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The Proterozoic Thule Supergroup, Greenland and Canada: history, lithostratigraphy and development

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Cover
The middle Proterozoic (Neohelikian) Nares Strait Group on the east side of Kissel Gletscher, Northumberland Ø, Greenland. The succession is dominated by shallow water siliciclastic strata with one main basaltic interval containing effusive, hypabyssal and pyroclastic rocks (Cape Combermere Formation, in centre). This succession represents the early fill of the central part of the Thule Basin. The initial recognition that the central basin straddled Nares Strait was based on the correlation of this succession with that at Clarence Head on the south-eastern coast of Ellesmere Island, Canada (see Fig. 49). The highest ice-capped summit is just below 1000 m a.s.l.; the sea is visible to the left. For map location, see Fig. 48.

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Abstract

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A new lithostratigraphic scheme for the Proterozoic (Neohelikian–Hadrynian) intracratonic Thule Basin of northern Baffin Bay is presented. This basin, preserved between 76° and 79°N in Greenland and Ellesmere Island, Canada, contains little deformed and unmetamorphosed strata at least 6 km thick that are referred to the Thule Supergroup. The succession is composed of continental to shallow marine sediments with prominent red bed units, and one main interval of basaltic volcanic rocks. Diabase sills representing both the Mackenzie (Neohelikian) and Franklin (Hadrynian) magmatic episodes occur at certain levels.

The bulletin has three main parts. The forerunner of the new supergroup, the Thule Group, is infamous for the nomenclatorial chaos that has surrounded its use. Consequently *the first part* is a historical summary as background to the definitive nomenclatorial revision. The *second and main part* on lithostratigraphy splits the Thule Supergroup into 36 formal divisions: 5 groups, 15 formations and 16 members. Twenty geological maps show the regional distribution of the defined units that are represented by 78 stratigraphic logs and sections. The *third part* summarises basin development as a restricted or semi-restricted depocentre on the northern margin of the Canadian–Greenlandic shield. Evolution was controlled by block faulting and basin sagging in a divergent plate regime.

The *Smith Sound Group*, up to 700 m thick, represents the northern platform and basin margin equivalent of the Nares Strait and Baffin Bay Groups of the central basin. Composed of sandstones and shales with subordinate stromatolitic carbonates, the Smith Sound Group represents an overall shelf environment with long-lasting conditions for shallow water to subaerial deposition. Supratidal to marginally marine and intermittently lacustrine sedimentation prevailed.

The *Nares Strait Group*, up to 1200 m thick and representing the basal strata of the central basin, is composed of sandstones and basaltic volcanics including flows, sills and volcaniclastic deposits, as well as shale- and carbonate-dominated intervals. The group represents deposition in alluvial plain, littoral and offshore environments, with accompanying terrestrial tholeiitic volcanicity.

The *Baffin Bay Group,* overlying conformably the previous group, represents the most widespread strata of the Thule Basin reaching a maximum thickness of up to 1300 m. Sandstones and quartz-pebble conglomerates, with important intervals of shales and siltstones, represent mixed continental to marine shoreline environments with an interval of deeper water deposition, possibly in a prodelta or offshore basin.

The *Dundas Group,* 2 to 3 km thick and following the previous group along a gradational contact, comprises sandstones, siltstones and shales with lesser amounts of carbonate and evaporite. Deposition was in an overall deltaic to offshore environment.

The youngest strata, the *Narssârssuk Group*, 1.5 to 2.5 km thick, are preserved in a graben on the south-eastern margin of the basin. The cyclic carbonate – red bed siliciclastic sequence with evaporites represents deposition in a low-energy, hypersaline, peritidal environment in conditions perhaps analogous to modern coastal sabkhas.

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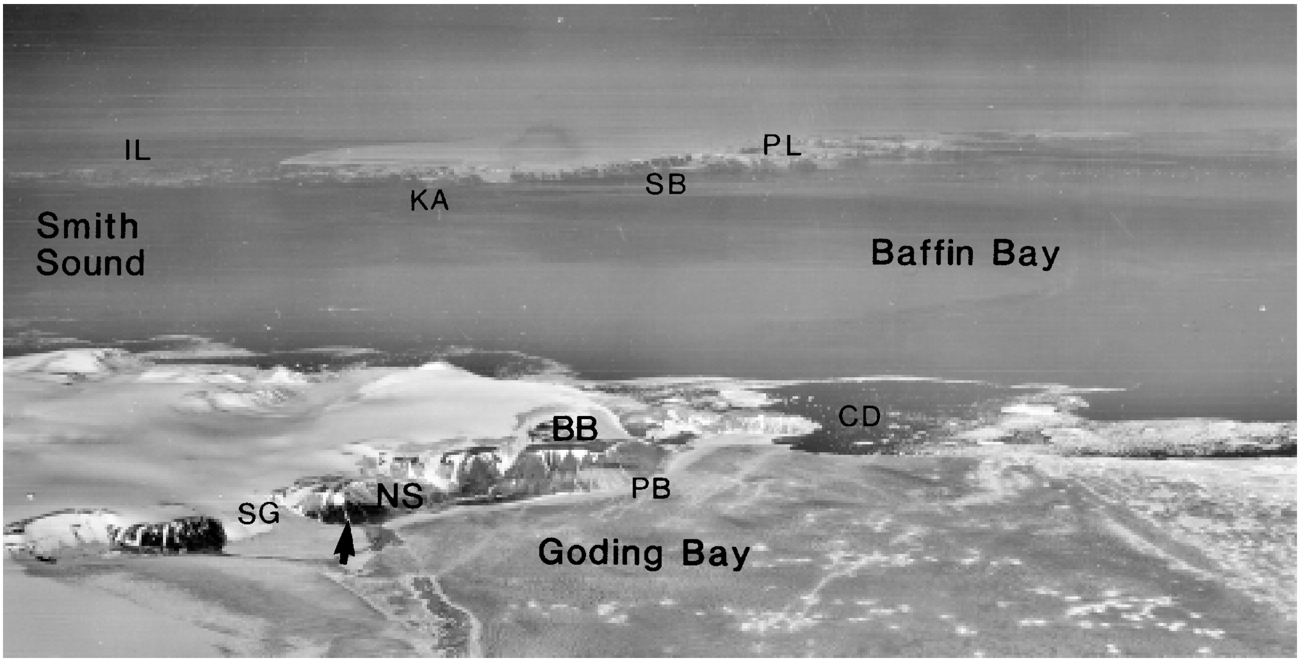


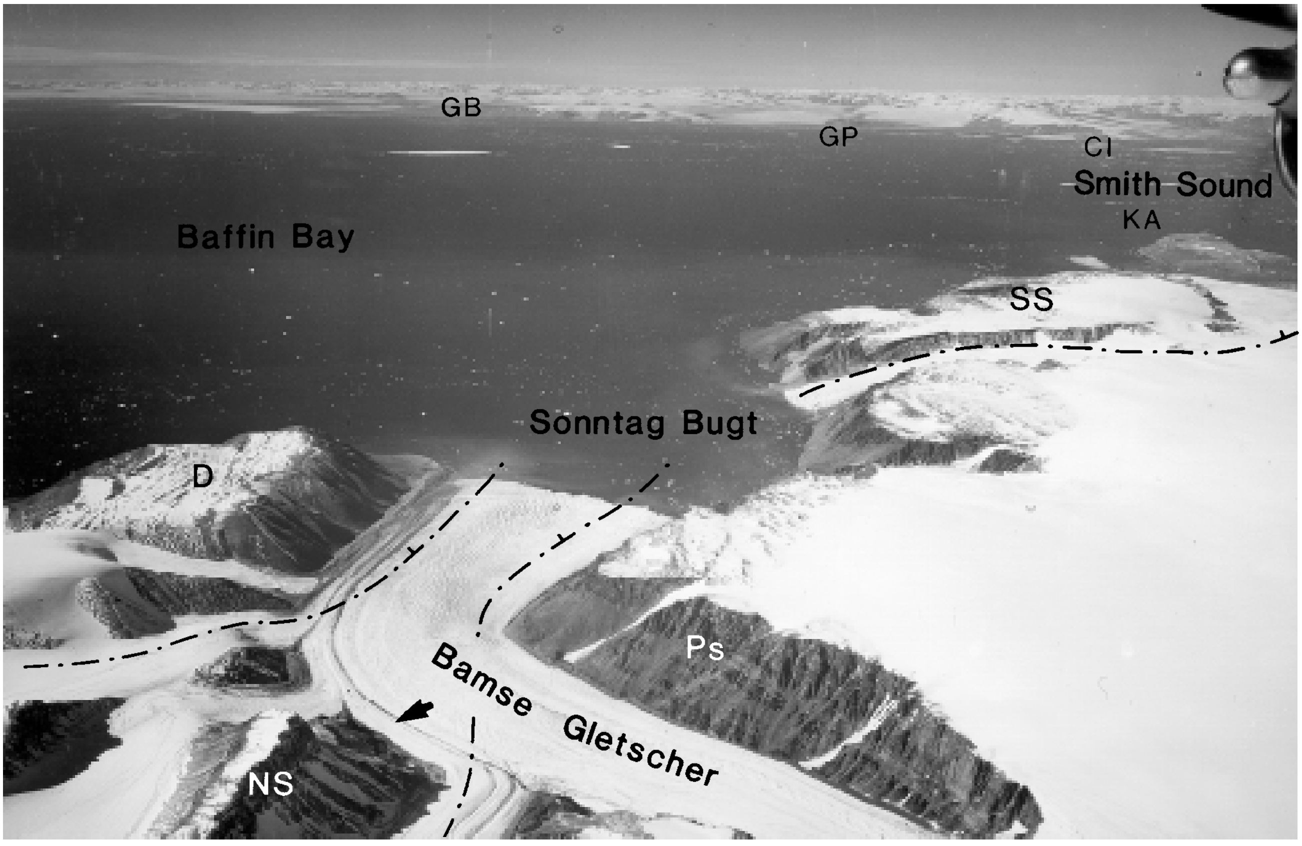


Fig. 1. The Thule Supergroup on opposite sides of northern Baffin Bay – Smith Sound. **Above**, view to Greenland from Goding Bay Canada; **below**, view to Canada from Sonntag Bugt, Greenland, with a distance of less than 50 km between Kap Alexander (KA) and Cape Isabella (CI; see Fig. 2). Height of plateau surface in both views is between 500 and 700 m (see geological maps, Figs 27, 80). The sections arrowed, through the Nares Strait Group (NS), at Sparks Glacier (SG) and Bamse Gletscher are comparable: dark basaltic rocks of the Cape Combermere Formation overlain by the recessive Josephine Headland Formation and topped by the pale cliff-forming sandstones of the Clarence Head Formation (for section detail, see Figs 64, 81B). In Greenland, main faults illustrate coastal down-faulting with Dundas Group (D) as the youngest strata in the outer coastal block (see Figs 5B, 27). Ps = Precambrian shield, SS = Smith Sound Group, BB = Baffin Bay Group; locations: CD = Cape Dunsterville, GP = Gale Point, GB = Goding Bay, IL = Inglefield Land, PB = Paine Bluff, PL = Prudhoe Land, SB = Sonntag Bugt. Aerial photos: above, T403 R-41 National Air Photo Library, Ottawa, Canada; below, 543 E-V 5729, Kort- og Matrikelstyrelsen, Copenhagen, Denmark.

Introduction

This bulletin describes the unmetamorphosed middle to late Proterozoic (Neohelikian–Hadrynian) strata of the Smith Sound – northern Baffin Bay region. The strata outcrop between 76º and 79ºN in Greenland and Ellesmere Island, Canada (Figs 1, 2). A new formal lithostratigraphic scheme is presented in which the strata are referred to the Thule Supergroup.

The Thule Supergroup, comprising little-disturbed sedimentary and magmatic rocks, overlies the Precambrian shield with profound unconformity. Apart from fault-block tilting, minor local warps and broad flexures, the strata are not deformed. The rocks were laid down in the intracratonic Thule Basin on the northern margin of the Canadian–Greenlandic shield (Dawes *et al.*, 1982a).

The Thule Supergroup outcrops as three main successions: a basinal succession forming the dominant part both in Greenland and Canada, to the north a thin basin margin and platform succession, and to the east and south-east, only occurring in Greenland, a basin margin section with a superimposed graben sequence. The basinal succession, represented by the Nares Strait, Baffin Bay and Dundas Groups, is preserved mainly in fault-bounded blocks as essentially flat-lying to shallow dipping sections. The south-eastern marginal succession occurs as thin, scattered outliers composed of the Baffin Bay and Dundas Groups, and as a thick graben section composed of the Narssârssuk Group. These two successions are limited upwards by Quaternary and Recent deposits and by the present erosion surface. In contrast the platformal and northern margin succession represented by the Smith Sound Group is overlain in northernmost outcrops disconformably by Lower Palaeozoic deposits of the Franklinian Basin (Fig. 2).

The Thule Supergroup is most fully developed in Greenland where it has a composite thickness exceeding 6 km. Its outcrops cover more than 6500 km^2. Of the five groups, the Baffin Bay Group has the most extensive geographic distribution; the Narssârssuk Group is the most restricted, occurring only in the Bylot Sund area of Greenland. In Canada, only the lower part of the succession is preserved, composed of the three oldest groups, viz. the Smith Sound, Nares Strait and Baffin Bay Groups (Fig. 2). Formal subdivision and description of these three groups form the main part of this bulletin.

Field work

Field work by the author is based on Greenland exposures, which were mapped during five summers in the 1970s with some later observations in the environs of Qaanaaq and Pituffik (Thule Air Base) during transit visits in the early 80s. Outcrops in Canada, studied photogeologically and formally referred to the new lithostratigraphical scheme, have been mapped by geologists of the Geological Survey of Canada (Christie, 1962a, b, 1967, 1975; Frisch *et al.*, 1978; Frisch & Christie, 1982; Jackson, 1986).

The stratigraphic data from Greenland were collected during reconnaissance mapping of the entire region between 75º and 78º30′N. This region, in addition to the Proterozoic cover strata, is composed of extensive exposures of the Precambrian shield (Fig. 2). The field work was directed at the production of a 1:500 000 geological sheet of the national map coverage (Dawes, 1991a). The main exposures of the Thule Supergroup are covered by maps at 1:100 000 deposited in the archives of the Geological Survey of Denmark and Greenland in Copenhagen.

The stratigraphical work and logging of sections were undertaken concurrently with the geological mapping. Most of the early work, carried out in reconnaissance style using local boat transport, allowed for only brief examination of coastal sections. This work concentrated on recognition of mappable units rather than detailed examination and stratigraphic logging. Occasional foot traverses were made inland. Much section correlation was achieved by binocular study or from aerial photographs. In 1978 and 1980, use of a helicopter gave access to inland sections as well as to Inglefield Land north of normally navigable waters. This allowed for detailed stratigraphic work to be carried out.

