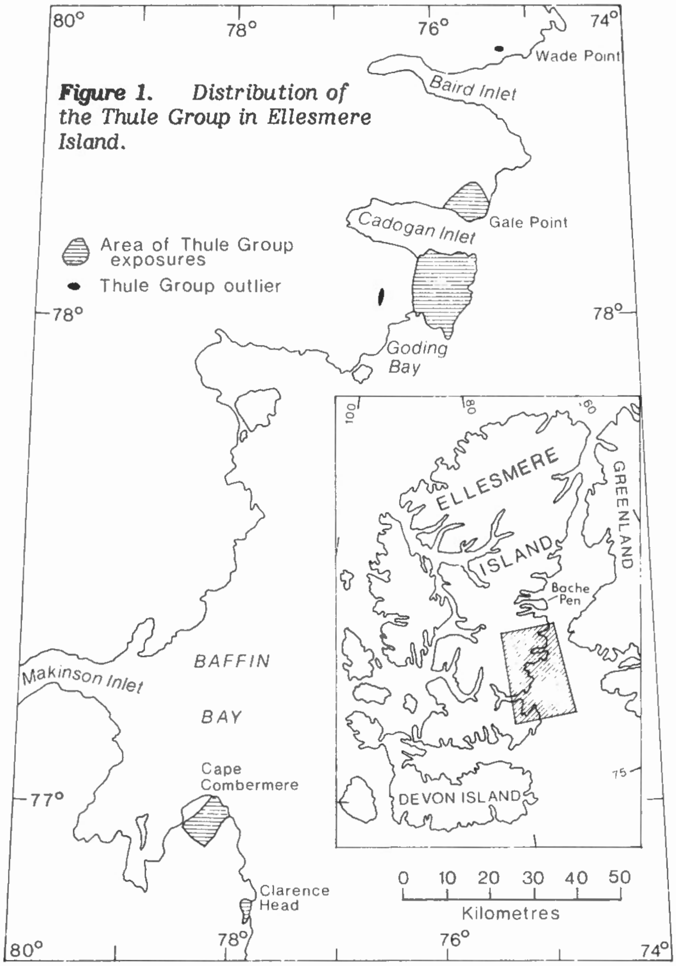

Figure 1. Distribution of the Thule Group in Ellesmere Island.

sections studied by Frisch overlapped, in whole or in part, sections measured by Christie. The data obtained in 1977, supplemented and amplified by information gathered in 1961, form the basis of the present report.

Sandstone terminology follows the classification used by Pettijohn (1975, Fig. 7-6).

Acknowledgments

Frisch acknowledges the contribution made to the 1977 mapping by W.C. Morgan, who also examined the lower beds of the Cape Combermere section in some detail. He thanks D. Brisbin and E. Lisle for field assistance; helicopter pilots J. Carlton, G. Curtis and M. Holzscheiter; and the Polar Continental Shelf Project for fixed-wing aircraft support and much other assistance.

Christie is grateful for field assistance by L.D. Ayres and N.E. Haimila and sledging services by Elijah, Isaac, Ookookoo and the late Pauloosie of Grise Fiord.

Critical reading of the original manuscript by G.D. Jackson led to numerous improvements. F.H.A. Campbell made particularly useful suggestions regarding the interpretation of depositional environments. J.H. Maley was very helpful in computer processing of the analytical data on the basaltic rocks.

CLARENCE HEAD

A relatively complete and little deformed section of the Thule Group is exposed in the cliffs extending southward from Clarence Head (Fig. 3, 4). All the major units of the Thule Group in Ellesmere Island are represented but only small thicknesses of the lowermost and uppermost units are preserved (Fig. 2). Total thickness of the section is 660 m.

Unit I

Less than 8 m of basal Thule beds are present in the measured section. The lowermost rock is white orthoquartzite composed of subangular to subrounded grains in a sparse matrix of detrital sericite. A rusty weathering, poorly sorted quartz-pebble conglomerate or conglomeratic sandstone overlies the quartzite. Clast size varies from 2 mm to 1 cm. Both the quartzite and the conglomerate are recessive.

Basal beds of unit I rest on highly metamorphosed supracrustal basement rocks with marked angular discordance (Fig. 5). Both the Thule and basement rocks are sheared adjacent to the contact. Twenty-two kilometres to the north, near Cape Combermere, unit I is 35 m thick and similar thicknesses occur elsewhere in that general area (see below). The relative thinness of unit I, the absence of a basal conglomerate, and the shearing are taken to indicate that the basement-Thule contact at Clarence Head is a fault.

Unit II

This dark weathering unit consists of igneous rocks, chiefly basalt sills and lavas, alternating with sedimentary rocks, mainly redbeds. Vertical faces of the resistant igneous units made measurement of the entire unit on foot impractical. Only the lower and upper parts of unit II were examined, the middle part being inaccessible. The thickness

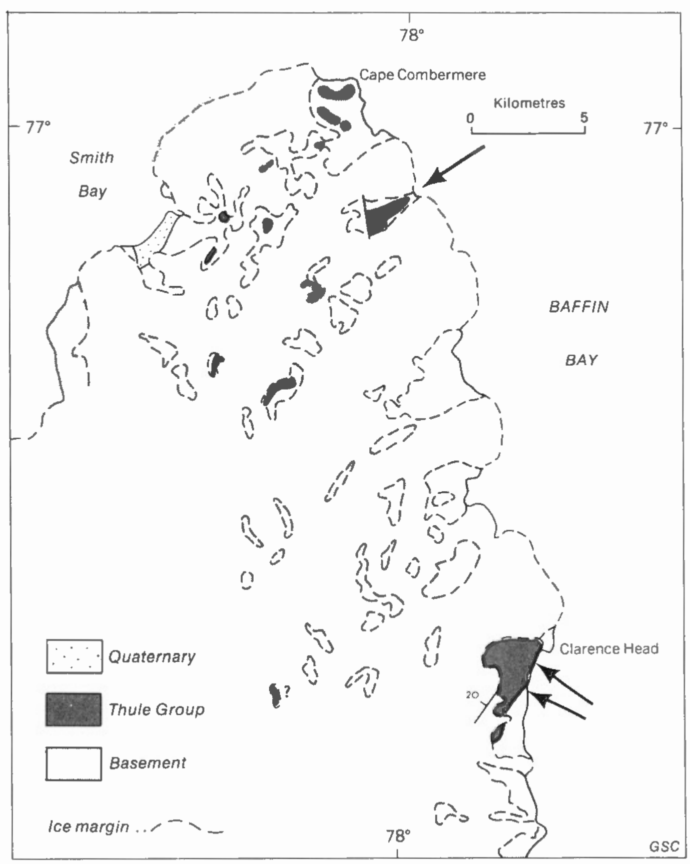

Figure 3. Geological sketch map of the Clarence Head-Cape Combermere area. Arrows point to the Thule Group sections studied.