This expansion of logistic support also allowed for the participation of two other geologists: Thomas Frisch (Geological Survey of Canada, Ottawa), who in 1977 mapped corresponding strata in Ellesmere Island (Frisch *et al.*, 1978), and Bernard O'Connor (then of the University of Minnesota, USA). In 1978 and 1980 Frisch undertook comparative studies of both Greenland and Canadian sections, reconnoitring with the author from Bylot Sund northwards to Inglefield Land (Fig. 2). Key sections were visited, including the lower part of the succession on Northumberland Ø, and this consoli-

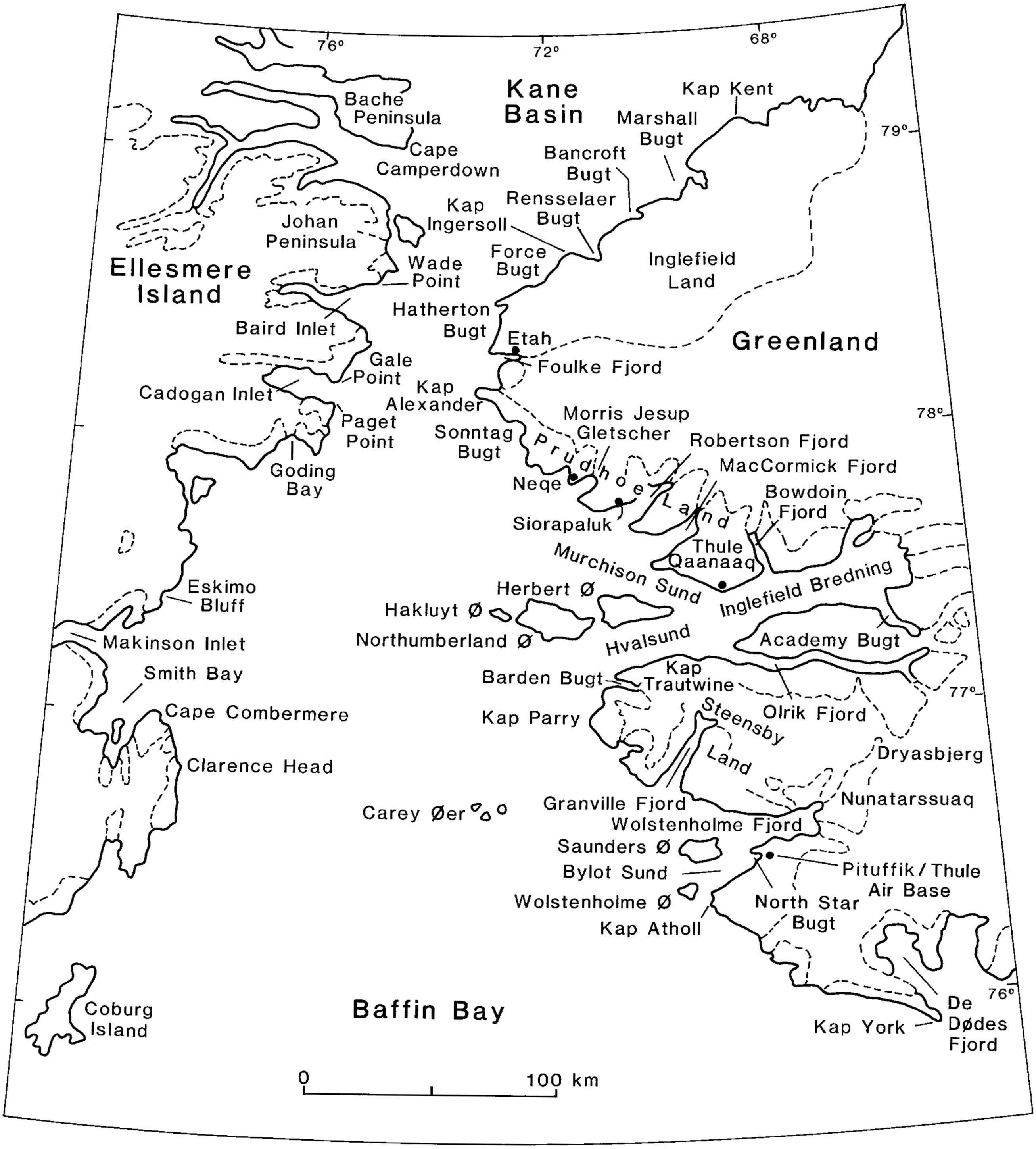


Fig. 2. Maps of the northern Baffin Bay – Smith Sound region. **Left:** Toponymic map. Other place names are shown on Figs 10 and 12, and on the 20 geological maps indexed on the geological map on the facing page. **Right:** Geological and location map showing the distribution of the five groups of the Thule Supergroup. Stars mark small isolated outcrops. A = Academy Gletscher, C = Clarence Head, F = Freuchen Nunatak, M = Magnetitbugt, Mc = MacMillan Glacier, R = Rampen, S = Sun Gletscher. Numbered frames refer to the 20 geological maps included as figures in the text.

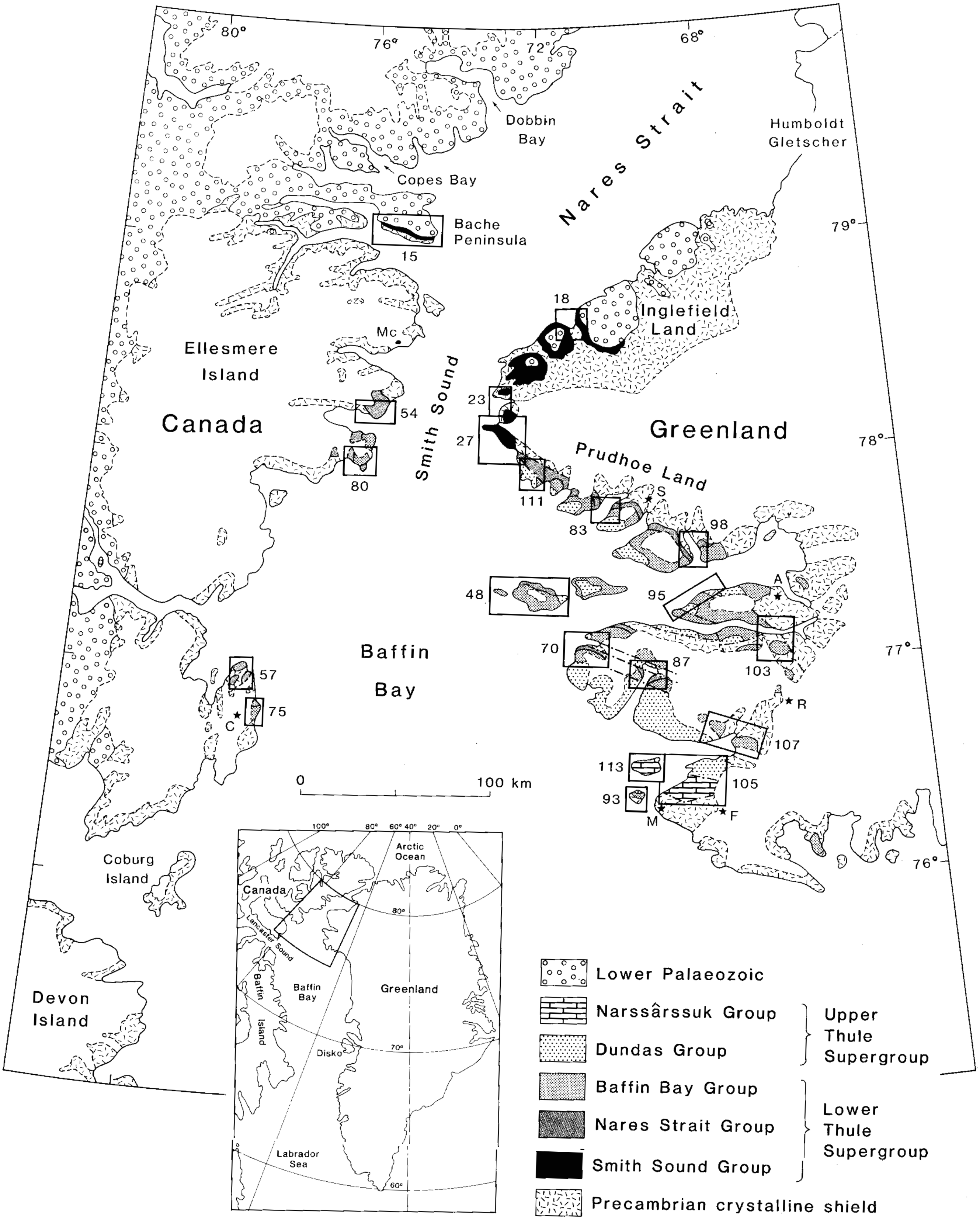


Fig. 2. See facing page.

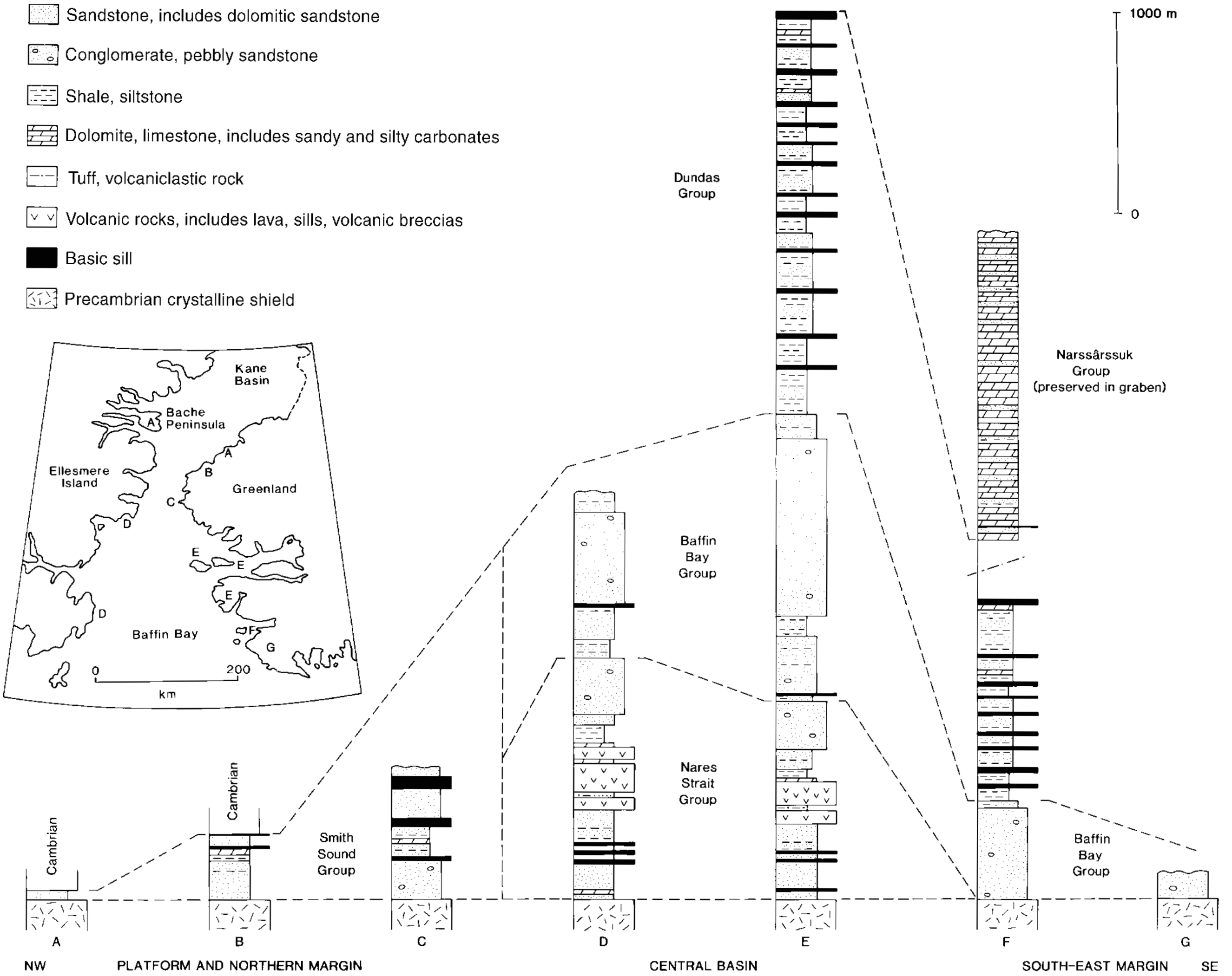


Fig. 3. Schematic columnar sections of the Thule Supergroup. The central basin sections are composite: the Greenland section (E) is based on Northumberland Ø, Herbert Ø and Steensby Land; that of Ellesmere Island, Canada (D) is from Gale Point, Goding Bay and Clarence Head.

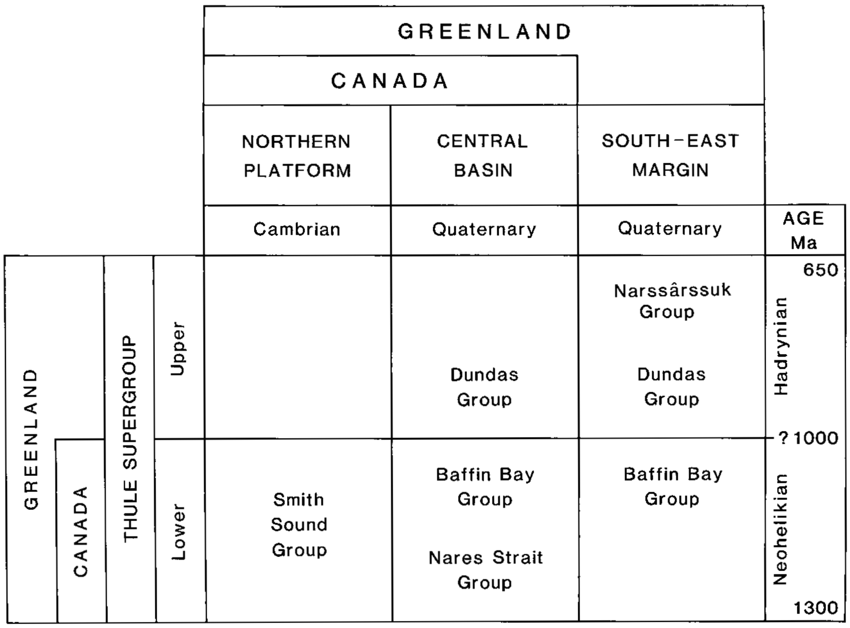
dated the unit to unit correlation of the Thule Basin succession across Nares Strait (Dawes *et al.*, 1982a). In 1980, O'Connor undertook stratigraphical and sedimentological work for five weeks. Measurement of the sections at Saunders Ø, Hartstene Bugt, Etah, Dodge Gletscher and Rensselaer Bugt was undertaken jointly with the author; later work at Narssârssuk, Barden Bugt, Robertson Fjord and Kap Powell was carried out by O'Connor alone. This paper draws on the field notes of O'Connor (1980).

The use of data from O'Connor and Frisch in the compilation of stratigraphic sections and geological maps is acknowledged in the relevant figure captions. Photograph credits to these coworkers, and to others, particularly of Canadian geology, are also given in the relevant figure captions.

Scope of this study

Observations on Thule strata go back to the last century during North Polar exploration along Nares Strait. Stratigraphical nomenclature, introduced by Koch (1929a) with the term Thule Formation, has had a very involved history. Nothing less than nomenclatorial chaos surrounds the use of this term and its successors, the Thule Group of Troelsen (1949, 1950a) and the Thule Group of Koch (1961) and Haller (1961, 1970, 1983). In the light of this, and because no synthesis of research into Thule strata has been published, this bulletin provides a detailed account of previous work and concepts as a background to the nomenclatorial revision.