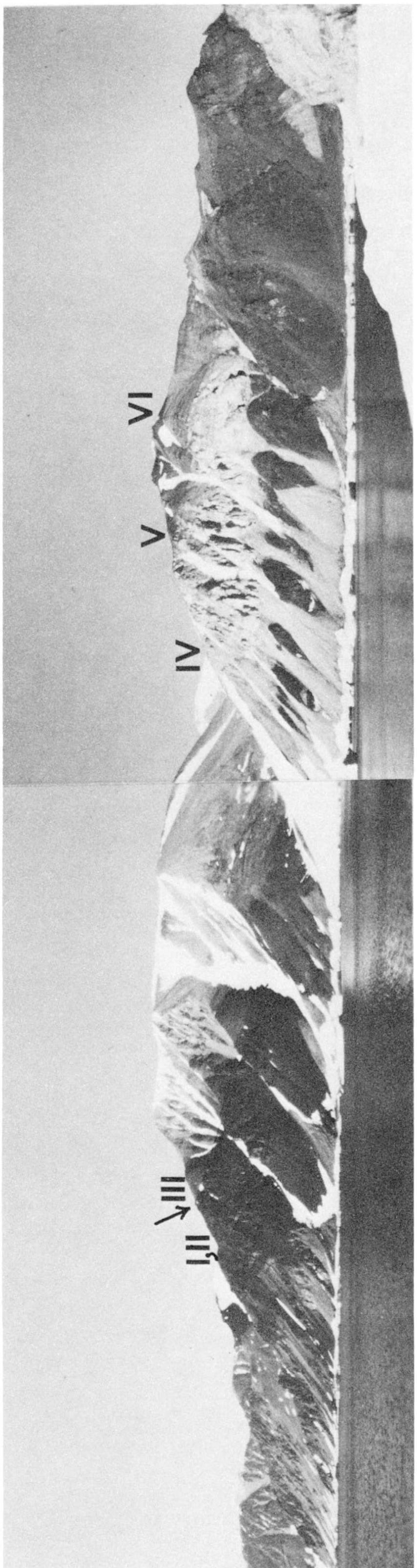

Figure 4. Panoramic view of the Clarence Head section. The Roman numerals refer to the six units into which the Thule Group has been subdivided. Arrow points to the resistant stromatolitic carbonate bed at the base of unit III.

Figure 5. *Thule Group rocks (chiefly unit II) unconformably overlying steeply dipping crystalline basement rocks in the Clarence Head section. Arrow points to an occurrence of green copper staining.*

of 218 m shown in the stratigraphic column of Figure 2 is an estimate derived from measured elevations and the dip of the rocks. Igneous rocks account for nearly three-quarters of this thickness.

Green copper staining, probably malachite, was observed from the air at one place in the lower part of unit II (Fig. 5). It was not accessible and whether it is associated with igneous or sedimentary rock is not known.

Igneous Rocks

Distinction between lavas and sills is generally difficult in the Thule Group exposures. Both weather dark grey or dark greenish grey and are more or less altered. Weathering has commonly obscured contacts. Locally, however, diagnostic features such as chilled top and bottom contacts, flow-top breccia, or upward concentration of amygdules enable one to determine the origin of a particular igneous body.

The thickness of individual lavas and sills measured ranges from little more than 1 m to 42 m. Units more than 30 m thick appear to be flows.

A pyroclastic unit, 24 m thick, occurs near the base of unit II. It consists of poorly sorted blocks and smaller fragments, chiefly of reddish epiclastic rock, and bombs up to 23 cm in diameter in a dusky red matrix, and is best described as volcanic breccia. A thin section reveals an aggregate of quartzose sedimentary rock fragments, pumice, altered glass(?) shards and indeterminate carbonated rock fragments. Pyroclastic rocks were not recognized elsewhere in the Clarence Head section but volcanic breccias were noted at two levels in a section measured by Christie.

In thin section, the lavas and sills are very similar. Both are porphyritic olivine basalt with intergranular to subophitic texture. Olivine and clinopyroxene form phenocrysts in a matrix of clinopyroxene, saussuritized plagioclase, Fe-Ti oxide and alteration minerals such as chlorite, calcite and clays. Olivine has not been recognized as a groundmass mineral and orthopyroxene is rare. Pyroxene generally shows little alteration but olivine is commonly strongly altered and indeed may be wholly replaced by serpentine, chlorite or clay minerals, though crystal outlines may be preserved. All mineral alteration is considered to be deuteric. Neither the igneous nor the sedimentary rocks of the Thule Group show evidence of metamorphism.

The basalts are classified according to the chemical scheme of Irvine and Baragar (1971). Analyses showing more than 4 weight per cent ($H_2O + CO_2$) are considered not to be representative of the original magma composition, due to the effects of excessive alteration. Only two of the seven analyzed basalts from the Clarence Head section pass this chemical screen. Both are silica-saturated rocks (Ca-poor pyroxene and olivine in the norm; Table 1, columns A, B). All seven rocks (analyses of the five altered samples are listed in the Appendix) fall on or below the line separating tholeiitic and alkaline basalts in the alkali-silica diagram (Fig. 6) and so are tholeiitic by this definition. All but one fall in the tholeiitic field of the AFM diagram (Fig. 7); the exception, an altered rock, contains 4.34 per cent Na_2O and is nepheline-normative, features not thought to be primary.

Sedimentary Rocks

The typical sedimentary rock of unit II is recessive, reddish, thin bedded, fine- to medium-grained sandstone, commonly with red or green siltstone or shale partings. The sandstone is arkosic and rich in hematite dust and patchily distributed calcite. The finer grained rocks locally show ripple marks and sand-filled mud cracks. Buff to orange sandstones are sporadically present.

Environment of Deposition and Intrusion

The mudcracked and rippled redbeds of unit II accumulated in a terrestrial to shallow marginal marine environment. The absence of well developed fining-upward cycles, coarse terrestrial clastics, and biogenic carbonates suggests that the bulk of these clastics was deposited in an intertidal to fluvial regime. This interpretation is supported by the typical subaerial features of the pyroclastics and lavas associated with the sediments.

Close similarity in petrography and chemistry suggests strongly that the lavas and sills are related and are expressions of a single phase of igneous activity. Extrusion and hypabyssal intrusion of basalt were widespread in northern Canada in the late Precambrian and have been attributed to stable crust volcanism by Baragar (1977). The basalts of the Thule Group are yet another example of this phenomenon.

Unit III

Lithology and Thickness

Unit III is divided into two parts: a lower sequence, 13 m thick, of carbonate rock, in part stromatolitic, and an upper sequence, 66 m thick, of interbedded varicoloured sandstone and shale/siltstone.

The carbonate rocks form a resistant layer (Fig. 4) conformably overlying either redbeds or what appears to be amygdaloidal lava of unit II. Christie found evidence of an intrusive contact with a sill at one locality elsewhere at the same stratigraphic level.

Well bedded, brown, calcareous dolomite forms the lower 10 m of the carbonate sequence. Much of it contains laterally-linked stromatolites (Fig. 8) and brown, mudcracked shaly partings. Locally, a thin layer of carbonate granule conglomerate underlies the stromatolitic dolomite. The upper 3 m of the carbonate unit consists of well bedded, dark grey limestone.

The upper, sandstone-shale sequence lies conformably on the limestone with a sharp contact. Overall, the sequence is recessive but the sandstones are resistant relative to the shales. Bedding is well developed and predominantly lenticular (Fig. 9). Thin (20 cm) beds of red, pink, white and buff, fine- to coarse-grained sandstone are separated by green shaly partings. Herringbone crossbedding and ripple marks in the sandstone and mud cracks in the shaly partings are abundant. Soft, crumbly, dusky red shale or shaly siltstone forms lenticular interbeds a little more than one metre thick in the sandstone.

The sandstones consist of subangular or rounded quartz grains and subordinate quartzose rock fragments with interstitial or matrix calcite. The calcite matrix of one specimen includes abundant tiny quartz chips in addition to larger, well rounded grains.

Environment of Deposition

The lenticular bedding, herringbone crossbedding, ripple marks, and mud cracks together are strongly indicative of deposition of the upper, sandstone-shale sequence of unit III in an intertidal to supratidal environment. The basal stromatolitic carbonates probably accumulated during the initial transgression, when the supply of terrigenous clastic detritus was at a minimum.