In presenting a new lithostratigraphic scheme for



			GREENLAND			
			CANADA			
			NORTHERN PLATFORM	CENTRAL BASIN	SOUTH-EAST MARGIN	
			Cambrian	Quaternary	Quaternary	AGE Ma
GREENLAND	THULE SUPERGROUP	Upper		Dundas Group	Narssârssuk Group Dundas Group	650 Hadrynian
CANADA		Lower	Smith Sound Group	Baffin Bay Group Nares Strait Group	Baffin Bay Group	? 1000 Neohelikian 1300

Fig. 4. Lithostratigraphic scheme of the Thule Supergroup showing location and regional setting of the five groups, and general ages.

the Thule Supergroup, formal description at formation and member level is for convenience restricted to the lower Thule Supergroup (Smith Sound, Nares Strait and Baffin Bay Groups) that defines the geographical limits of the Thule Basin straddling Nares Strait (Figs 1–4). The thicker and youngest strata of the Thule Supergroup (Dundas and Narssârssuk Groups), more restricted in outcrop and occurring only in Greenland, are subdivided but not formally defined here.

This study supersedes all previous accounts by the author of the middle to late Proterozoic strata in North-West Greenland, both progress reports written after field seasons (e.g. Dawes, 1972, 1975, 1976b, 1979a) and regional syntheses (e.g. Dawes, 1976a; Dawes *et al.*, 1982a). In terms of correlation and stratigraphic nomenclature it also supersedes publications dealing with Canadian outcrops, viz. Christie (1962a, b, 1967), Christie *et al.* (1981b), Frisch & Christie (1982), Dawes *et al.* (1982a), Jackson (1986) and Frisch (1988); the reader is referred to these works for a full description of the western outcrops of the Thule Basin. I have reinterpreted Canadian outcrops and stratigraphy, and this in part is based on the unpublished notes and sections of Christie (1975).

Peel *et al.* (1982) adapted a revised nomenclature for the platform succession in Inglefield Land (Greenland) and Bache Peninsula (Canada), and referred the formal unit description to a sequel paper quoted as Collinson *et al.*, 'in press'. Unfortunately that paper was not published as planned. This bulletin supersedes the revision mentioned in Peel *et al.* (1982).

The stratigraphical revision of the Thule strata has been heralded (e.g. Dawes *et al.*, 1982a) and Thule Supergroup terminology is found in Hansen & Dawes (1990), Escher & Kalsbeek (1990), Dawes (1991a, b) and Escher & Pulvertaft (1995).

The name Thule and place-name terminology

In usage, the name Thule is unique among place-names of Greenland. Remarkably, Thule has been the authorised Danish name for two settlements located 100 km apart (Fig. 2). This varying geographical position, and the presence of a military air base also known by the name Thule is unfortunate.

In this bulletin the name Thule is used geologically, both formally (Thule Supergroup) and informally (Thule strata), as well as toponymically, in the sense of its original usage, i.e. the site of the now abandoned trading station at North Star Bugt (Figs 2, 105). Dundas, the abandoned Danish settlement at the trading station site, is retained as a stratigraphic term, and the Greenlandic name Qaanaaq, present-day Thule and capital town of Avanersuup municipality situated on Inglefield Bredning, is introduced as a new stratigraphical name. Qaanaaq is used when referring to the capital town; the Greenlandic name Pituffik is used for Thule Air Base. Sioraq, Greenlandic for 'sandy plain', is the lowland on which the air base is located; Pitugfiup kûgssua is the river draining the lowland (see Fig. 105).

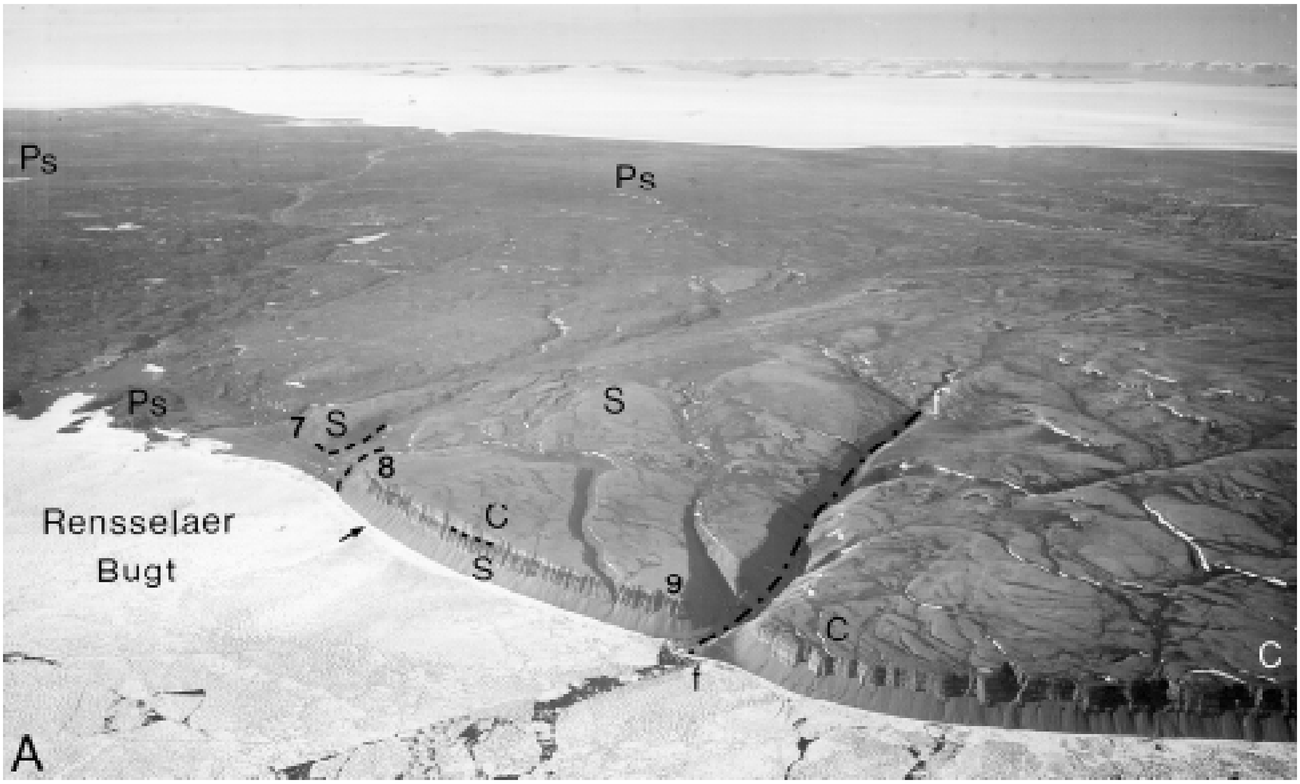


Fig. 5. Contrasts in physiography and exposure of the Thule Supergroup. **A:** plateau landscape in Inglefield Land with the Smith Sound Group (S) overlying the Precambrian shield (Ps). View is south over Rensselaer Bugt to Prudhoe Land with plateau elevation south-west of Rensselaer Bugt up to 400 m. The disconformity with the Cambrian (C) of the Franklinian Basin is just below the pale marker (for stratigraphic detail, see Fig. 32). In the down-faulted westerly block the Smith Sound Group is mostly scree covered. Outcrop of the Precambrian shield at sea-level is arrowed (see geological map, Fig. 18); section locations 7, 8 and 9 are indicated.

The 'Thule region or district' is used herein informally to describe the entire country from Kap York to Kap Alexander; Inglefield Land is used in its authorised sense as the land between Kap Alexander and Humboldt Gletscher.

Place-names are located in Figs 2, 10, and 12, and on the geological maps indexed in Fig. 2. For the spelling of place names used stratigraphically, e.g. Narssârssuk, see section on *Lithostratigraphy*.

Physiography and exposure

The northern Baffin Bay region, magnificently sculptured by glacial erosion, is dominated by uplands and mountainous highlands covered to varying degrees by ice; contrast is provided by Inglefield Land in the north, which forms a dissected plateau of rolling relief. Much of the region is underlain by the Precambrian shield. The overlying Thule Supergroup mainly occupies the outer coastal region preserved mainly in down-faulted blocks or, as in Inglefield Land, as platform outcrops (Fig. 5). In Greenland, Thule strata form continuous outcrops between 76°25′ to 78°50′N; in contrast, in Canada the strata occur as relatively small, widely separated outcrops (Fig. 2).

The Thule Supergroup is generally well exposed. Of the five groups the Dundas Group and Smith Sound Group, with predominant fine-grained clastic lithologies, are most prone to erosion. The Dundas Group forms several poorly exposed lowland areas but it is invaded by resistant dolerite sills. In places these produce miniature mesas that preserve good sedimentary sections beneath their dolerite caps. The celebrated landmark of the Thule district, Dundas Fjeld, is one such landform (see Fig. 105). In Inglefield Land coastal and inland scree-covered slopes are prevalent (Figs 5A, 8, 9).

Supposedly, large areas of Thule strata are hidden by ice and permanent snow. Ice-caps cover central areas of the peninsulas in Prudhoe Land and large parts of Steensby Land, while the Inland Ice encroaches over exposures inland of Pituffik. Recently ice-released land is often covered by thick drift.

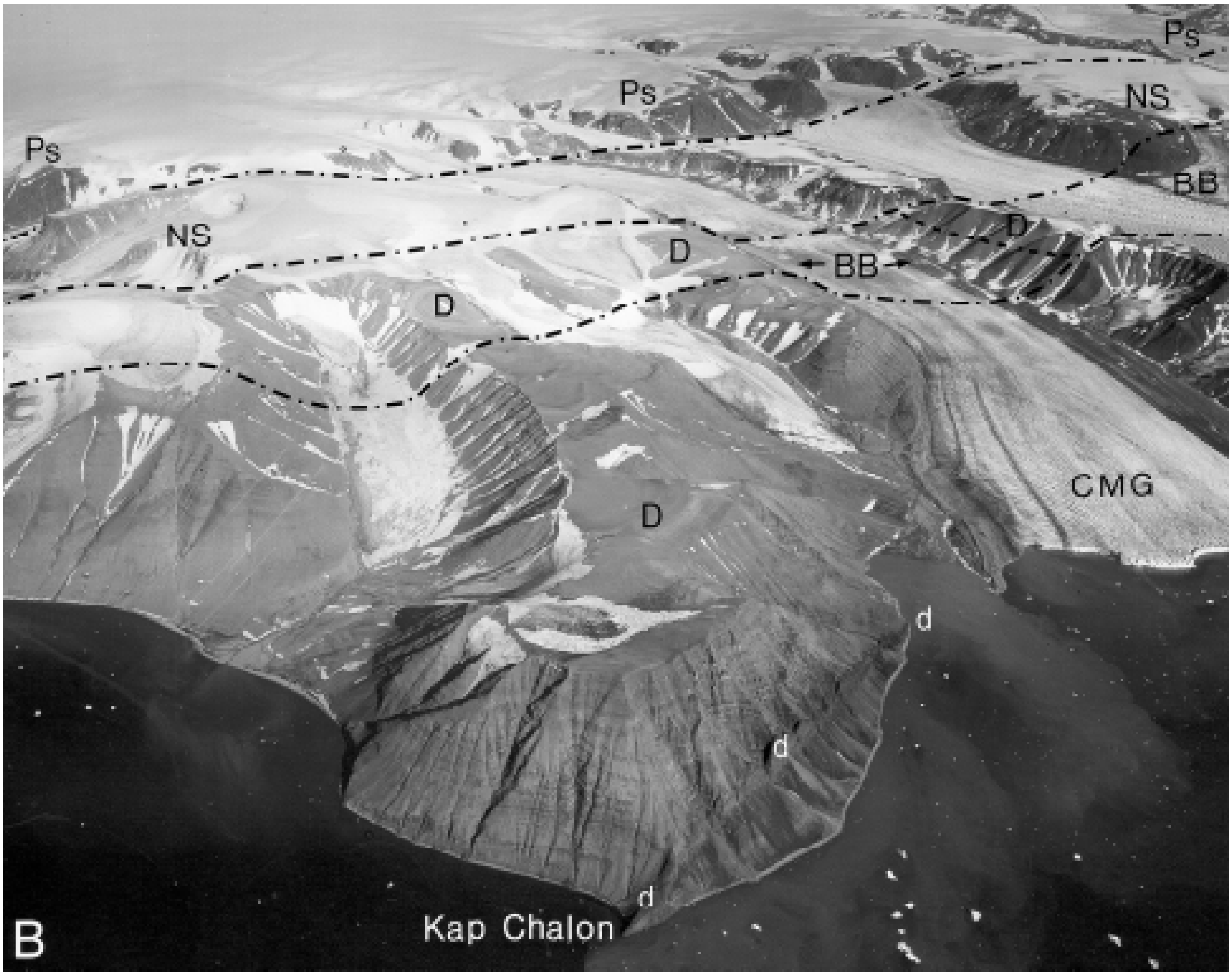


Fig. 5 cont. **B:** The Nares Strait (NS), Baffin Bay (BB) and Dundas (D) Groups in the central basin outcropping in coast-parallel fault blocks with the Precambrian shield (Ps) inland. View is east over Clements Markham Gletscher (CMG), Prudhoe Land. Main faults controlling outcrops at group level are shown. Kap Chalon, cut by a late Hadrynian basic dyke (d), is about 600 m high. For geological map, see Fig. 111. Photos: A, 544A/9297, July 1949; B, 543 B-NØ/2727, July, 1950; Kort- og Matrikelstyrelsen, Denmark.

The Thule strata form rolling uplands to dissected plateau landscape, with upper surface elevations between 400 and 800 m and with partial ice cover (Figs 1, 5). More locally, ice-covered rugged mountains and nunataks are over 1000 m high. The fault-block structure of the region in many places forms spectacular, steep and cliffed coasts, exposing magnificent sections where thin stratal units can be followed over large distances. However, the homoclinal structure produces many sections that are precipitous and inaccessible. Talus can also be profuse.

On the rolling uplands and dissected plateaux, good exposures can occur along glaciers and in river valleys, but on hill tops and plateau surfaces exposures are scarce due to frost-shattered rubble, solifluction deposits or substantial Quaternary deposits. Valleys are usually broad and shallow but steeper valleys, in places canyon-like, occur locally, for example in the carbonate-rich Narssârssuk Group, south of Pituffik. In the high and rugged mountainous terrain, for example Northumberland Ø and Cape Combermere, characterised by closely-spaced cirque glaciers, there are good cliffed inland sections, some of which are accessible from the ice-fields (see Figs 48, 57).

Many fjords and major valleys are fault-controlled. Notable lowlands developed as such and supporting Quaternary and Recent deposits, e.g. the narrow coastland of outer Steensby Land or the broad valley at Pituffik, have limited exposures.

History and status of geological research

Recorded observations of the strata now called Thule Supergroup fall into three periods: (1) 1852–1909 when sporadic observations were made primarily from ships; (2) 1910–1945 when specific geological work was carried out, typically by dog-sledge and boat, and launched from wintering bases; and (3) 1946 onwards, summer exploration made possible by aircraft.

Ship-borne exploration (1852–1909)

Following William Baffin and Robert Bylot's charting of northern Baffin Bay in 1616, Smith Sound, the narrow seaway seen to the north, remained unexplored for more than two centuries. Then, a succession of British and American expeditions heading for the far north visited the Thule district. Information establishing the presence of flattish-lying, multicoloured sedimentary and volcanic strata resting on crystalline granitoids is scattered through the journals of these expeditions, e.g. Inglefield (1853), Kane (1856), Haughton (1859), Hayes (1867), Nares (1878) and Bessels (1879). Sandstones, with grits, conglomerates and calcareous rocks, intercalated with layers of igneous rocks termed 'greenstones', 'traps', 'basalts' or 'greenstone-porphyry' were recorded. Of particular note are the observations of P. C. Sutherland (1853a, b) who, as surgeon of E. A. Inglefield's expedition in 1852, sketched in detail coastal cliff sections passed by their ship. He described the shallowly-dipping dark sandstones – also called 'slaty quartzose grits' – around 'Mount Dundas', Wolstenholme Fjord and Granville Bugt recognising the association with layers and dykes of basalt (see Figs 105, 106) – an early description of the Dundas Group of this bulletin.