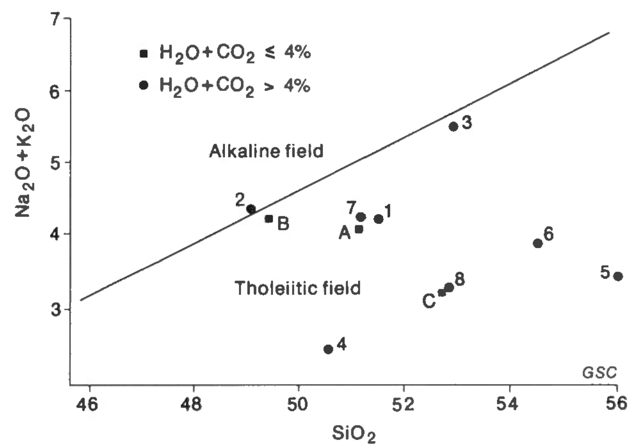

Figure 6. Basalts of the Thule Group of Ellesmere Island in the alkali-silica diagram (after Irvine and Baragar, 1971). Analyses have been recalculated anhydrous. Letters and numbers refer to analyses listed in Table 1 and Appendix, respectively.

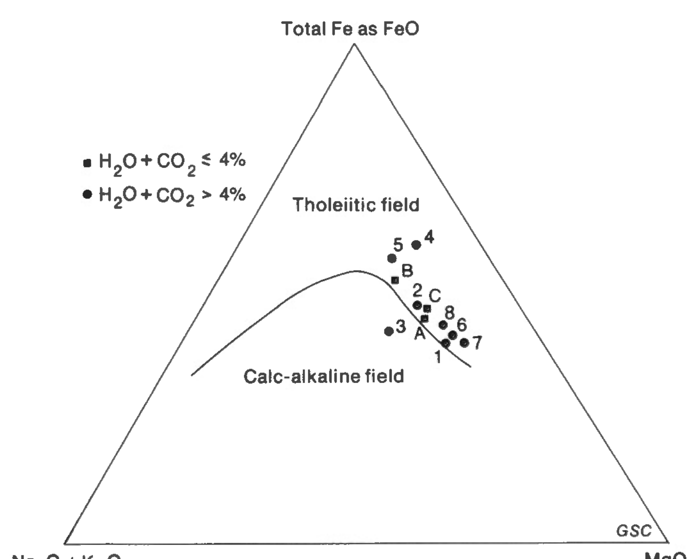

Figure 7. Basalts of the Thule Group of Ellesmere Island in the AFM diagram. Analyses, which are listed in Table 1 and Appendix, have been recalculated anhydrous. Line dividing tholeiitic and calc-alkaline fields modified after Irvine and Baragar (1971).

Table 1. Chemical analyses of basalts of the Thule Group, Ellesmere Island

	A	B	C
SiO_2	49.0	47.6	51.3
TiO_2	0.97	1.16	1.05
Al_2O_3	13.9	15.5	14.4
Fe_2O_3	3.3	5.3	5.7
FeO	7.1	7.2	4.3
MnO	0.18	0.22	0.13
MgO	8.58	6.73	7.62
CaO	9.02	8.49	9.48
Na_2O	3.4	3.4	2.0
K_2O	0.47	0.68	1.14
P_2O_5	0.09	0.12	0.20
CO_2	0.0	0.1	0.2
H_2O_{tot}	4.0	3.9	2.1
Total	100.0	100.4	99.6
S	0.00	0.07	0.00
CIPW norm			
Q	-	-	4.24
Or	2.90	4.18	6.93
Ab	29.97	29.58	17.46
An	22.17	26.17	27.85
Di	13.32	7.71	10.06
Hd	6.00	5.50	4.37
En	4.78	2.98	14.83
Fs	2.47	2.44	7.39
Fo	7.92	7.60	-
Fa	4.51	6.86	-
Mt	3.73	4.00	3.79
Il	1.92	2.28	2.04
Cr	0.09	0.05	0.08
Ap	0.22	0.29	0.47
Py	-	0.15	-
Cc	-	0.24	0.47
Trace elements (ppm)			
Rb	2	4	36
Sr	240	230	250
Ba	230	310	390
Co	52	50	42
Cr	320	160	310
Cu	130	430	75
Ni	140	110	110
V	340	370	260
Zr	46	55	190
Li	18	21	15
Cs	0.1	1.0	1.2
B	60	59	65

A. Lava or sill, Clarence Head section (sample FS-77-93).
B. Lava or sill, Clarence Head section (FS-77-100; K-Ar age 1065 ± 73 Ma).
C. Sill, Gale Point section (FS-77-241).

Major, minor and trace elements determined by "everyday" methods, except Rb, Li and Cs, which were determined by the "screw-rod" technique (Abbey, 1979). Normative compositions computed from analyses recalculated anhydrous, following procedure of Irvine and Baragar (1971).

Figure 8. *Laterally linked stromatolites in dolomite at the base of unit III in the Clarence Head section. Diameter of the coin is 1.9 cm.*

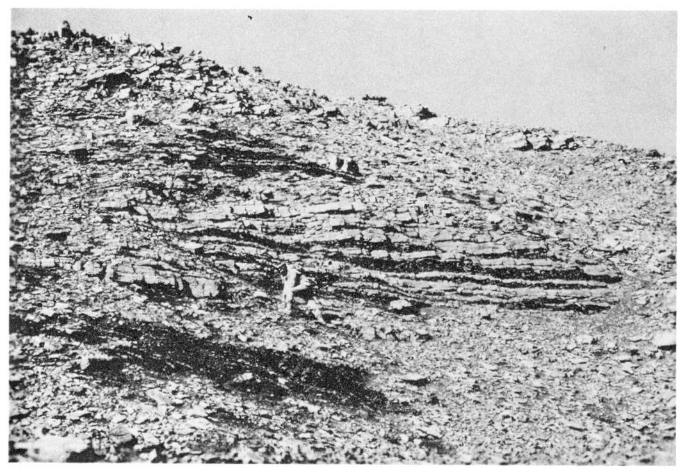

Figure 9. *Alternating, lenticular bedded sandstone and shale of unit III in the Clarence Head section.*

Unit IV

Lithology and Thickness

Unit IV, composed of white orthoquartzite, is a wedge-shaped, cliff-forming unit (Fig. 4), which conformably overlies unit III. Steepness of outcrop prevented precise measurement of thickness, which varies from less than 100 m to more than 200 m.

The lowermost 63 m of the measured section consist of white and purple banded, thick bedded to massive, medium grained orthoquartzite and subarkose that are locally conglomeratic and rarely have grey hematitic partings (Fig. 10). A thin section of one rock from this part of the unit shows an uneven grained aggregate of rounded quartz grains scattered among subangular quartz and feldspar (chiefly microcline) grains in a sparse matrix of detrital sericite. Strata are commonly crossbedded and ripple marked.