Attempts at stratigraphical division based on observations from ships, essentially by laymen, were not the order of the day, but it is interesting that Nares (1878, vol. 1, p. 47) was impressed by the alternating units of bright red and light yellow sandstone making up the picturesque high, perpendicular cliffs of Northumberland Ø and Hakluyt Ø, viz. formations of the Nares Strait and Baffin Bay Groups: "the whole series dipping at an angle of 4º or 5º to the south" (see Fig. 77).

Expeditions led by Robert E. Peary wintered in the Thule district in 1891–92 and 1893–95, during which the coasts between 76º and 78ºN were surveyed. Brief references to geology occur in Peary's (1898) narrative and Thule strata are illustrated. However, it was left to the summer auxiliary expedition of 1894 to attempt a geological synthesis when glaciologist T. C. Chamberlin made the first subdivision of Thule strata based on the country around Inglefield Bredning.

"The clastic series embraces three distinguishable members" wrote Chamberlin (1895, p. 172; Fig. 6). Lower red and middle lighter coloured sandstone units are overlain by an upper unit of "more thin-bedded sandstones and shales of reddish-brown and dark hues". This tripartite division corresponding to units of the Baffin Bay and Dundas Groups is well seen on the south coast of Inglefield Bredning (see Fig. 95). Chamberlin stressed that the unit boundaries are conformable and that the succession may represent a consecutive sedimentation. Although "the full extent of this clastic series could not be determined … because it reached back under the ice cap", Chamberlin (1895, p. 172) was able to deduce that the strata form a coastal belt bordered by crystalline basement. This is the first reference that Thule strata form a coastal basin.

Ideas of this period about the age of the Thule strata were based on resemblance to successions of known (or supposed) age elsewhere. Thus the combination of undeformed sandstones and basalts led to correlation with Tertiary strata of Disko in West Greenland (Fig. 2; Sutherland, 1853a, b; Feilden & De Rance, 1878; De Rance & Feilden, 1878; Dawson, 1887). Comparisons were also made with strata farther south in Canada. Thus, for sandstone and conglomerate around Thule a Silurian age was initially inferred by reference to Lower Palaeozoic beds in Lancaster Sound (Haughton, 1858, 1859). The first notes on Thule strata in Canada were made by H. W. Feilden, senior naturalist on the Nares expedition 1875–76. At Bache Peninsula he described 'coarse basement beds' comparable to those at 'Wolstenholme Sound' in Greenland overlain by mural cliffs of limestone (Feilden & De Rance, 1878; Fig. 7). Fossils from the limestone prompted a Silurian age designation for the clastic rocks beneath, and by inference for the strata at Wolstenholme Fjord. Chamberlin (1895), however, remarking on the conspicuous absence of fossils, reserved opinion noting that Thule strata may be of more than one age; a discernment also seen in Feilden & De Rance (1878).

Per Schei, in 1898, and A. P. Low, in 1904, briefly examined the coastal geology around Foulke Fjord, Inglefield Land (see Fig. 23). Schei also visited Bache Peninsula and he correlated the homoclinal successions across Smith Sound, demonstrating strata at least as old as Cambrian at Bache Peninsula (Schei, 1903, 1904; Holtedahl, 1913, 1917). Low, in misinterpreting metamorphosed carbonate and clastic rocks at Sunrise Pynt, north of Foulke Fjord, assigned the Thule strata to the Huronian system of mainland Canada (Low, 1906, p. 208). Thus, as it happens, the placing of the Thule strata in the correct system (Precambrian) was made on spurious evidence. Willis (1912) adhered to a Precambrian (Huronian or Algonkian) age but followed Feilden & De Rance (1878) in maintaining a Tertiary age for thinner sections around Kap Alexander.

Exploration from stations (1910–1945)

The establishment of the Thule trading station at North Star Bugt in 1910 by Knud Rasmussen and Peter Freuchen heralded a new chapter in scientific exploration. The first expedition launched from this base (1st Thule expedition, 1913) did little geological work around Thule, but Freuchen (1915) and Bøggild (1915) described from Independence Fjord in eastern North Greenland sandstones and diabase that were later to be included in the Thule Formation by Koch (1929a; see Fig. 10). It was on the 2nd Thule expedition (1916–18) that the first regional geological survey was embarked on by Lauge Koch (1918, 1919, 1920), a study continued on the Bicentenary Jubilee expedition 1921–23 (Koch, 1923a, b, 1925, 1926, 1929a, 1933). Koch compiled maps at 1:700 000 and *c.* 1:1 000 000 of Inglefield Land and the Thule district, respectively (Koch, 1933; Dawes & Haller, 1979), and illustrated the faulted nature of the Thule district by cross-sections of Prudhoe Land (Koch, 1926).

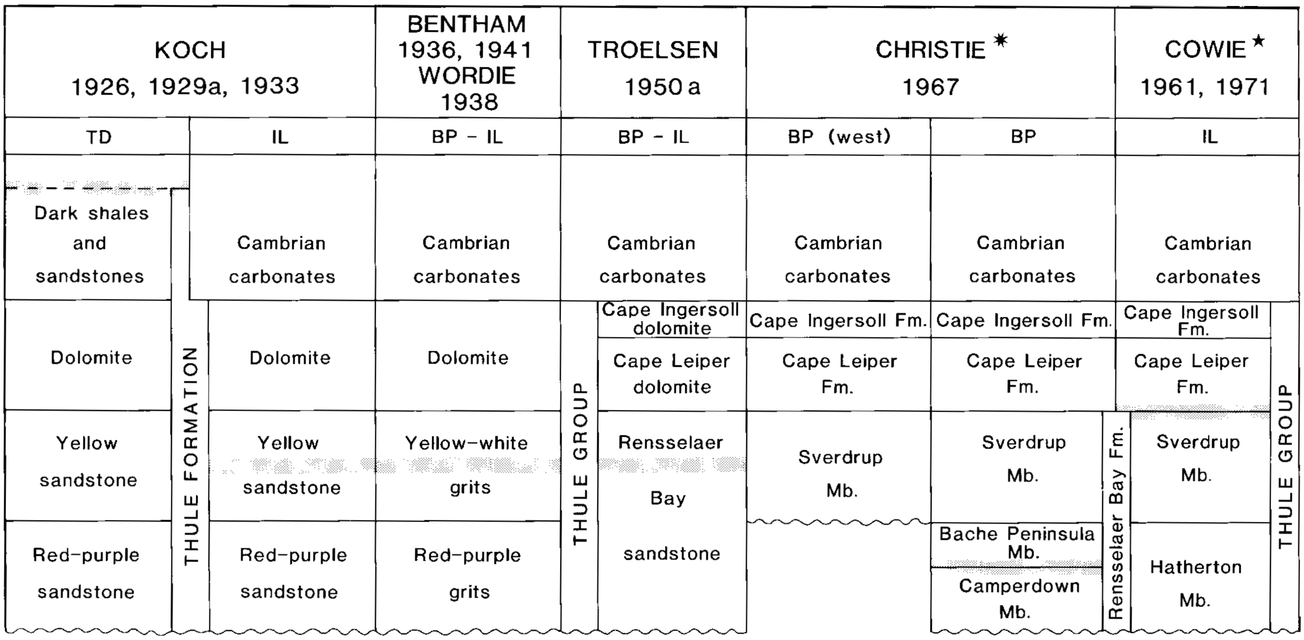
The name Thule Formation was introduced by Koch (1929a, p. 220) to cover late Precambrian strata with a type locality at “Wolstenholme Fjord, around Thule” (see Fig. 105). He included in this clastic and intrusive rocks in Canada and as far away as the east coast of Greenland (see section below on *Stratigraphic nomenclature*). Koch noted the thickness difference between the type area where the formation was said to exceed 800 m (now known to be much more), and Inglefield Land where “150 to 200 meters is the usual thickness”. In North-West Greenland he adopted Chamberlin’s tripartite subdivision (Koch, 1926, p. 304), although he erected a sub-unit of dolomites (Figs 6, 95).

A summary of Koch’s stratigraphy from North-West Greenland (Koch, 1925, 1926, 1929a, 1933) is: a ‘lower sandstone’ of red, purple and brown colours, including arkose and conglomerates, with *Cryptozoon* reefs, an ‘upper sandstone’ of yellow and red yellowish sandstone with some conglomerate, and ‘an uppermost series’ of cliff-forming pale dolomites overlain by dark grey micaceous hard sandstone, black shale and slate. Dolomites in Inglefield Land were noted to contain *Cryptozoon* and chert. Important here is Koch’s observation that the dark grey sandstones and shales, so conspicuous around Thule (Dundas Group) and for him representing the youngest strata, are absent in Inglefield Land, cliff-forming dolomites there being disconformably overlain by Lower Cambrian carbonates (Koch, 1933; Figs 6, 8).

Koch mapped a fourth unit – diabase – that he showed penetrating the Thule Formation in all areas except north-east Inglefield Land (Dawes & Haller, 1979, plate 1). Koch could but speculate on the absence of diabase in north-eastern Inglefield Land: only decades later did it become evident that the intrusion-free strata are Lower Cambrian and therefore post-date the Proterozoic magmatism (Peel *et al.*, 1982).

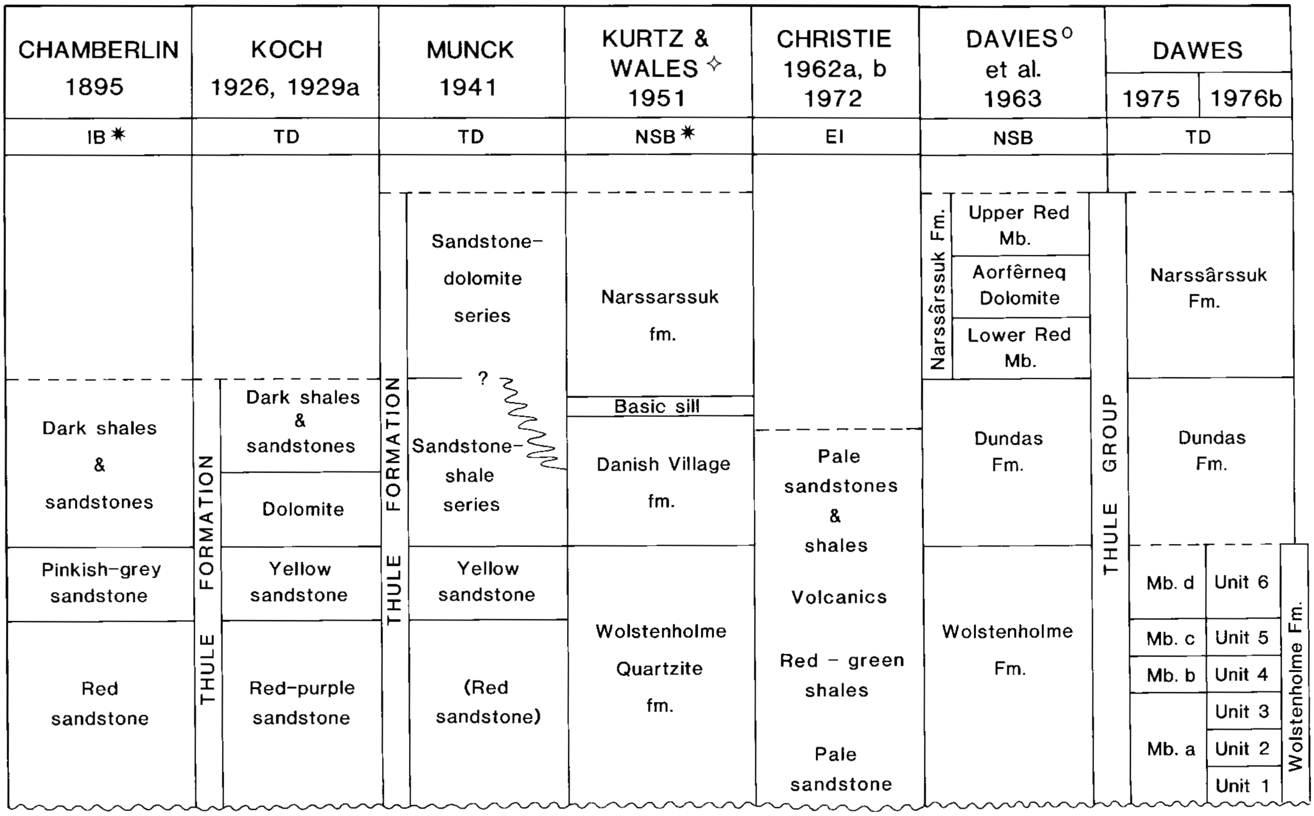
Koch applied Chamberlin’s tripartite scheme widely in the Thule district and, with modification, in Inglefield Land, but he had difficulty in maintaining it fully. In the south, around Bylot Sund, the presence of a thick carbonate-rich red bed succession (Narssârssuk Group) was difficult to reconcile with the scheme. The problem was rooted in his assumption that the succession’s southern boundary, with the crystalline shield, is a stratigraphic contact and not a master fault (Narssârssuk Fault; see Fig. 105). Koch’s interpretation is very understandable: he mapped an unconformity on Wolstenholme Ø (see Fig. 93) and assumed the same relationship on the mainland. Hence, strata regarded today as the youngest (Narssârssuk Group) were referred to the basal part of the succession, and Saunders Ø and adjacent mainland (between Narssârssuk and Sioraq) were regarded as recording a complete section through the Thule Formation.