Higher in the section, the sandstone becomes an all white, medium grained orthoquartzite, typically containing a few microcline grains and quartzose rock fragments. Thick bedding (1-2 m), crossbedding and ripple marks are characteristic of this and underlying rocks of unit IV. Paleocurrents were not systematically measured but from visual estimates it appears that westward transport was

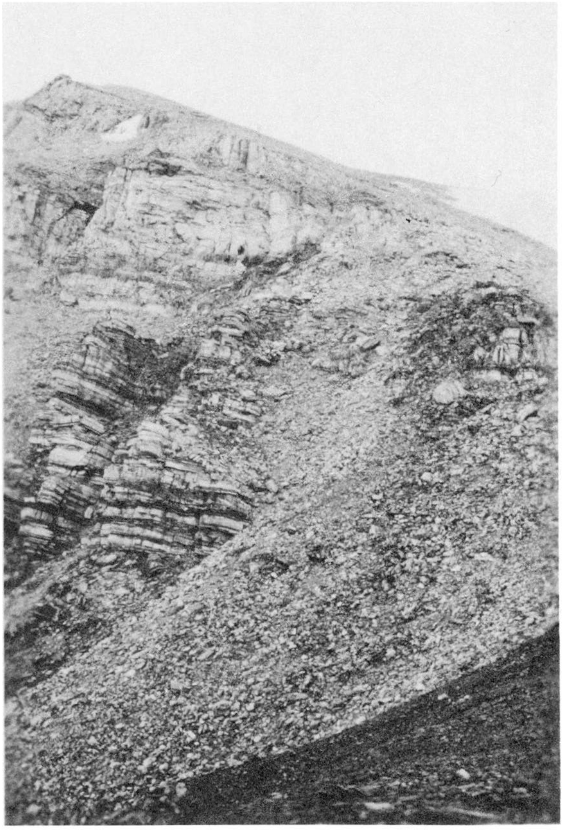

Figure 10. *Orthoquartzites of unit IV in the Clarence Head section. Banded purple and white orthoquartzites form the base of the unit and are overlain by more homogeneous white orthoquartzite.*

important, although abrupt reversals in current direction occurred. Conglomeratic layers with well rounded, white quartz pebbles about 1 cm in diameter are irregularly distributed throughout the white orthoquartzite.

Thin sections of orthoquartzite samples from unit IV reveal a generally uneven grain size: the larger grains tend to be subrounded to rounded, the smaller ones are subangular. Syntaxial silica overgrowths on the larger grains are very well developed in certain specimens and result in strongly silica-cemented rocks. Detrital sericite is a common but minor interstitial mineral.

Environment of Deposition

The abundant crossbedding, ripple marks and conglomerate within unit IV all suggest a shallow marine depositional environment. The absence of fining-upward cycles and fine grained sediments and the poor sorting imply strong wave and/or current activity. The abrupt reversals in paleocurrent pattern throughout the section indicate either tidal action or a combination of longshore and tidal currents.

Unit V

Lithology and Thickness

Unit V is a redbed unit of thin bedded sandstone and siltstone, slightly less than 120 m thick.

In the section measured, the base of unit V was taken at a break in slope marked by the upper surface of pale pink sandstone with specularite partings. The presence at the top of unit IV of a pink, hematite bearing sandstone, instead of the characteristic clean white orthoquartzite, suggests, on an outcrop scale at least, a gradational contact of units IV and V. On a larger scale, however, the contact is clearly expressed by a marked colour change from white to red.

The lowermost 15 cm of unit V comprise a dusky red, hematitic orthoquartzite in which subrounded to rounded quartz grains are mantled by fine hematite and are associated with a few rounded, quartzose rock fragments and a sparse detrital sericite matrix.

The next 91 m are pink sandstone with red siltstone partings, weathering reddish overall, ripple marked and crossbedded. Beds range in thickness from 10 cm to 0.5 m and bedding surfaces are veneered by hematite (commonly specularite and locally mammillary). Some beds grade upward from pink, medium grained sandstone to dusty red, fine grained sandstone that is thinly coated with mammillary hematite or specularite. Hematite coatings also occur on fracture surfaces perpendicular to bedding. In general, hematite content increases upward in this sandstone-siltstone sequence of unit V. Quartz grains are subangular in some of the sandstones, rounded with syntaxial overgrowths in others. A sparse matrix of very fine grained sericite is commonly present.

The uppermost part of unit V is dark red, shaly siltstone, hematitic and flecked with muscovite, that forms a recessive sequence 26 m thick. Minor dark laminated hematitic sandstone beds are exposed at the top of the unit, beneath a basalt sill.

Environment of Deposition

Unit V appears to have been deposited in a gradually deepening littoral environment. In the sandstones/siltstones, which form the bulk of the unit, abundant ripple marks and crossbedding indicate shallow water and the extensively developed hematite suggests that sedimentation was in part subaerial. Indeed, the basal redbed of unit V may represent a paleosol. The sandstone-siltstone alternations imply sharp fluctuations in current velocity, such as would be found in a tidal flat. The homogeneous and regularly bedded upper siltstones were deposited in a low-energy, presumably deeper water regime.

An alluvial origin for the majority of the deposits of unit V cannot be excluded. The graded sandstone beds described above might be interpreted as examples of fining-upward cycles of sedimentation. However, the lack of conglomerate and channelling renders an alluvial origin for the sandstones/siltstones less likely than a shallow marine origin.

Unit VI

Lithology and Thickness

Unit VI is a light weathering orthoquartzite, quite distinct from the dark red, shaly rock of the upper part of unit V. At Clarence Head, the two units are separated by a basalt sill and the top of unit VI is an erosion surface. Only about 24 m of unit VI are preserved and the outcrops are heavily frost shattered.

The orthoquartzite is a laminated, medium grained rock that weathers pale pink. Neither crossbedding nor ripple marks were observed but their absence may be only apparent, as outcrops are poor. The sandstone typically consists of rounded quartz grains, syntaxially overgrown by silica, and subordinate finer, subangular quartz between laminae a few millimetres thick of silica-cemented, slightly hematitic orthoquartzite.

Environment of Deposition

Lack of sedimentary structures limits speculation on the origin of unit VI. However, the rocks appear to be broadly similar to those of unit IV and, like them, are underlain by hematitic shaly rocks. It seems probable that unit VI represents part of another sand body deposited in relatively shallow water.

CAPE COMBERMERE

The lower part (about 200 m) of the Thule Group section 5 km south of Cape Combermere was examined by Christie in 1961 and by W.C. Morgan in 1977. At this locality (Fig. 1, 3) essentially flatlying sedimentary and basaltic rocks of units I and II unconformably overlie metasediments of the basement complex. The contact is covered by scree.

The section closely resembles the equivalent part of the Clarence Head section. Basal Thule strata (unit I) are white orthoquartzite about 35 m thick, with planar crossbedding and asymmetric ripple marks. Overlying rocks of unit II include variegated, fine grained sediments and basalt flows and sills. The sediments are chiefly thin bedded, red and green siltstone and shale interbedded with red, green or buff sandstone. Graded bedding is common: typically, red sandstone at the base passes upward into red and green silty sandstone or siltstone. A few green or brown dolomitic beds occur among the lower beds of unit II. Mud cracks, ripple marks and specularite veins abound. Interspersed with the sediments are altered, greenish basalt flows, 3-30 m thick, which may be vesicular or amygdaloidal at the top, and green- or brown-weathering sills. Only minor pyroclastic rock was noted: a few centimetres of basaltic tuff mantling a flow.

Airborne surveys in 1977 of the area south of Cape Combermere revealed numerous other outcrops of the Thule Group, though none are as extensive as the section described or contain beds above unit II. Typical outcrops comprise the basal light coloured sandstone and overlying basalts and dark sediments, and form caps to some of the highest mountains in the area, which rise to nearly 1000 m above sea level and consist chiefly of basement rocks (Fig. 11). Clearly, major uplift has occurred since Precambrian time.

GODING BAY

Outcrops on the northern shore of Goding Bay (Fig. 12) provide the thickest section (1000 m) of the Thule Group in Ellesmere Island. Several faults disturb the exposures but almost the entire section can be reconstructed from the outcrops at the northeastern corner of the bay. The lower contact of the group is not exposed in any of the sections measured and the lowest beds are assigned to unit II.

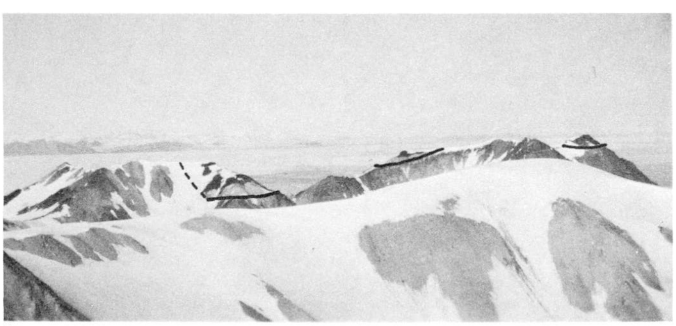

Figure 11. *Sandstone and basalt of the Thule Group (units I and II) overlying basement on the summits of mountains south of Cape Combermere. View northward with Smith Bay in the distance.*

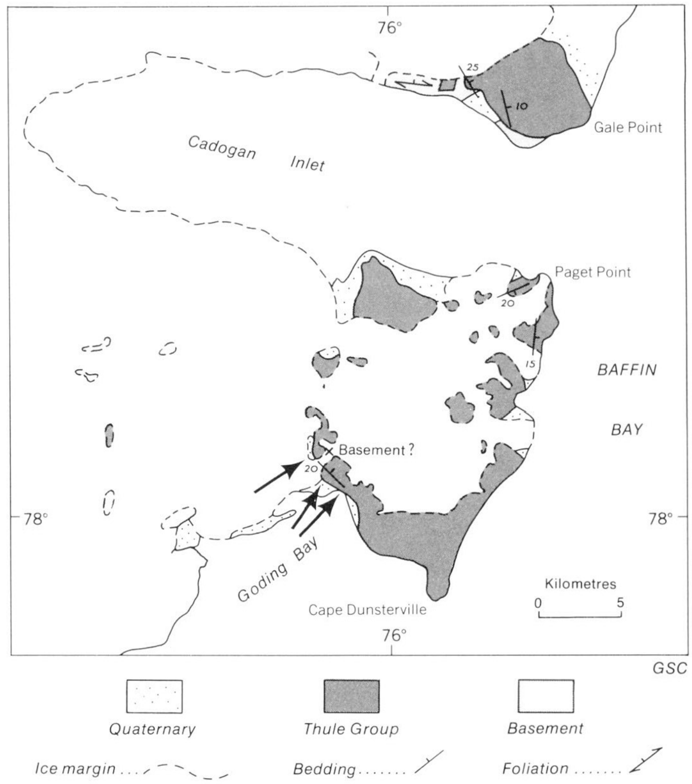

Figure 12. *Geological sketch map of the Goding Bay-Cadogan Inlet-Gale Point area. The Goding Bay and Gale Point sections were measured at the localities indicated by arrows.*

The highest beds are truncated by an erosion surface. The various units that make up the Goding Bay section (Fig. 2) are identified with reference to the Clarence Head section.

Unit II

The lowermost rock exposed is basalt, possibly lava. There follow about 130 m of recessive red shale and a few interbeds of resistant, light coloured sandstone, the lowest of which is locally underlain by a basalt sill. Overlying the redbeds are 30 m of interbedded greenish sandstone and mudcracked dark shale or siltstone. The sandstone tends to be coarse to very coarse and consists of rounded quartz grains, locally hematite-stained, in a green argillaceous matrix; thin green shale partings are common.

A basalt sill nearly 140 m thick forms most of the remainder of unit II. It has a distinctive green weathering and is greenish on a fresh surface. Columnar jointing extends unbroken throughout the entire sill, suggesting that the body is a single cooling unit. Alteration is strong throughout but it appears from thin section study that the basalt was made up essentially of plagioclase, clinopyroxene and Fe-Ti oxide; much of the clinopyroxene has been deuterically altered to pale green hornblende.

Above the sill lies a dark shale of a type not found elsewhere in the Thule Group of Ellesmere Island. The shale is black to dark grey except in the upper beds, which are reddish and greenish. The shale unit, 12 m thick, is thin bedded and recessive and is intruded by resistant, thin basalt sills, 25-30 cm thick, that follow the bedding. The shale contains ovoid, greenish siliceous concretions, 25-30 cm in diameter, studded with 8 mm-long specularite blades.

Aggregates of siderite are developed locally in some concretions. Because of its association with basalt sills and its position immediately below stromatolitic carbonate rocks, the shale is assigned to unit II.

Unit III

Unit III is composed of a thin basal dolomite and recessive red and green sandstone and shale, with a total thickness of a little more than 100 m. The unit conformably overlies the dark shale of unit II.

The basal dolomite, 5 m thick, is dark brown or grey, weathers pale brown, and is thin bedded. Stromatolitic layers, up to 10 cm thick, alternate with reddish brown and green shaly partings. As at Clarence Head, the dolomite forms a prominent ledge between recessive shaly strata.

Eighteen metres of interbedded shaly sandstone and shale overlie the dolomite. The sandstone is a greenish, poorly sorted orthoquartzite, crossbedded and rippled, in beds generally about 1 m thick and commonly separated by brown shaly partings. The shale units, 1-2 m thick, are deep red and characterized by abundant hematitic mud or sand balls 2-4 mm (rarely up to 3 cm) in diameter.

The remainder of unit III, 80 m thick, is poorly exposed. It appears to consist mainly of red shale or siltstone with subordinate green quartz sandstone. Three narrow basalt dykes traverse the sequence.

Young Basalt Dykes

The aforementioned basalt dykes are but three of a large number cutting the Thule Group in the Goding Bay area and elsewhere. K-Ar age determinations indicate that the dykes are of Hadrynian age (600-800 Ma). As discussed in a later section of this report, the Thule Group is of Neohelikian age and so the dykes are significantly younger than, and evidently unrelated to, the deposition of the group. Furthermore, chemical analyses show that the basalt of the dykes is more differentiated than that which forms the lavas and sills of the Thule Group.

Unit IV

The lower contact of unit IV, although conformable, marks an abrupt change from the recessive, dark shale of unit III to a resistant, very light weathering sandstone. Unit IV consists of a remarkably clean, fine- to medium-grained orthoquartzite. The lower beds are mostly pink and in places weather slightly darker pink or purplish. The remainder of the unit is white or buff on both fresh and weathered surfaces. Crossbeds about 0.5 m thick are common throughout and indicate a general easterly transport direction. In contrast to the equivalent unit at Clarence Head, conglomeratic beds were not observed. A thin section of a rock considered to be representative shows subangular quartz grains, 0.2-0.3 mm in diameter, sparse interstitial detrital sericite and hematite dust.

The top of unit IV is placed below a maroon, shaly siltstone (see unit V, below). The uppermost orthoquartzite bed in the measured section is mantled by loose slabs of fine grained red sandstone that are thought to belong to unit V, the remainder of which is eroded. If this interpretation is correct, the thickness of unit IV is a little over 180 m in the measured section. However, 3 km to the south-southeast, Christie measured 265 m of unit IV in a section in which the lower beds are not exposed. It is probable that, as at Clarence Head, unit IV markedly varies in thickness over distances of a few kilometres.

Unit V

This unit, about 84 m thick, of interbedded sandstone and siltstone and siltstone/shale forms a dark weathering band between the underlying and overlying light sandstones of units IV and VI.

The basal 24 m of unit V are recessive, maroon, micaceous, shaly siltstone with buff or purplish sandstone partings, all thinly bedded. In a nearby section to the southeast, sandstone is more abundant and shows crossbedding indicating currents mainly from the northeast, with some from the southeast and east.