Koch (1918) initially suggested an Algonkian or Lower Cambrian age for the Thule strata. Later, on the basis of Holtedahl’s (1913, 1917) assessment of Bache Peninsula, he switched to a Cambrian–Ordovician age (Koch, 1920). Finally, after the discovery in Inglefield Land (Kap Kent) of Lower Cambrian strata disconformably above clastic strata referred by him to the Thule Formation, he designated a Precambrian (Algonkian) age (Koch, 1926, 1929a). (It should be noted that these



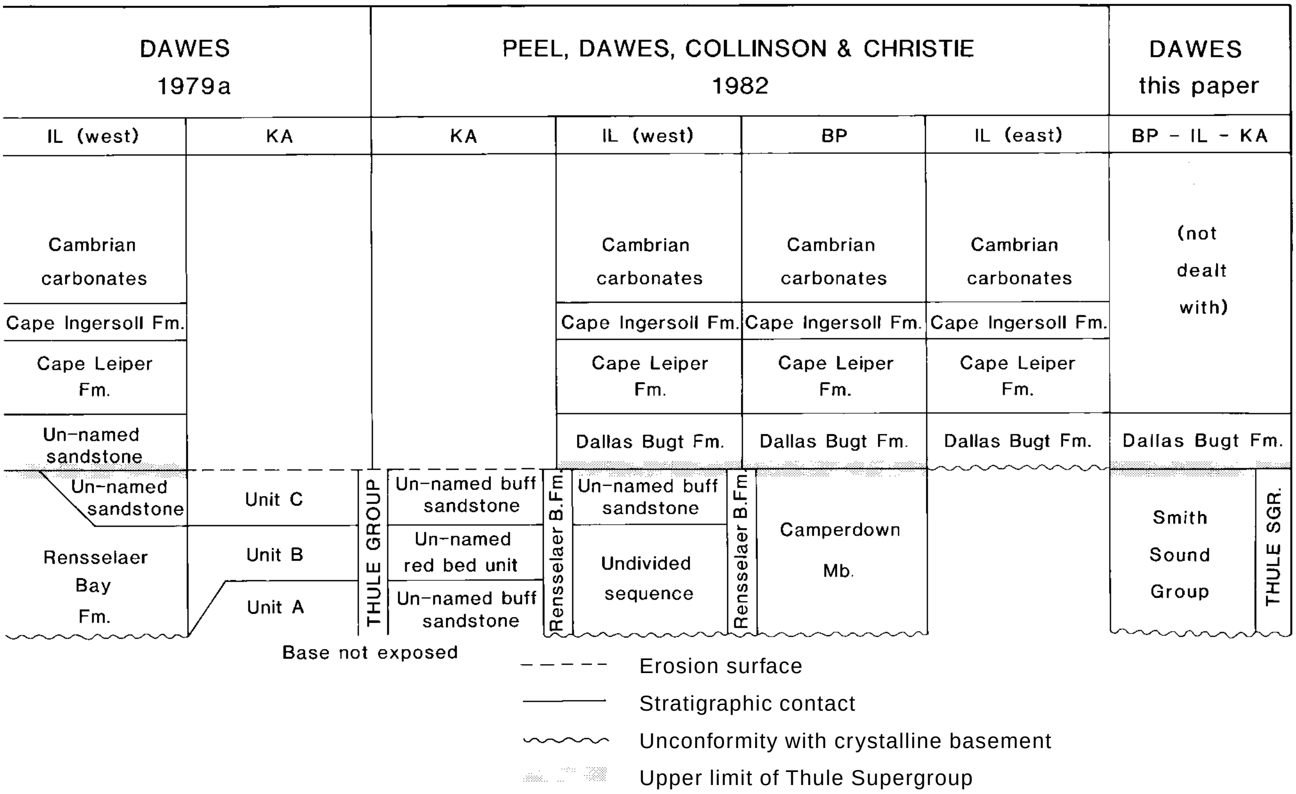
TD – Thule district
BP – Bache Peninsula
IL – Inglefield Land
KA – Kap Alexander

✷ Christie (1967) purposely did not use the name Thule Group
★ Cowie (1961) referred the section to the Thule Group; later he (Cowie, 1971) refrained from using the term



IB – Inglefield Bredning area
TD – Thule district
NSB – North Star Bugt area
EI – Ellesmere Island

✧ Kurtz & Wales did not refer the succession to the Thule Group
✷ The stratigraphic entity of these units is based on investigations in a restricted part of the Thule Basin
o Davies (1954) referred to the three formations as, in ascending order, “Quartzite Series”, “Black Shales” and “Red Beds”; Davies (1957) also mentions the formational nomenclature



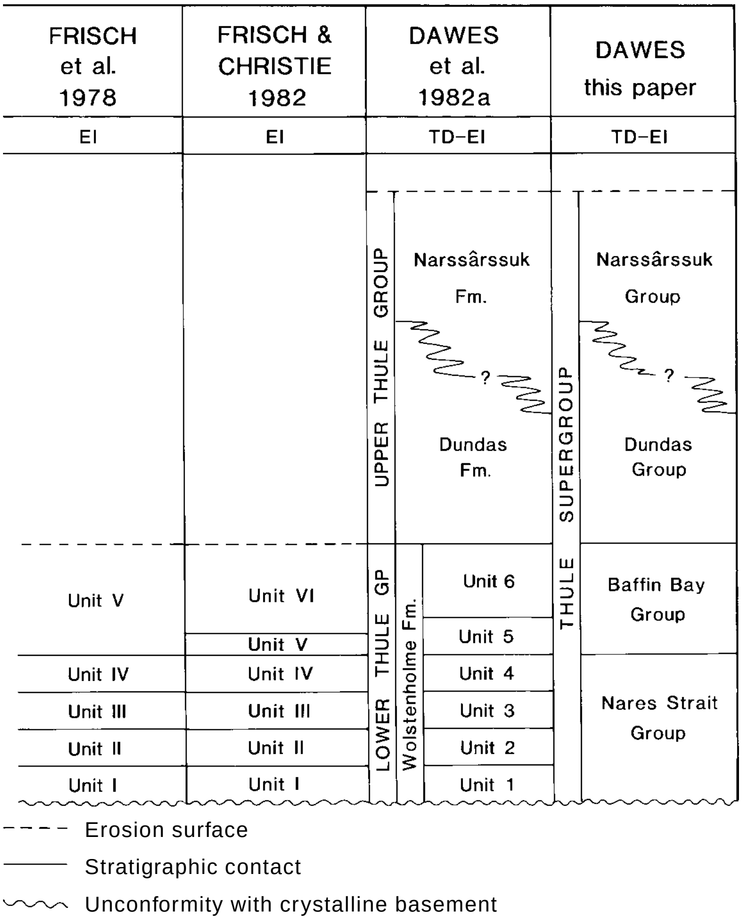
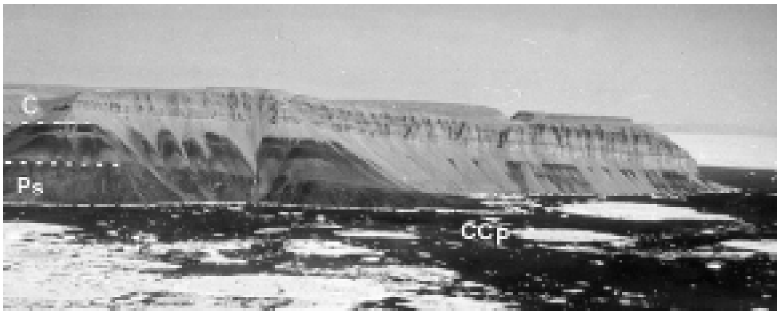


Fig. 6. Previous and present lithostratigraphic schemes for Thule strata from the northern Baffin Bay – Smith Sound region.
Above: strata of the platform and northern margin of the Thule Basin, with Koch's (1929a) subdivision from the Thule district (TD) for comparison.
Below: central basin and south-east margin deposits.



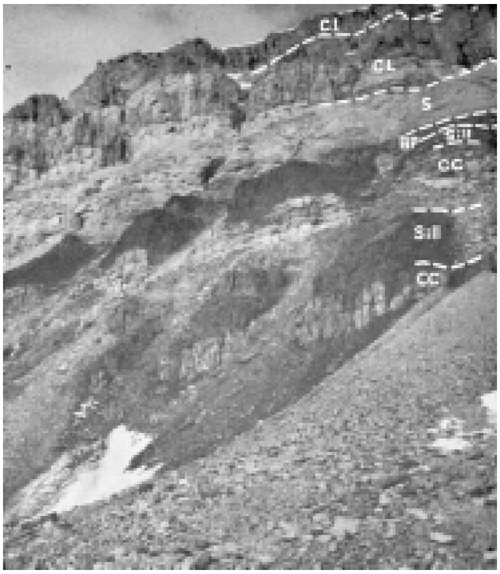


Fig. 7. South coast of Bache Peninsula, Canada. **Above:** Thule Supergroup (Smith Sound Group) overlying the peneplaned shield (Ps) and capped by Cambrian strata (C). This view illustrates the geology initially described by Feilden & De Rance (1878): the thin dark Thule strata (recessive but with basic sills) regarded for almost a century as basal red beds conformable with the Palaeozoic. **Right:** section west of Cape Camperdown (CCp) shows Christie's (1967) tripartite division of the Rensselaer Bay Formation; Cape Camperdown (CC), Bache Peninsula (BP) and Sverdrup (S) Members. CL = Cape Leiper Formation; CI = Cape Ingersoll Formation. The Thule Supergroup includes strata CC with the disconformity to the Cambrian on or just above the upper basic sill (cf. Fig. 8). Height of cliffs about 600 m (see Fig. 15)

particular clastic strata at Kap Kent have turned out to be Cambrian and not part of the Thule Supergroup.)

During a short summer cruise in 1936, Sole Munck studied the Thule Formation at several localities (Munck, 1941). Of the sections examined, two were measured: one at Siorapaluk (500 m thick), the other at Uvdle, Wolstenholme Fjord (400 m thick); her work represents the first section logging. Munck remarked on the lithological distinctiveness of the sequence forming the coastal cliffs between Narssârssuk and Sioraq (called the sandstone-dolomite series, viz. the Narssârssuk Group of this paper). Noteworthy here are Munck's inferences about the Chamberlin–Koch stratigraphical scheme (Fig. 6). The recognition of the importance of dolomites with stromatolites south of Sioraq and the conformable contact at Uvdle between Koch's lower sandstones and the upper sandstone-shale series, led to the rightful conclusion that the sandstone-dolomite series must overlie the sandstone-shale series (not underlie as previously thought) or represent "different facies within contemporaneous depositions" (Munck, 1941, p. 28).

Robert Bentham on two expeditions, 1934–35 and 1936–38, wintering in both Greenland and Ellesmere Island, recognised the continuity of the Thule strata between the two lands. He correlated both sedimentary units and basic sills remarking astutely that parts of the Bache Peninsula section "are indistinguishable from the Thule Formation of Inglefield Land" (Bentham, 1936, p. 336). Bentham referred the clastic part of the Bache section to the Thule Formation.

J. M. Wordie and H. I. Drever made a brief visit to Inglefield Land and Bache Peninsula in 1937. Finding no break in the succession and Lower Cambrian trilobites in carbonates directly above the clastic section, they "decided that at Bache the Thule beds are merely the basement lower Cambrian" (Wordie, 1938, p. 399; Fig. 7). Bentham (1941) adhered to this age assignment.

J. C. Troelsen wintered in northern Prudhoe Land in 1939 and 1940, working on both sides of Nares Strait (Troelsen, 1950a). He recognised the lithological complexity of the Thule Formation, noting the basic differences between the thin sections of Bache Peninsula and Inglefield Land (Smith Sound Group), and the basinal succession to the south with its greater lithological variety. Although he concentrated his efforts on Inglefield Land, in northern Prudhoe Land he measured through nearly 1 km of sandstones and conglomerates without observing either top or the bottom, viz. Baffin Bay and Dundas Groups of this bulletin. He raised the Thule strata to group status by defining in Inglefield Land three formations, from base to top: Rensselaer Bay sandstone, Cape Leiper dolomite and Cape Ingersoll dolomite (Figs 6, 8). Stressing the importance of an erosional disconformity with fossiliferous Cambrian beds, Troelsen assigned the group an Eo-Cambrian age. Following Koch (1929a), he extended the Thule terminology to eastern North Greenland, although his use of it was radically different (Troelsen, 1949, 1950b, 1956a, b; see later under *Stratigraphic nomenclature*).

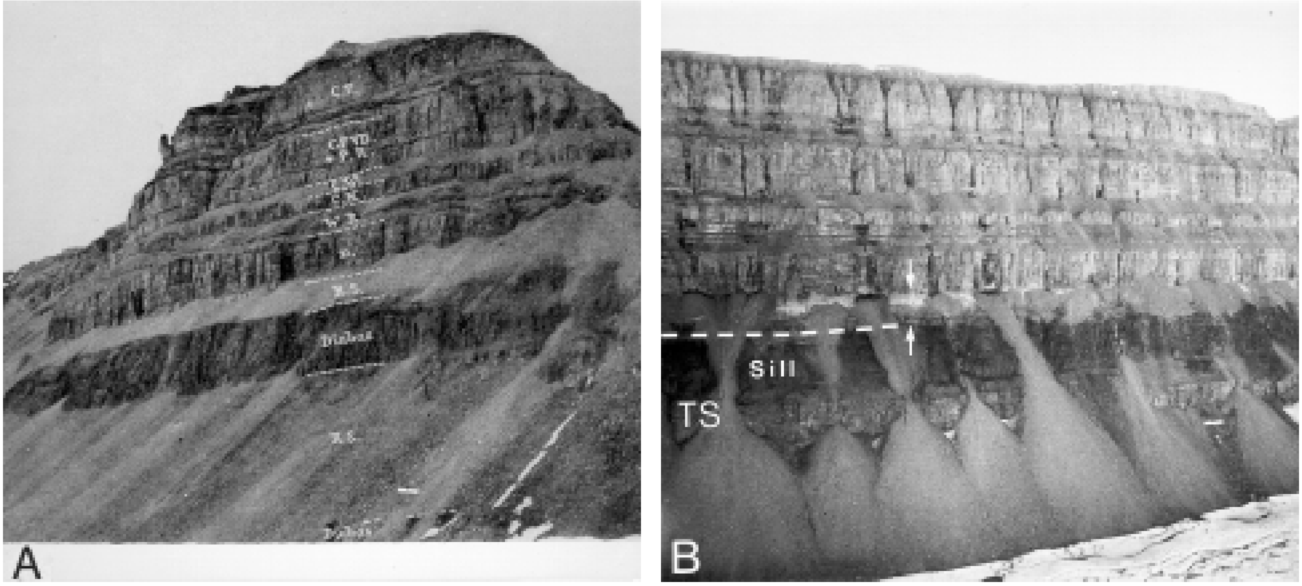


Fig. 8. Kap Ingersoll, Inglefield Land, Greenland, showing past and present definitions. **A:** Koch's (1933) Algonkian *Thule Formation*, RS = Red sandstone with diabase sills and D = dolomite, overlain by Lower Cambrian (WR = Wulff River Formation). Troelsen (1950a) based his Eocambrian *Thule Group* on this section defining the Rensselaer Bay sandstone (RS) and splitting D into two formations, the Cape Leiper and Cape Ingersoll dolomites. **B:** *Thule Supergroup* (TS) includes only *part* of the oldest formation of Troelsen's Thule Group. Strata between arrows, viz. thin red beds overlain by pale sandstones, make up the Cambrian Dallas Bugt Formation that disconformably overlies Thule red beds and a Neohelikian sill. In places in Inglefield Land the erosional hiatus truncates the sill (see Figs 32, 44). Cliffs are about 250 m high. For comparison with Bache Peninsula, see Fig. 7.

Modern investigations (1946 and onwards)

The vast lowland, Sioraq, came into focus as an aircraft landing site during the Second World War, and between 1951 and 1953 a military air base was constructed. Geological investigations were carried out in connection with its planning and construction and later as a consequence of its support facilities. Thus the first helicopter work was in 1949 when Kurtz & Wales (1951) made a 10-day survey of the Bylot Sund area. Three formations were recognised, from base to top: the Wolstenholme Quartzite formation of "coarse, red to white, crossbedded, massive, partially conglomeratic orthoquartzite", the Danish Village formation of "dolomites, shaly dolomites, and black bituminous shales" and the Narssarssuk formation of "red siltsones, coarsely crystalline, grey, porous dolomite, and fine-grained, shaly dolomite, arranged in cyclical fashion" (Fig. 6). Unfortunately, Kurtz & Wales (1951) made no mention of J. C. Troelsen or of the Thule Group; Troelsen's field work from 1939–40 remaining essentially unpublished until 1950 (see Troelsen, 1940, 1949). However, these authors did not even refer to prior work on the very strata studied by them: work that included Koch's (1926) mapping of stratigraphic units and Munck's (1941) descriptions. Fortunately, their published sketch-map provides a means for stratigraphic comparison. Hence the Narssarssuk formation in essentials equates with the sandstone-dolomite series of Munck, and the Danish Village formation represents her sandstone-shale series (Fig. 6). Munck (1941) had pondered on the relationship of these two series, recognising that the contact might be found around Sioraq; Kurtz & Wales (1951) assumed a conformable relationship and chose a diabase sill north of Sioraq as the boundary.