The basal siltstone-sandstone unit is overlain by interbedded green sandstone and green siltstone that form a resistant sequence 36 m thick. The sandstone is a laminated, locally dolomitic subarkose in thin, commonly lenticular beds 7-20 cm thick. The siltstone is shaly, micaceous, ripple marked and mudcracked. Marcasite nodules up to 2 cm in diameter are present in the siltstone.

Unit V is completed by a very recessive, dark reddish weathering shale and siltstone sequence about 24 m thick. This recessive sequence is apparently 120 m thick one kilometre to the southeast and there contains interbedded red sandstone in 15 cm thick beds and red shale, with crossbedding, ripple marks and mud cracks.

Unit VI

At Goding Bay, unit VI, the stratigraphically highest unit of the Thule Group in Ellesmere Island, comprises over 300 m of light weathering sandstone truncated by an erosion surface. The lower half of the unit contains minor shale as partings between the sandstone beds; the upper half is a more uniform orthoquartzite.

The lower half of unit VI, 158 m thick, is made up of laminated purple and white or buff, medium grained orthoquartzite in beds 10-30 cm thick. Herringbone crossbedding and ripple marks are abundant. Thin green shaly partings are found at irregular intervals.

A recessive 3 m thick bed of laminated dolomitic subarkose separates the lower and upper halves of unit VI. A thin section shows a poorly sorted rock composed of subrounded, millimetre sized quartz grains and subrounded to subangular quartz and microcline grains, 0.2-0.3 mm in diameter, in a dolomite matrix.

The upper 168 m of unit VI are composed of pinkish and buff, rarely white orthoquartzite. It commonly is conglomeratic, with pebbles of white quartz, and rippled. A representative specimen consists of rounded quartz grains, 0.7 mm across and syntaxially overgrown by silica, and subangular to subrounded quartz grains, 0.3 mm across, tightly cemented by silica; fine hematite disseminated in the matrix makes the rock pink.

Environment of Deposition of the Thule Group at Goding Bay

The sedimentary rocks exposed in the Goding Bay outcrops are interpreted to be of shallow marine origin. The sediments of unit II appear to have been deposited in a progressively shallowing environment, the lower fine grained facies of shale giving way upwards to interbedded sandstone and shale/siltstone with mud cracks. Even the dark shale at the top of unit II appears to be a shallow water deposit, as the contained hematite- and siderite-bearing concretions indicate oxidizing conditions during sedimentation (Johnson, 1978, Fig. 9.55).

Following formation of a carbonate bank of low amplitude stromatolites, muds and sands were deposited alternately in intertidal and supratidal environments. Abundant ripple marks, crossbedding and mud cracks and the presence of hematitic mud and sand balls in unit III confirm this interpretation.

The clean white orthoquartzites of unit IV and VI probably represent offshore sand bars, while the intervening variegated, interbedded sandstone and siltstone/shale of unit V, which is similar to unit III, were deposited in intertidal to supratidal environments. The sand bars of units IV and VI probably prograded or regraded during transgression and/or regression under the influence of longshore currents. Longshore currents can be important dispersing agents of sediments, particularly in deltaic areas, and this could account for the striking juxtaposition of sediments of different depositional environments, as seen in the Thule Group at Goding Bay and Clarence Head.

GALE POINT

The outcrops of Thule Group in the vicinity of Gale Point, at the mouth of Cadogan Inlet (Fig. 12), are much faulted but provide good exposures of the lowermost beds of the group, which are very thin at Clarence Head and absent at Goding Bay (Fig. 2).

Unit I

The sediments of unit I, nearly 40 m thick, rest on garnetiferous granulite gneiss (Fig. 13) but the lowermost 2.5 m of strata are covered. The lowest exposed bed is pink weathering impure dolomite that passes upward into dolomitic sandstone to form a total thickness of 6 m. The dolomite is pale brown, thin bedded to platy, stromatolitic and composed of very fine grained dolomite and tiny angular fragments of quartz. The sandstone, pink or grey and thin bedded, is made up of rounded quartz grains, generally 0.6 mm but up to 1 mm in diameter, subangular quartz and microcline grains, 0.2-0.3 mm in diameter, and abundant interstitial dolomite. The dolomite forms a cement in some of the rocks but occurs in discrete grains in others. The sandstone also contains scattered sericite flakes and rare tourmaline; both minerals are detrital.

The strata described above are overlain by 30 m of subarkose and dolomite alternating to form a varicoloured sequence. The sandstone is white, pale greenish or buff, thin bedded to platy, crossbedded and sparsely rippled. In a thin section a close packed aggregate of subrounded to subangular quartz grains, 0.3-0.5 mm across and commonly syntaxially overgrown by silica, is interspersed with abundant microcline grains and quartzose rock fragments. Some detrital sericite and a little carbonate material are present.

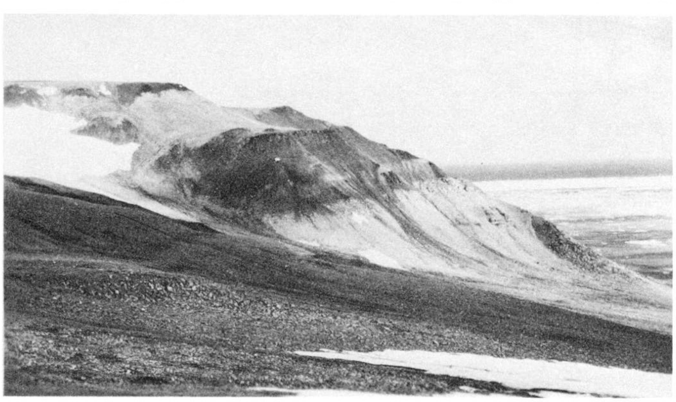

Figure 13. *The Gale Point section, viewed eastward: dark resistant basement at bottom of slope, overlain by partly resistant unit I rocks, sills in middle part, and lava at top, which lies about 500 m above sea level.*

Figure 14. *Stromatolites in dolomite of the upper part of unit I in the Gale Point section. The length of the hammer head is 18 cm.*

The dolomite beds are more brightly coloured and inhomogenous than the sandstone. They contain lenses and fragments of chert that is pink, brown, buff, green or purple. Partings in the lower dolomite beds are green when shaly and red when sandy. Domal stromatolites up to 15 cm high form numerous layers in the upper dolomite strata (Fig. 14).

Unit II

Top and bottom of unit II in the Gale Point section are arbitrarily defined. The base of the unit is drawn at the bottom of a covered interval that separates the stromatolitic dolomites of unit I and white orthoquartzite underlying a basalt sill. The top of unit II is drawn at the contact between green shale and overlying recessive silty sandstones. Thus demarcated, unit II is nearly 200 m thick and includes four bodies of basalt.

Igneous Rocks

Three of the four basalt bodies in unit II are known to be sills and the fourth, the uppermost, is probably a sill. Contacts generally are not well exposed but upper margins commonly show evidence of quick chilling, such as aphanitic texture, absence of vesicles and brecciation, and local baking of the adjacent sedimentary rock. The sills range from 12-30 m in thickness.

Alteration is moderate to severe and varies from sill to sill, both as to intensity and minerals affected. All four igneous bodies are basalt with subophitic to intersertal texture, containing clinopyroxene, plagioclase, olivine and Fe-Ti oxide. The minerals most consistently altered are olivine (to serpentine or an indeterminate mixture of phyllosilicates) and calcic plagioclase (generally crystal cores to saussurite). Where alteration has been most intense, mafic minerals are completely chloritized and plagioclase is strongly saussuritized.

Three samples from chilled margins of the three lower sills were chemically analyzed (Table 1 and Appendix). A fourth sample analyzed came from a sill in unit II exposed in a fault block 3 km west of the measured section. Only one of the four samples was sufficiently fresh to be considered a representative of the original magma, which appears to have been a quartz-normative tholeiite (Table 1, column C). A thin section of this sample shows scattered pseudomorphs almost certainly after olivine, yet 4.2 weight per cent quartz appears in the norm. This discrepancy between modal and normative mineralogy suggests modification of the bulk composition due to alteration. All four analyses fall in the tholeiite fields of the alkali-silica and AFM diagram (Fig. 6, 7).

Sedimentary Rocks

The basal 70 m of unit II being covered, this part of the measured section is presumably occupied by easily weathered sedimentary rock. Overlying are 50 m of white orthoquartzite, which are intruded by two basalt sills. The orthoquartzite is thick bedded (1-2 m), fine grained and locally conglomeratic with white quartz pebbles up to 5 mm in diameter. The rock typically consists of subrounded quartz grains with silica overgrowths and very minor microcline and quartzose rock fragments.

The remainder of the sedimentary part of unit II comprises banded green and red silty sandstone capped by green shale. The sandstone is thin bedded to platy, variably silty and commonly mudcracked. It consists of fine grained subangular to subrounded quartz grains in a matrix of detrital sericite and hematite dust. The uppermost green shale forms a very fissile unit 20 m thick.

Unit III

This unit consists of 120 m of recessive, micaceous sandstones overlain by a thick lava flow. The top of the flow is an erosion surface and is the highest level in the measured section.

The sandstones are thinly interbedded, buff and red, fine grained subarkose, slabby weathering, ripple marked and mudcracked. They contain up to 10 per cent feldspar (chiefly microcline), variable amounts of detrital mica (biotite in some rocks, sericite in others) in flakes up to 0.6 mm long (mica is particularly common in the red sandstone), and disseminated fine hematite. Quartz and feldspar are well sorted and subangular. One of the rocks examined also contains minor amounts of quartzose rock fragments and detrital tourmaline, and syntaxial overgrowths were observed on some quartz grains.

Dusky red, colourfully altered lava forms a cap, 39 m thick, to the Gale Point section. Its inclusion in unit III is arbitrary; igneous rocks are not present in unit III elsewhere in Ellesmere Island. Vesicles filled with calcite and agate are present throughout the lava but increase in abundance and size upwards. The larger examples, up to 10 cm across, are handsome geodes consisting of massive pink agate enclosing finely banded white chalcedony. Veins of calcite and chalcedony criss-cross much of the lava.

Well developed breccia on the surface of the lava body indicates that this is the flow top as well as an erosional plane that truncates the measured Gale Point section.

Units II, III and IV are poorly exposed in a downdropped fault block immediately west of the measured section (Fig. 15). The upper part of unit II is overlain by strongly weathered and frost shattered red siltstone and sandstone, which are assigned to unit III. The lava at the top of the measured section was not seen, perhaps because of its removal by erosion or cover by scree from the overlying cliff-forming sandstone of unit IV. The latter rock is typical of unit IV: buff or white, locally conglomeratic orthoquartzite.

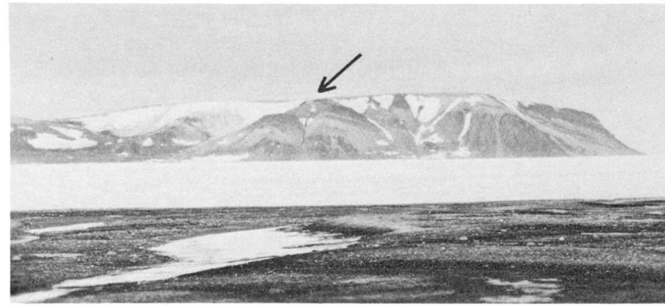

Figure 15. *Thule Group exposures on the north shore of Cadogan Inlet, west of Gale Point. Arrow marks the measured Gale Point section, to the west of which light weathering orthoquartzite of unit IV (mantled by snow) is exposed in a downdropped fault block.*

Environment of Deposition of the Thule Group near Gale Point

A marine shore zone is envisaged as the environment in which the Thule Group rocks near Gale Point were deposited. Shallow water carbonate deposition appears to have dominated during unit I sedimentation but was periodically interrupted by incursions of sand, possibly of terrigenous origin.

Lack of interstitial clastics, relatively steep walls and absence of lateral linkage (Fig. 14) suggest that the stromatolites in unit I formed in a rapidly subsiding or sediment starved region, perhaps a lagoon or supra-deltaic lake. Eventually, these stromatolites were buried under the accumulating sand represented by the orthoquartzite of unit II.

The varicoloured, mud cracked and ripple marked silty sandstones and shales of unit II and subarkose of unit III, which are overlain by a subaerial lava flow, were probably laid down in an intertidal to terrestrial environment.

On the basis of their similarity to equivalent rocks at Goding Bay and Clarence Head, the orthoquartzites of unit IV are thought to be of shallow marine origin.

MACMILLAN GLACIER

An outlier of Thule Group rocks was discovered in 1977 near MacMillan Glacier, about 7 km due west of Wade Point and north of Baird Inlet (Fig. 1). Although small, this exposure is significant because it helps to define the northern limit of the Thule Basin (Kerr, 1967; Christie, 1972) in eastern Ellesmere Island.

The outlier consists of a downfaulted area of sandstones and sandy dolomites about one kilometre wide. A section a few tens of metres thick is exposed in cliffs overlooking MacMillan Glacier. The basement-sediment contact is easily seen, but the sedimentary beds are badly frost heaved.

The sandstones are quartz-rich and variably dolomitic, chiefly buff and purple, less commonly greenish, thin bedded, fine grained and ripple marked. Carious weathering is pronounced in those rocks having a significant dolomite content, such as the purple sandstones. One such rock in thin section consists of rounded quartz grains, 1 mm in diameter, and finer subangular quartz, feldspar and quartzose rock grains in a dolomite matrix. A sample of laminated buff and green sandstone contains subrounded to rounded fine grained quartz with exceptionally well developed syntaxial overgrowths of silica, significant amounts of feldspar and quartzose rock fragments, and, in one thin layer, interstitial detrital sericite. Interbedded with the sandstones are thin layers of sandy dolomite that are commonly stromatolitic.

Table 2. Whole-rock ^{40}K-^{40}Ar ages of basalts of the Thule Group, southeastern Ellesmere Island

Location	Section and/or level	Rock body	Age (Ma)
76°47'N, 77°49'W;	Clarence Head, unit II	Lava or sill	1065 ± 73
2 km SW of Clarence Head	Clarence Head, between units V and VI	Sill	978 ± 46
78°13.5'N, 75°42'W; 5 km W of Gale Point	Gale Point, unit II	Sill	1284 ± 37
78°14'N, 75°50'W; 3 km W of Gale Point	Unit II	Sill	1173 ± 43

Mudcracked silty partings occur at intervals throughout the sandstones and dolomites. The sediments are clearly of shallow water origin and were probably deposited in a marine shore zone.

These rocks closely resemble the lower beds of unit I in the Gale Point section, 40 km to the south. They differ considerably from the late Precambrian rocks overlying basement on Bache Peninsula, 50 km to the north (Christie, 1967). The Proterozoic part of the sedimentary section of Bache Peninsula was probably deposited contemporaneously with parts of the Thule Basin sequence but the lithological differences suggest separate basins of deposition (Dawes et al., in press). The MacMillan Glacier occurrence is the northernmost known of rocks of the type exposed between Clarence Head and Gale Point. The northern margin of the Thule Basin in Ellesmere Island is here taken, therefore, to lie between 78°32'N (Wade Point) and 79°N (Bache Peninsula).