Kurtz & Wales (1951) mapped several faults on Wolstenholme Ø and adjacent mainland (see Figs 93, 105). The Narssârssuk Fault, juxtaposing the Narssarssuk formation and crystalline basement, was suggested to represent a downthrow of at least 3 km. Kurtz and Wales' discovery that *both* stratigraphic and tectonic contacts of Thule strata with crystalline basement were present in the Bylot Sund area, allowed them to complete a fundamental stratigraphic revision that had been astutely hinted at by Munck.

Geologists of the U.S. Geological Survey surveyed parts of the Thule district by helicopter in the summer

Fig. 9. Geology of Hatherton Bugt, Inglefield Land, showing the peneplaned Precambrian shield (Ps) and the bipartite division of the Thule strata (Smith Sound Group): recessive Rensselaer Bay Formation (RB) and cliff-forming Sonntag Bugt Formation (SB) with basic sills. These units equate with the Hatherton and Sverdrup Members of Cowie (1971); the Sverdrup Member at the type locality in Bache Peninsula in Canada is now known to be Cambrian. Section above the peneplain is about 200 m thick.

of 1953. W. E. Davies and colleagues described the North Star Bugt area (Davies, 1954, 1957; Davies *et al.*, 1963), compiling a geological map at 1:100 000; a smaller area, Nunatarssuaq, to the north-east was reported on by Goldthwait (1954) and Fernald & Horowitz (1954, 1964). The latter authors made the first report of fucoidal markings in Thule strata (Fernald & Horowitz, 1964, p. 32).

The three-fold division erected by Kurtz & Wales (1951) was adopted by Davies *et al.* (1963) who referred the succession to the Thule Group. The Danish Village formation was renamed the Dundas Formation and the Narssârssuk Formation was divided into three members, viz. the Lower red member of cyclic-bedded red siltstone and grey dolomite with some limestone, shale and gypsum; the Aorfêrneq dolomite member of grey vuggy dolomite with some limestone and gypsum (Arferfik member of Davies, 1957); and the Upper red member with lithology similar to that of the lowest member but with prominent grey-green sandstones. The Narssârssuk Formation was shown to be restricted to the Bylot Sund area, while the lower formations were traced north into Prudhoe Land (Davies *et al.*, 1963; fig. 2). Davies and coworkers regarded the Narssârssuk Formation as overlying the Dundas Formation and, despite the limited exposure, they speculated that the relationship was an unconformity (Davies *et al.*, 1963, p. 31).

The first study of Thule beds in Inglefield Land in the post-war period was by John Cowie in 1957: one month's field work mainly on foot (Cowie, 1961). Measured sections at Kap Ingersoll, Etah and Hatherton Bugt were referred to Troelsen's (1950a) Rensselaer Bay, Cape Leiper and Cape Ingersoll Formations (Fig. 6), but Cowie adhered to Koch's (1929a) Precambrian age assignment.

The important discovery of Thule strata in Canada south of Bache Peninsula was made by R. L. Christie who mapped south-eastern Ellesmere Island in 1960–61. Working essentially by dog-sledge, Christie (1962a, b, 1972, 1975) mapped the 2 km thick succession of multicoloured sandstone, shale and basaltic rocks overlying the crystalline basement between Clarence Head and Gale Point (Figs 2, 6). He compared the strata to the Thule Group of the Thule district and assigned them a Precambrian age.

Christie (1967) made also a detailed study of Bache Peninsula, subdividing the Rensselaer Bay Formation into three: in ascending order, the Camperdown Member of variously coloured sandstones and shale with calcareous beds and basic sills; the Bache Peninsula Member of purplish brown sandstone and conglomerate; and the Sverdrup Member of yellowish sandstones that contain 'scolithid-like sand pipe structures' (Figs 6, 7). The two upper members were shown to overlap westwards, with the Sverdrup Member overlapping the crystalline basement. Kerr (1967a) also recognised *Skolithus* in the Bache Peninsula Member and this, as well as the suggested correlation between strata at Bache Peninsula and Cambrian geosynclinal rocks of the Franklinian Basin to the north, led to the inference that the Rensselaer Bay Formation was Lower Cambrian (Kerr, 1967a, b; Thorsteinsson & Tozer, 1970; Cowie, 1971). Christie (1967, 1972), more cautious, argued that the basal strata with basic sills may be older.

The Rensselaer Bay Formation in Greenland was formally subdivided by Cowie (1971) into two members, the upper one being transferred from Canada. A lower Hatherton Member, 100 m of recessive maroon red and purple sandstones with conglomeratic beds and dolomite with stromatolites, equates, at the type area around Hatherton Bugt, with Koch's (1929a, 1933) lower sandstone while the overlying Sverdrup Member, 50 m of pale sandstone and siltstone, equates with the upper yellow sandstone of Koch (Figs 6, 9). The recognition of the Sverdrup Member in Greenland was to prove unfortunate. In Greenland the unit contains basaltic sills while in the type area at Bache Peninsula, it is intrusion-free (Figs 7, 9). This is chronostratigraphically significant; it is now known that the two units are of profoundly different ages (Proterozoic and Cambrian, see below).

The concept of a discrete basin subsidence in the Thule district in contrast to the platform to the north, initially broached by Koch (1929a, p. 271), was expounded on by Troelsen (1956a, p. 75) who defined a structural high between Inglefield Land and Bache Peninsula bounding the basin on the north. Christie's (1962a, b) discovery in Canada of thick Thule strata south of 78°N influenced thinking on the Proterozoic depositional framework: a major intracratonic sedimentary basin straddled Nares Strait. Kerr (1967a) introduced the names 'Thule basin' for the depocenter and 'Bache Peninsula arch' for the northern structural high. The Thule Basin concept quickly found a place in the literature (e.g. Cowie, 1971; Dawes, 1971; Christie, 1972; Dawes & Soper, 1973).

Advances in the last two decades

By 1970 the gross distribution of Thule strata was known. In the last two decades new outcrops were discovered only in the inner part of Inglefield Bredning and at De Dødes Fjord in Melville Bugt (Dawes, 1976b) and in Canada, at MacMillan Glacier and on inland nunataks (Frisch *et al.*, 1978; Frisch & Christie, 1982). On the other hand the stratigraphic limits and stratal age of the Thule Group were conjectural. The main advances in the last two decades can be summarised as follows:

1. The basic sills and dykes closely associated with the Thule strata have been dated isotopically as Precambrian (Dawes *et al.*, 1973). Preliminary results have been confirmed both on the Greenlandic and Canadian material; distinct periods of magmatism are of Neohelikian and Hadrynian age (Dawes *et al.*, 1982b; Frisch & Christie, 1982; Dawes & Rex, 1986; LeCheminant & Heaman, 1991).

2. The Proterozoic ages inferred from radiogenic dating have been confirmed by microfossils. The upper part of the Wolstenholme Formation (now Robertson Fjord and Qaanaq Formations of the Baffin Bay Group) and the main part of the Dundas Formation (now Dundas Group) have yielded typical Riphean (Neohelikian–Hadrynian) acritarch assemblages while possible Vendian (late Hadrynian) acritarchs occur in the upper Dundas Formation and the Narssârssuk Formation (now Narssârssuk Group) (Vidal & Dawes, 1980; Dawes & Vidal, 1985).

3. The Wolstenholme Formation in Greenland has been shown to be many times thicker, and considerably more complex in gross composition, than previously thought showing marked thickness variations. The wide variety of lithological types includes basaltic effusive and volcaniclastic strata (Dawes, 1975, 1976b). Unit to unit correlation has been established with the succession mapped and logged by Frisch *et al.* (1978) and Frisch & Christie (1982) in Ellesmere Island (Dawes *et al.*, 1982a).

4. A major erosional disconformity was detected in Inglefield Land within Troelsen's Rensselaer Bay Formation (Peel, 1978; Dawes, 1979a; Peel *et al.*, 1982; Figs 6, 8). This hiatus separates an intrusion-invaded clastic sequence of Proterozoic age that includes the Hatherton and Sverdrup Members of

Cowie (1971), from overlying clastics containing the trace fossils *Skolithos* and *Rusophycus*. Peel *et al.* (1982) refer the upper sequence to the Dallas Bugt Formation. This basal Cambrian formation oversteps the Proterozoic succession so that in central and north-eastern Inglefield Land it is in direct contact with crystalline basement (Fig. 2). Thus it was proved that the Thule Formation of Koch (1929a, b; 1933) and Thule Group of Troelsen (1950a) in the Kane Basin region compose two sandstone sequences of widely different age.

5. Stratigraphic correlation has been achieved between the basinal section and the thin Inglefield Land strata to the north; clastic units in the Wolstenholme Formation of the basin (Nares Strait and Baffin Bay Groups of this paper) thin and extend northwards to interfinger with the lower part of the Rensselaer Bay Formation (Smith Sound Group of this paper) (Dawes, 1972, 1976a, 1979a).

In addition to the above, field work on Thule strata has been carried out by two other groups. In 1978 Strother *et al.* (1983) examined the Narssârssuk Formation south of Pituffik collecting carbonaceous cherts for micro-organic study, while in 1982 a group from the Geological Survey of Canada studied sections at Goding Bay, Clarence Head, Northumberland Ø and in the North Star Bugt area (Jackson, 1986). Material collected by Jackson and others forms the basis of a microfossil study by Hans Hofmann (G. D. Jackson, personal communication, 1993).

Stratigraphic nomenclature

The Thule Formation (Koch, 1929a) and Thule Group (Troelsen, 1949, 1950a) – the forerunners of the Thule Supergroup – are perhaps those Greenlandic stratigraphic terms used with the highest degree of inconsistency. The terms have covered strata of different ages and of different geological settings, correlating outcrops from Baffin Bay to the Greenland Sea, a distance of some 2000 km (Fig. 10). Strata designated 'Thule' include:

- intracratonic basin and platformal strata in Ellesmere Island and North-West Greenland (Koch, 1929a, 1933; Troelsen, 1950a);
- a shelf carbonate-clastic sequence, including tillites in southern Peary Land (Troelsen, 1949, 1950b, 1956a, b);
- folded and thrusted shelf and miogeosynclinal strata in Ellesmere Island (Blackadar, 1957; Blackadar & Fraser, 1961; Thorsteinsson, 1963);
- platformal rocks of the North Greenland homocline (Koch, 1929a);
- autochthonous and allochthonous, in part metamorphic, strata of both geosynclinal and platformal parts of the East Greenland Caledonian fold belt (Koch, 1961; Haller, 1961, 1970, 1971, 1983).

The highly irregular nomenclatorial practice surrounding the Thule terminology is detailed chronologically below.

1. The Thule *Formation* (or formation) was coined by Koch (1929a) with a type area around Thule. However, it duly became part of the 'Grönlandium' (Greenlandian), viz. the vast homoclinal Precambrian strata overlying the peneplained shield in North, North-East and East Greenland as far south as 76°N (Koch, 1935b; Fig. 10).

2. The initial use of Thule *Group* (or group) was by Troelsen (1949, 1950a, b) who simply remarked that "the Thule group was named in 1929 by Lauge Koch …" (Troelsen, 1949, p. 9) and that "the group was first defined by Koch …" (Troelsen, 1950a, p. 35). This informal use implies a straightforward raising in rank of Koch's Thule Formation. This is highly misleading; Troelsen's Thule Group is not a synonym of Koch's Thule Formation.

3. Troelsen's (1950a) definition of the Thule Group was not made at or near the type area of the Thule Formation but 250 km distant in Inglefield Land. This led several authors (e.g. Christie, 1967, 1972; Kerr, 1967a, b; Cowie, 1971; Dawes, 1971) to abandon

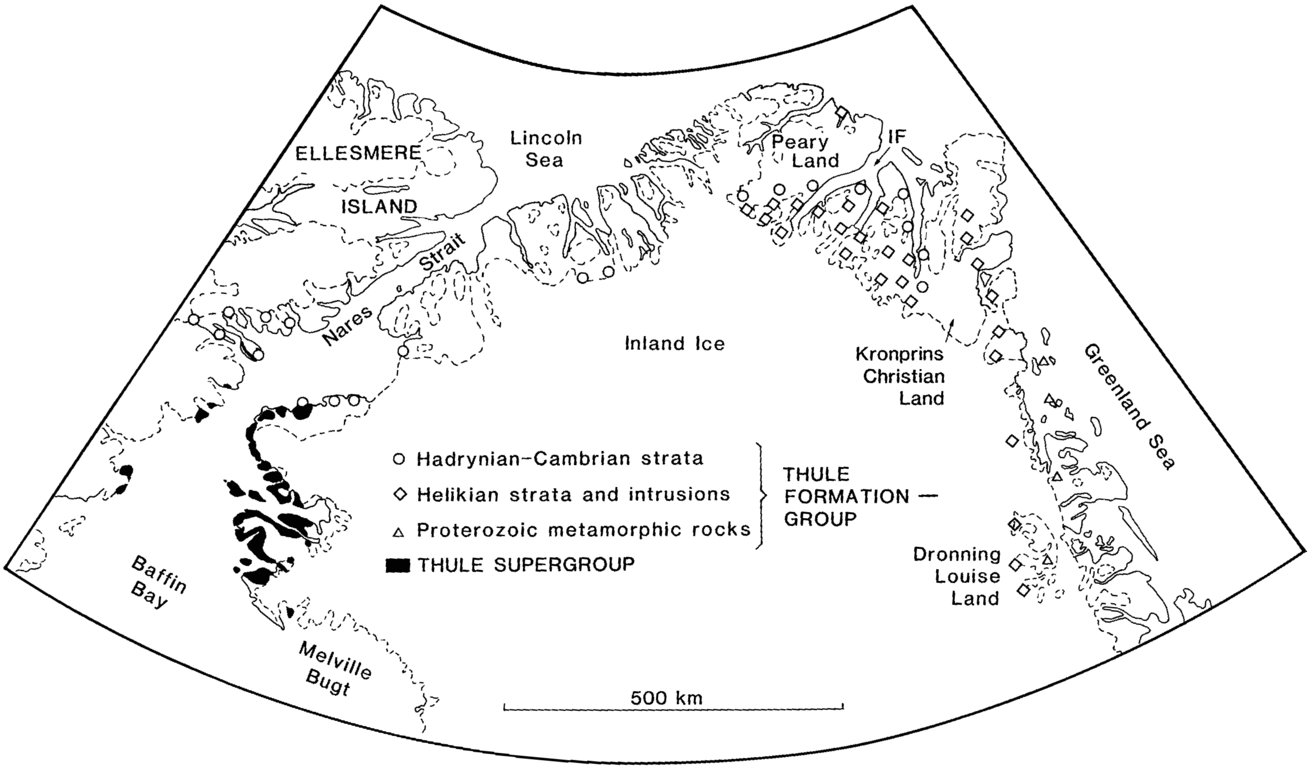


Fig. 10. Geographical distribution of the Thule Supergroup compared to that of its forerunners, the Thule Formation and Thule Group. IF = Independence Fjord.

the use of the name Thule in the very region (Inglefield Land) where its group status was defined.