AGE OF THE THULE GROUP OF SOUTHEASTERN ELLESMERE ISLAND

The strong similarities and good correlation between all the outcrops of the Thule Group in southeastern Ellesmere Island indicate a common age for these rocks. For reasons given earlier, the sills intrusive into the Thule sediments are considered to be temporally related to deposition of the Thule Group.

Four igneous bodies have been dated by the whole-rock ^{40}K-^{40}Ar method (Table 2). Unaltered basalt is rare if not absent in the Thule Group but the freshest looking chill zone was sampled in each body.

Three of the four samples dated are relatively fresh although only one contains less than 4 weight per cent ($H_2O + CO_2$). This is the chemically analyzed sample, listed in column B of Table 1, from a lava or sill in unit II of the Clarence Head section. In it, olivine microphenocrysts are completely serpentinized and plagioclase is moderately saussuritized but the pyroxene phenocrysts are barely altered. The age obtained was 1065 ± 73 Ma.

Two other rocks dated are similar in mineralogy and state of alteration. The mafic silicates are strongly altered and interstitial glass has devitrified but the plagioclase is largely fresh. One rock comes from the sill intruded between units V and VI of the Clarence Head section and gave an age of 978 ± 46 Ma. The other sample (Appendix, number 8) is from a sill in the fault block 3 km west of the Gale Point section; it yielded an age of 1173 ± 43 Ma.

The fourth rock (Appendix, number 7), from a sill in unit II of the Gale Point section, was dated at 1284 ± 37 Ma. In thin section, this rock, although texturally well preserved, is seen to be thoroughly altered, both plagioclase and mafic silicates being affected. It seems likely that the isotopic system was disturbed after crystallization and little reliance is placed on the age obtained as an indication of the time of intrusion.

The two ages from Clarence Head agree within error limits. An average of the three "reliable" ages, to the nearest 100 Ma, is 1100 Ma (late Neohelikian). An age of 1.0-1.2 Ga for the Thule Group in southeastern Ellesmere Island seems well founded and agrees with whole-rock ^{40}K-^{40}Ar ages between 1070 Ma and 1190 Ma obtained on sills in the lowest clastic rocks of the Thule Group in northwest Greenland (Dawes et al., 1973).

SUMMARY

Sedimentary and igneous rocks of the late Precambrian Thule Group outcrop chiefly in two coastal areas of southeastern Ellesmere Island: Clarence Head – Cape Combermere and Goding Bay – Gale Point.

The rocks of the Thule Group are predominantly sandstone, siltstone and shale, and, mainly in the lower part of the section, hypabyssal and extrusive basalt. They rest unconformably, with gentle dips, on high grade metamorphic rocks of the Precambrian Shield. They are extensively block faulted but otherwise little deformed and unmetamorphosed.

The Thule Group in Ellesmere Island may be divided into six units, from bottom to top:

Unit I (up to 40 cm thick): Orthoquartzite and conglomerate; stromatolitic dolomite; dolomitic sandstone.

Unit II (up to 300 m): Olivine-tholeiitic basalt sills and lavas interbedded with red sandstone, siltstone and shale or, less commonly, with white or buff orthoquartzite; rare pyroclastic rocks.

Unit III (79-120 m): Red and green sandstone, siltstone and shale, typically floored by a thin stromatolitic carbonate bed. Near Gale Point, basalt lava overlies micaceous subarkose of unit III.

Unit IV (100-265 m): White or buff orthoquartzite, commonly conglomeratic.

Unit V (84-120 m): Red and green sandstone, siltstone and shale.

Unit VI (minimum 300 m): Pale pink, buff or white orthoquartzite. At Goding Bay, the lower beds have minor shaly partings and the upper ones are commonly conglomeratic. At Clarence Head, a basalt sill occurs between units V and VI.

Crossbedding and ripple marks in sandstone and mud cracks in siltstone and shale are virtually ubiquitous in the Thule Group. Lenticular bedding and herringbone cross bedding are particularly characteristic of unit III. The entire Thule Group formed in a shallow marine to subaerial environment, probably largely on or near tidal flats. A strong westerly component of sediment transport was evident from reconnaissance observations of crossbedding.

Whole-rock ^{40}K-^{40}Ar ages of basalt lavas and sills suggest that the Thule Group was deposited in late Neohelikian time, between 1.0-1.2 Ga ago.

The thickest section of the Thule Group is that at Goding Bay, where 1000 m of strata were measured. However, the base of the section is not exposed and the top is an erosion surface.

All the sections examined have been truncated by erosion and major uplift of the Thule Group has occurred, particularly in the Clarence Head – Cape Combermere area. Judged purely from total thicknesses of the sections, Thule Group deposition appears to have thinned northward and southward from a maximum in the area of Goding Bay. No Thule Group rocks are known north of 78°32'N and the northern limit of Thule deposition is considered to lie between this latitude and 79°N. Because no Thule Group rocks occur south of the Clarence Head section (650 m thick), the southern limit of deposition is unknown. However, the fact that on Philpots Island, off the east coast of Devon Island, Paleozoic rocks rest directly on crystalline basement (Frisch, 1981) suggests that the southern limit of the Thule Basin lies between Clarence Head (76°48'N) and Philpots Island (75°N).

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APPENDIX

Chemical analyses of altered basalts (with (H_2O + CO_2) >4.0%) of the Thule Group, Ellesmere Island

	1	2	3	4	5	6	7	8
SiO_2	48.7	46.8	50.5	48.3	53.6	51.9	46.7	49.4
TiO_2	0.71	1.01	0.83	1.52	1.35	0.88	0.82	0.77
Al_2O_3	12.6	13.8	13.9	12.9	13.8	14.5	14.0	14.4
Fe_2O_3	5.6	7.0	4.7	10.5	8.7	8.8	5.9	7.8
FeO	4.5	5.3	5.0	4.0	3.8	2.1	6.0	1.9
MnO	0.24	0.21	0.19	0.16	0.28	0.05	0.06	0.08
MgO	10.67	8.72	7.25	6.66	5.49	10.93	13.37	8.76
CaO	7.57	8.27	7.71	9.08	5.42	2.28	0.47	7.32
Na_2O	2.9	3.7	4.3	2.3	2.0	1.7	0.5	1.5
K_2O	1.07	0.48	0.90	0.10	1.29	2.03	3.37	1.62
P_2O_5	0.10	0.10	0.12	0.15	0.12	0.15	0.12	0.13
CO_2	0.1	0.1	0.5	0.0	1.1	0.0	0.1	1.5
H_2O_{tot}	4.7	4.5	4.0	4.5	3.3	4.4	7.4	4.8
Total	99.5	100.0	99.9	100.2	100.2	99.7	98.8	100.0
S	0.02	0.04	0.03	0.04	0.02	0.02	0.00	0.01
Trace elements (ppm)								
Rb	29	1	5	NF	32	22	37	27
Sr	100	190	130	180	200	110	38	180
Ba	330	510	330	520	580	390	290	340
Co	39	35	33	50	43	35	40	31
Cr	530	220	220	110	150	340	380	470
Cu	12	12	36	77	90	14	17	17
Ni	200	110	71	110	53	92	120	93
V	200	320	240	460	340	270	220	210
Zr	74	46	90	80	80	68	72	69
Li	73	44	23	18	53	122	271	37
Cs	0.1	0.1	2.1	0.3	0.2	4.2	0.4	1.0
B	53	53	52	57	55	68	63	88

NF = not found

1 - sill?; 2,3 - lavas; 4 - lava?; 5 - sill: Clarence Head

6,7,8 - sills, Gale Point and vicinity