4. Troelsen (1949, 1950b) used the name Thule in eastern North Greenland for a succession that post-dates Koch's (1930, 1934, 1935b) Grönlandium. Troelsen's Thule Group is a carbonate-shale sequence overlain by Cambrian dolomite but underlain by basalt-invaded sandstone that, in fact, is Koch's Thule Formation. Red beds at the base of Troelsen's Thule Group were recognised as a tillite and referred to the Varangian glaciation (Troelsen, 1950b, 1956a, b). Thus, remarkably, the terms Thule Formation and Thule Group came to be used by different schools for integral parts of a bipartite succession: Koch's Thule Formation of supposed Precambrian age below, Troelsen's Eocambrian Thule Group above. Later, and again confusingly, Troelsen (1956a, b) reverted to formational status and used the name in a third concept, viz. to cover both parts of the bipartite succession.

5. The initial naming of stratigraphic units of formational rank in the type area was made by Kurtz & Wales (1951) without reference to the established and mapped units of Koch (1926, 1929a) or to the Thule Group of Troelsen (1949, 1950a) or to its tripartite division.

6. The annexation of sections in Canada, north of Bache Peninsula, to the Thule Group (Blackadar & Fraser, 1961; Thorsteinsson, 1963; Fig. 10) and the incorporation of part of the Bache–Inglefield succession in the Cambrian Ellesmere Group (Kerr, 1967a) were made at a time when the age of the Thule Group at the type area was unknown.

7. Geologists working in North-East Greenland adhered to Koch's rather than Troelsen's use of Thule Formation/Group by restricting the name to the basalt-invaded strata at the base of the succession (e.g. Nielsen, 1941; Fränkl, 1954, 1955, 1956; Haller, 1961; Koch, 1961; Haller & Kulp, 1962; Harland, 1969). The Thule Group came to be redefined by Haller (1961, 1970) after local geological conditions and it came to assume a chronostratigraphic significance that was not applicable to the far distant type area around Thule. Redefined, the Thule Group covered

> a specific phase of late Precambrian sedimentation in North and North-East Greenland – the so-called pre-Carolinidian (orogeny) cycle. The strata were subdivided into a Lower and an Upper Thule Group and informally referred to as 'Thulean beds'. Although these rocks have age equivalents in the Thule Basin, the Carolinidian orogeny was not demonstrable in North-West Greenland and has since been disputed even in the type area of Kronprins Christian Land (Jepsen & Kalsbeek, 1981; Haller, 1983).

For a detailed history of the use of Thule Formation/ Group in North and North-East Greenland, the reader is referred to the papers cited above and to the discussion in Adams & Cowie (1953, pp. 16–17), Berthelsen & Noe-Nygaard (1965, p. 227), Jepsen (1971, pp. 7–10) and Dawes (1971, pp. 204–210, 1976a, pp. 265–267). More recently Collinson (1980) has introduced the Independence Fjord Group to cover sediments of Koch's Thule Formation as defined in Peary Land and areas to the south-east. In Haller (1983) Thule Group is retained although it is placed in inverted commas.

Selected nomenclatorial practice

This bulletin raises the Thule Group to supergroup status and drastically restricts its geographical distribution. Paradoxically, however, the supergroup includes only *part* of *one* of three formations that compose the initial Thule Group of the Smith Sound area; a part that has been referred to another stratigraphical unit, viz. the Ellesmere Group of Kerr (1967b). These facts plus the considerable nomenclatorial confusion that has surrounded the Thule Group constitute a case for the abandonment of the name Thule in any definitive revision. However, the name is considered to be so entrenched in the literature that its replacement would be confusing.

There is also a case for reuniting nomenclatorially Proterozoic successions across northern Greenland. Investigations in eastern North Greenland (Collinson, 1980; Jepsen *et al.*, 1980; Kalsbeek & Jepsen, 1984), reviewed by Sønderholm & Jepsen (1991), confirm that clastic and basaltic rocks, originally part of Koch's (1929a) Thule Formation, are of the same age and type as the lower Thule Supergroup. Koch's initial correlation across northern Greenland can be maintained. Thus, the Independence Group of Collinson (1980) and the Zig-Zag Dal Basalt Formation of Jepsen *et al.* (1980) might be referred to the lower Thule Supergroup, with the overlying Hagen Fjord Group (Clemmensen & Jepsen, 1992) as part of the upper Thule Supergroup. This is not done here, however, since direct links between exposures in North and North-West Greenland are lacking and the Thule Basin is regarded as a discrete depocenter, one of several on the northern margin of the North Atlantic craton (Dawes *et al.*, 1982a). Present practice tends to restrict nomenclatorial names to successions that can be correlated within individual depocentres, rather than between the separate basins (see Young, 1979; Campbell, 1981).

Lithostratigraphy

The formal units of the lithostratigraphic scheme are discussed in general ascending stratigraphic order and starting with the relatively thin northern platform and basin margin succession. Lithostratigraphic schemes of the Thule Supergroup are given in Figs 4 and 11; regional stratigraphy is summarised in Fig. 3. Generalised stratigraphic sections for 26 stations through the lower Thule Supergroup are displayed in Fig. 12 and the stratigraphical relationships of the groups and formations are illustrated in a schematised cross-section given in the last chapter (see Fig. 120).

Stratigraphic sections. The stratigraphic sections presented have been compiled from data of variable detail; some are based on detailed logs; elsewhere, only qualitative reconnaissance sections are available. The precise thickness of the Thule Supergroup is unknown. The sheer extent of the succession (seen in relation to the scope of the field work) and in many places the steepness of slope, have prevented systematic measurement. Some unit measurements are estimates based on partially measured sections. As far as possible the material has been standardised and it is presented both

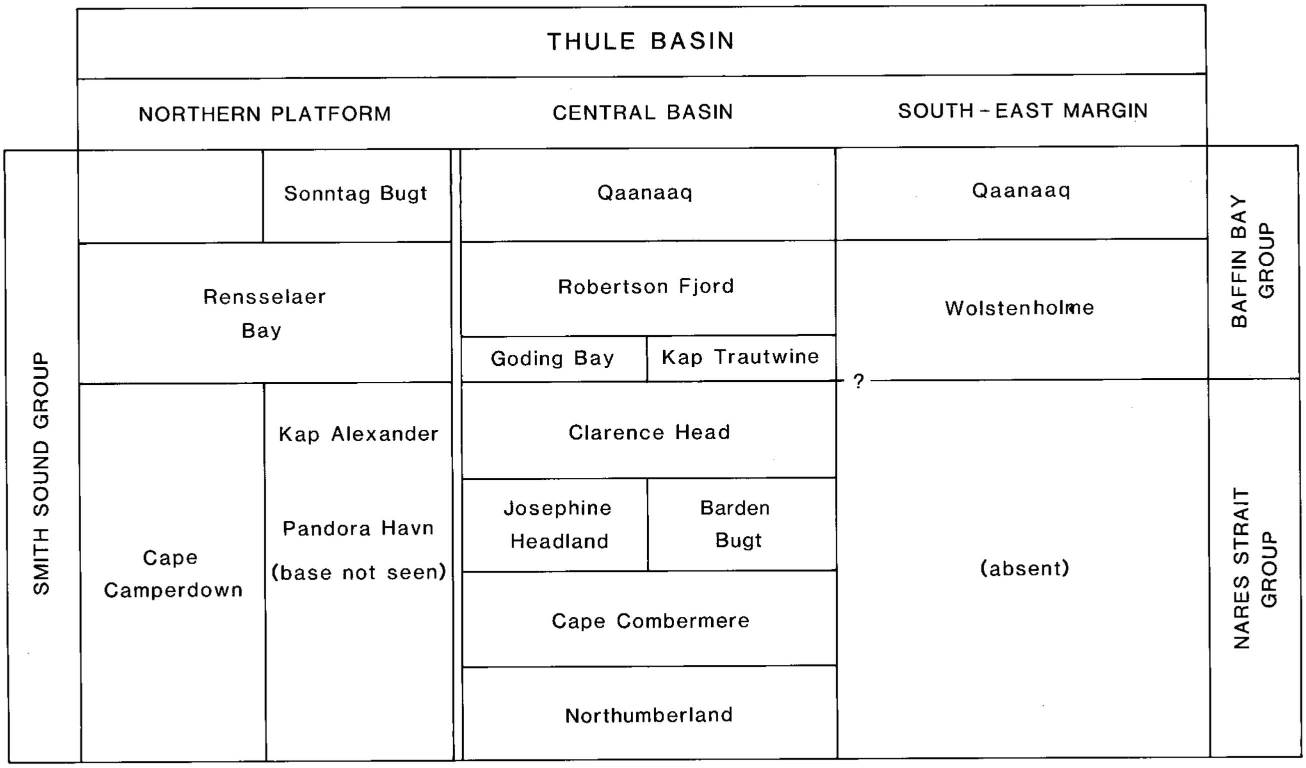


Fig. 11. Lithostratigraphic scheme of the lower Thule Supergroup showing groups and formations.

as stratigraphic logs and generalised sections with a common legend (see Plate 1 at rear). Sections of Canadian outcrops are compiled by the author from data in Christie (1967, 1975), Frisch & Christie (1982) and Jackson (1986) and these are presented in matching form.

Unit descriptions. To meet formal lithostratigraphic procedure, each unit description has a section on depositional environment. Determination of the depositional milieu of Precambrian successions is notably problematic; in the absence of systematic sedimentological analysis, it is tentative. The interpretations offered here, based on variable sedimentological detail taken from both published (e.g. Frisch & Christie, 1982; Strother *et al.*, 1983; Jackson, 1986) and unpublished data in Survey files, are in places necessarily speculative.

Names: spelling and derivation. Lithostratigraphic names for Thule strata have hitherto been of mixed derivation, based both on English and Greenlandic spelling of geographical localities. Authorised place names in Greenland have now Greenlandic or Danish spelling, and formal stratigraphic names in this paper are so derived. Likewise all stratigraphic names from Ellesmere Island are based on authorised Canadian (English) spelling. Where Greenlandic names are introduced as stratigraphical terms, the new spelling form is used, e.g. Qaanaaq Formation (rather than Qânâq). Following the guidelines of stratigraphic nomenclature (e.g. Holland *et al.*, 1978; Salvador, 1994), the initial spelling of stratigraphic units should be preserved even when redefined. Hence, the English form, Rensselaer Bay Formation, is adhered to although the type area is Rensselaer Bugt – the authorised Danish form.

The scarcity of geographical names in Canada has dictated that two non-geographical names have been used for new lithostratigraphic units. To accord with the guidelines of formal designation (Hedburg, 1976; Salvador, 1994) the proper names used (Bentham and Troelsen, deceased geologists who studied Thule strata) are unique, relevant and convenient to use.

Three names, Smith Sound, Nares Strait and Baffin Bay, refer to international waters. Fittingly and also because the names cover strata in both Canada and Greenland, the English spelling is used.

One stratigraphic name has been spelt inconsistently in the literature: the Narssârssuk Group of this paper is derived from the Narssarssuk formation of Kurtz and Wales (1951) who, like Davies (1957), did not use a circumflex accent. Davies *et al.* (1963) used the then authorised spelling of Narssârssuk, the form followed here.

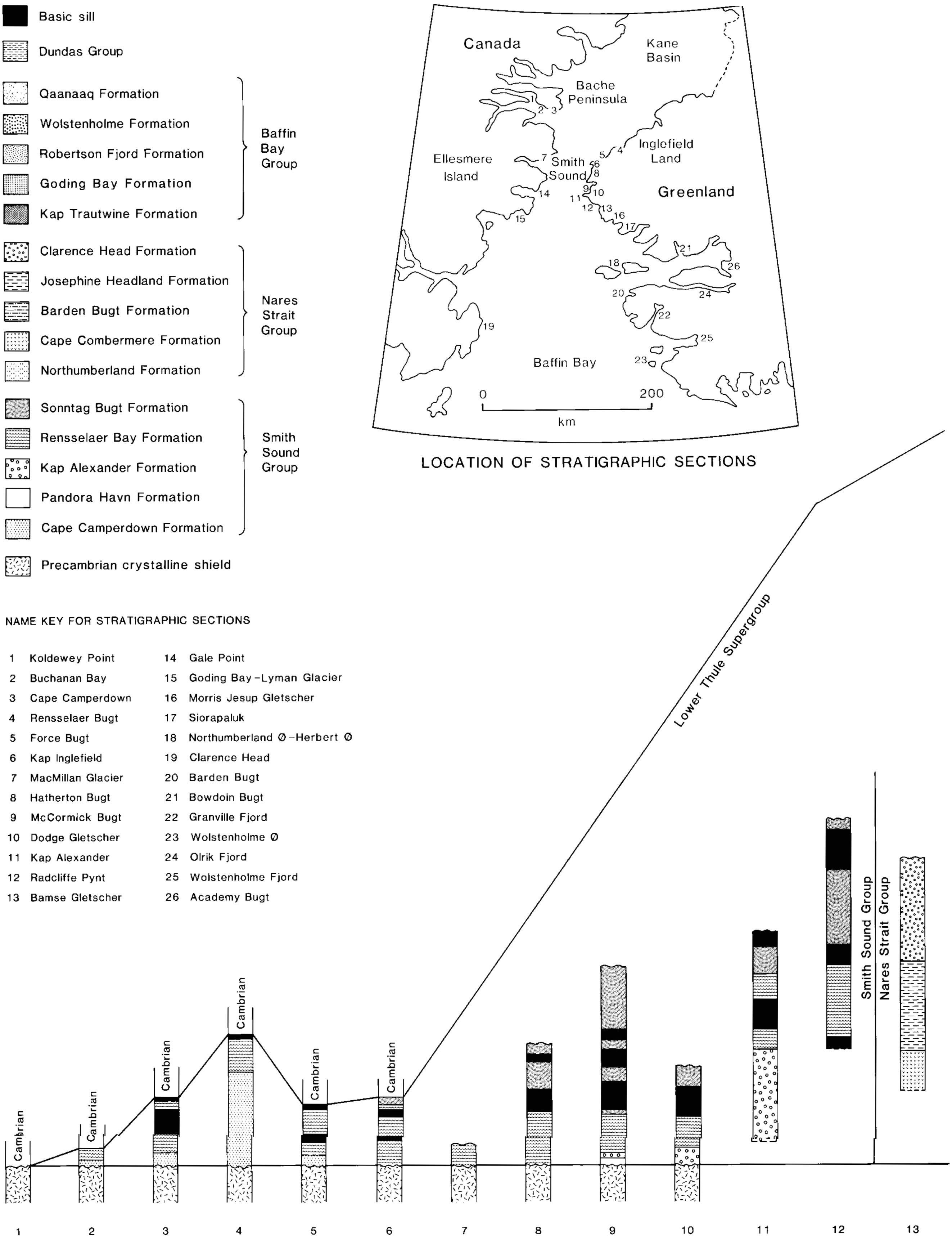


Fig. 12. Stratigraphic chart of the lower Thule Supergroup based on 26 areas. Distribution of the overlying Dundas Group is shown in Fig. 2.

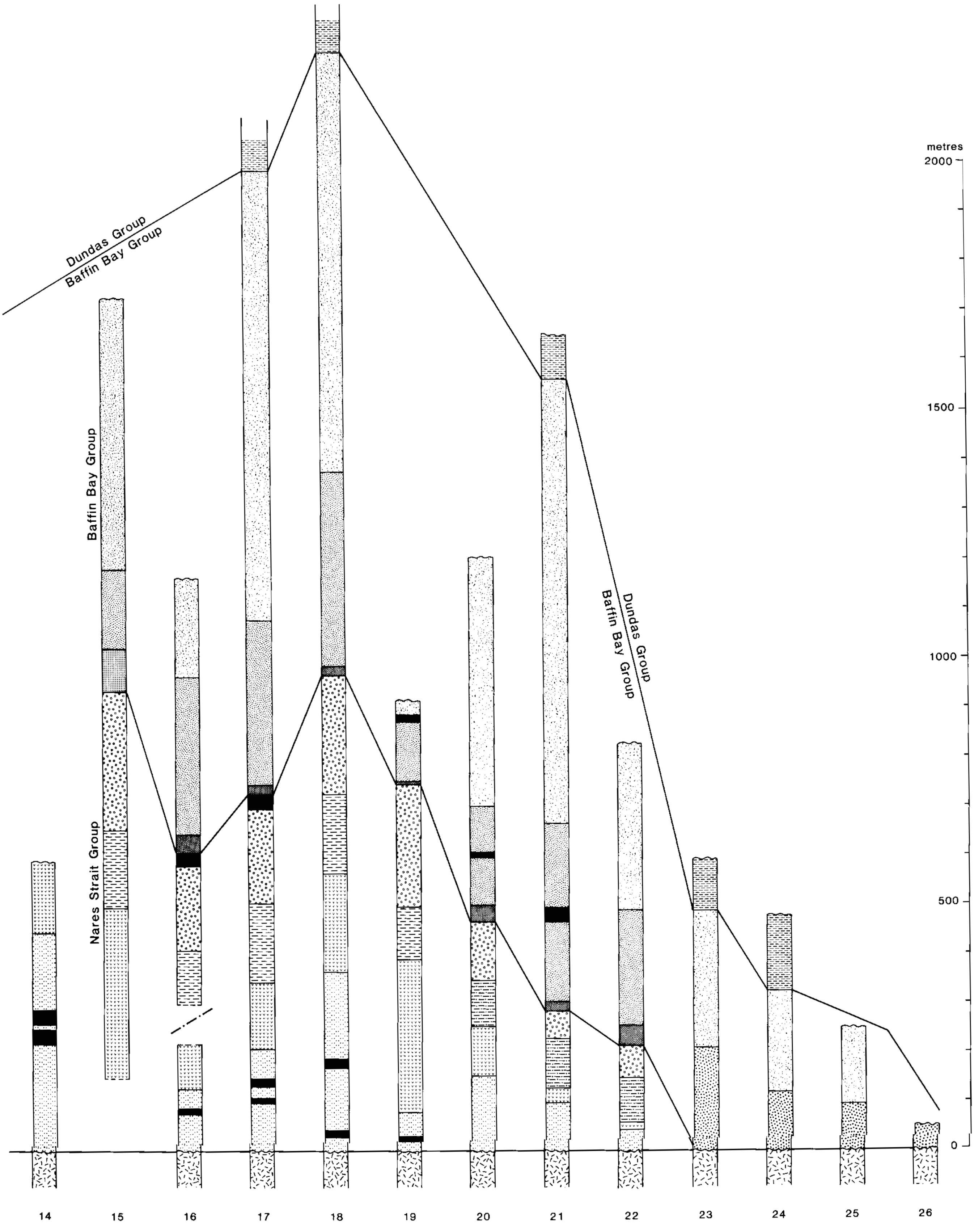

Dundas Group
Baffin Bay Group
Baffin Bay Group
Nares Strait Group
Dundas Group
Baffin Bay Group
metres
2000
1500
1000
500
0
14
15
16
17
18
19
20
21
22
23
24
25
26

Fig. 12 cont.

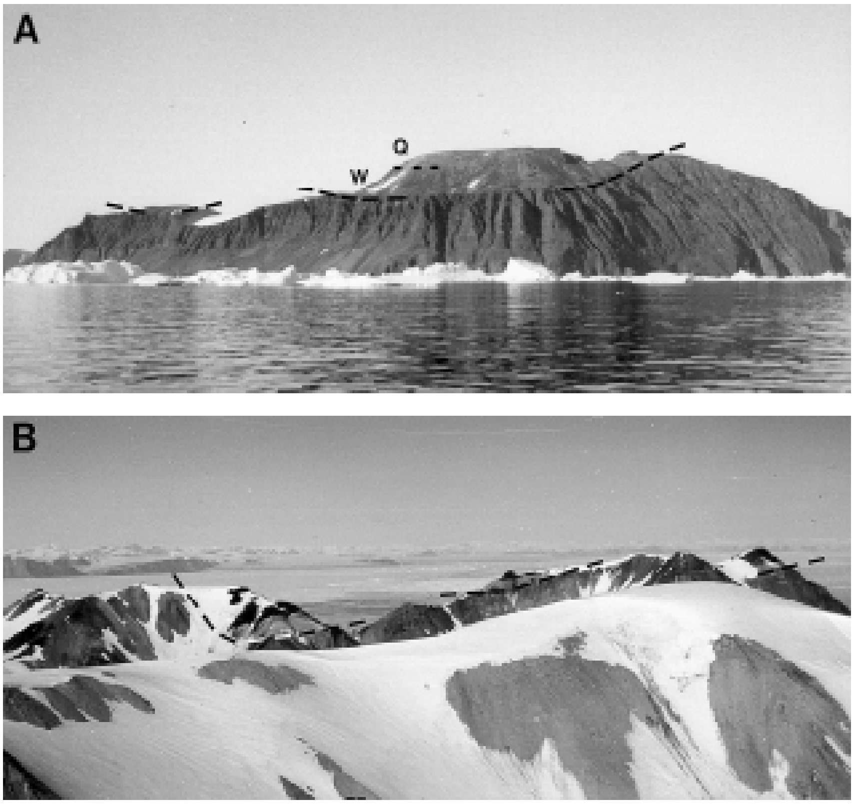


Fig. 13. Small outliers of Thule Supergroup on the Precambrian shield at the margins of the Thule Basin in Greenland (A) and Canada (B).
A: Baffin Bay Group (Wolstenholme and Qaanaaq Formations, W and Q) at De Dødes Fjord, Melville Bugt, with summit at around 600 m.
B: Nares Strait Group (pale sandstones of the Northumberland Formation overlain by dark volcanics of the Cape Combermere Formation) forming mountain summits south-west of Cape Combermere (see Fig. 57). The view is to the north with Greenland in the right background. Photo: T. Frisch.

Thule Supergroup

The Thule Supergroup is subdivided into 36 formal units: 5 groups, viz. the Smith Sound, Nares Strait, Baffin Bay, Dundas and Narssârssuk Groups, composing 15 formations and 16 members.

Thule Supergroup

new supergroup

Composition. The Thule Supergroup is derived from the Thule Formation of Koch (1929a) and Thule Group of Troelsen (1949, 1950a). As so described herein, it differs drastically from its forerunners with respect to geographic and chronostratigraphic limits. The supergroup is restricted to encompass middle to late Proterozoic strata of the Smith Sound – northern Baffin Bay region. It excludes strata in east central Ellesmere Island (Copes Bay – Dobbin Bay area) referred to the Thule Group by Thorsteinsson (1963, also *in* Blackadar, 1957) and in North and North-East Greenland, viz. Thule Formation of Koch (1929a, b, 1935a, b), Thule Group of Troelsen (1949, 1950b, 1956a, b) and the redefined Thule Group of Haller (1961, 1970, 1971, 1983) and Koch (1961).

The supergroup encompasses all strata in the Thule district referred by Koch (1929a, 1933) to the Thule Formation, as well as the basal part of that formation and the basal part of the lower formation of the Thule Group of Troelsen (1950a), in south-western Inglefield Land and Bache Peninsula. It includes strata described by Chamberlin (1895), Munck (1941), Kurtz & Wales (1951), Goldthwait (1954), Fernald & Horowitz (1964) and Dawes (1972, 1975, 1976b), the ‘little-disturbed formation (2)’ of Christie (1962a, b), the Camperdown Member and the Hatherton and Sverdrup Members of the Rensselaer Bay Formation as defined, respectively, by Christie (1967) and Cowie (1971), the ‘Thule basin rocks’ of Kerr (1967a), Christie (1972) and Frisch *et al.* (1978) and the Thule Group as used by Davies *et al.* (1963), Dawes (1971, 1976a, 1979a, b), Christie *et al.* (1981b), Dawes & Peel (1981), Dawes *et al.* (1982a, b), Frisch & Christie (1982) and Jackson (1986).

Name. After the site of the abandoned trading station, Thule, at North Star Bugt, North-West Greenland (Figs 2, 105).

Distribution. The supergroup borders the coasts of northern Baffin Bay, Smith Sound and southern Kane Basin between 76º and 79ºN (Figs 1, 2). The southernmost exposures are at 76º05′N at De Dødes Fjord, north of Kap York, where outcrops form mountain tops (Fig. 13); the northernmost exposures are at 79º07′N on Bache Peninsula (Fig. 7). Easternmost outcrops are at 66ºW, east of Academy Bugt at the head of Inglefield Bredning and in Olrik Fjord (see Fig. 103), and westernmost on nunataks at 78º28′W inland from Cape Combermere (Fig. 13).

Type area. The type area is between Bylot Sund and Inglefield Bredning (including islands), Greenland, where the Thule Supergroup has its most complete development (Fig. 2).

Thickness. Varies from feather-edge to at least 6 km, possibly as much as 8 km (Fig. 12).

Dominant lithology. The Thule Supergroup is a multicoloured, mainly shallow-water sedimentary succession with one main interval of basaltic volcanic rocks. Basic sills are common at several levels. In broad lithological terms the succession is bipartite, being composed of a lower siliciclastic part with basaltic rocks and subordinate carbonate, and an upper part of mixed siliciclastic-carbonate strata. Red beds form prominent units in both parts.

Lower strata are characterised by thick units of clean to ferruginous quartz arenites with conglomerates and some shale and carbonate intervals that give way upwards to an interbedded sequence of darker sandstone, siltstone and shale with subordinate dolomite. The upper part is composed of a well-layered carbonate-red bed siliciclastic sequence with algal laminites characterised by cyclicity, with evaporite and subordinate chert.

Depositional environment. The supergroup represents a variety of depositional environments from continental (subaerial to alluvial) to lacustrine and shallow marine (intertidal-subtidal) with intervals of cratonic magmatism. One of the magmatic episodes produced terrestrial tholeiitic effusives. The sediments, representing a very long time span (*c*. 600 Ma), are essentially undeformed but no major unconformities have been observed. Any fundamental breaks in shallow-water deposition must be represented by paraconformities.

The lower siliciclastic part of the succession mainly represents alluvial plain to shallow shelf sedimentation with alternating intervals of tide-dominated and alluvial-dominated deposition followed by deposition in overall deltaic to subtidal environments. The upper part, characterised by cyclic sedimentation involving algal laminated carbonates and evaporites, indicates a low-energy environment and hypersaline conditions analogous to modern lagoonal sabkha deposits.

The red coloration that is characteristic of many siliciclastic units could be taken to indicate a continental oxidising environment (Glennie, 1970). The relative lack of abundant organic matter in the Proterozoic may have increased the probability of oxidising rather than reducing conditions during the diagenesis of the Thule strata. However, much of the red colour is thought to represent diagenetic adjustment of iron contained in ‘normal’ clastic sedimentary material. Iron would be derived in abundance from the type of eroded granitoid crystalline terrain that surrounds the Thule Basin. Migration of iron compounds in the Thule detrital system has been generally high and is evidenced by the common appearance of liesegang rings and related phenomena.

Fossils. Stromatolites, algal laminites and microfossils (acritarchs and cyanobacterial organisms) have been described by Vidal & Dawes (1980), Strother *et al.* (1983), Dawes & Vidal (1985), Jackson (1986) and Grey (1995). Curvilinear to sinuous structures described as trace fossils by Dawes & Bromley (1975) and similar to the fucoidal markings of Fernald & Horowitz (1964), are reinterpreted as diastasis cracks.

Boundaries. The Thule Supergroup rests with profound unconformity on the eroded and peneplaned Precambrian shield (Figs 7, 9). Between 76º and 78º30′N the supergroup is overlain by Quaternary and Recent deposits; in Bache Peninsula and in Inglefield Land from Force Bugt eastwards, it is disconformably overlain by the Lower Cambrian of the Franklinian Basin (Figs 5, 7, 8, 14).

Geological age. Neohelikian–Hadrynian age between *c*. 1270 and *c*. 650 Ma. The crystalline shield underlying the Thule Supergroup contains Proterozoic (middle Aphebian) crust that has given U-Pb zircon and monazite ages between 1960 and 1912 Ma (Frisch & Hunt, 1988) and a Rb-Sr whole-rock age of 1850 Ma (Dawes *et al.*, 1988). The supergroup is also younger than a period of Paleohelikian basaltic dyking (including the Melville Bugt swarm of Nielsen (1987, 1990)) which in North-West Greenland has given K-Ar whole-

Fig. 14. Proterozoic–Palaeozoic unconformity in Inglefield Land; inland cliffs near Kap Inglefield. Smith Sound Group (RB = Rensselaer Bay Formation; SB = Sonntag Bugt Formation; D = dolerite sill) overlain by Cambrian strata (C). Section height above scree is about 150 m.

rock ages between 1667 and 1313 Ma (Dawes & Rex, 1986). Based on a ^{207}Pb/^{206}Pb baddeleyite age of a basaltic sill (LeCheminant & Heaman, 1991), the basal part of the supergroup is at least 1268 Ma (see Nares Strait Group). The supergroup is older than a swarm of Hadrynian basic dykes (K/Ar age range 630–725 Ma; Dawes *et al.*, 1973, 1982b; Dawes & Rex, 1986) that cuts the entire succession (Figs 5B, 64, 105, 106).

The microfossils so far identified from Thule strata are not particularly age-diagnostic and they have long stratigraphic ranges, i.e. Late Riphean – Vendian (Vidal & Dawes, 1980; Dawes & Vidal, 1985).

Following the time-scales of Harland *et al.* (1990) and the International Union of Geological Sciences (Plumb & James, 1986), the Thule Supergroup is of middle to late Proterozoic age (Proterozoic eras II and III or Meso-Neoproterozoic). In terms of Canadian chronostratigraphy (Douglas, 1980) it is of Neohelikian and Hadrynian age. Further details including quantitative data from isotopic age determinations are given under each group.

Subdivisions. The Thule Supergroup is divided into five groups: the Smith Sound, Nares Strait, Baffin Bay, Dundas and Narssârssuk Groups. The first three groups are referred to the lower Thule Supergroup, the latter two to the upper Thule Supergroup (Fig. 2). As listed above the groups are in younging stratigraphic order except that the Smith Sound Group is the basin margin and platform equivalent of the Nares Strait and Baffin Bay Groups (Fig. 4).

Smith Sound Group

The Smith Sound Group represents the northern basin margin and platform succession (Figs 2, 4, 120). It is subdivided into five formations, viz. the Cape Camperdown, Pandora Havn, Kap Alexander, Rensselaer Bay and Sonntag Bugt Formations; with the Rensselaer Bay Formation being split into two members – the Hatherton Bugt and Force Bugt Members.

Smith Sound Group

new group

Composition. Strata of this group are mainly part of the lower red sandstone unit of the Thule Formation of Koch (1929a, 1933; see also Dawes & Haller, 1979, plate 1). The group includes the lowermost strata of the Rensselaer Bay sandstone of Troelsen (1950a), which at Bache Peninsula equates with the Camperdown Member of Christie (1967). Troelsen (1950a, 1956b) restricted the Rensselaer Bay sandstone to Bache Peninsula and Inglefield Land; strata farther to the south between Kap Alexander and Sonntag Bugt referred to the Rensselaer Bay Formation by Dawes (1976a, 1979a) and Peel *et al.* (1982), are included in the group.

Name. After Smith Sound, the seaway separating southwestern Inglefield Land and central Ellesmere Island (Figs 1, 2).

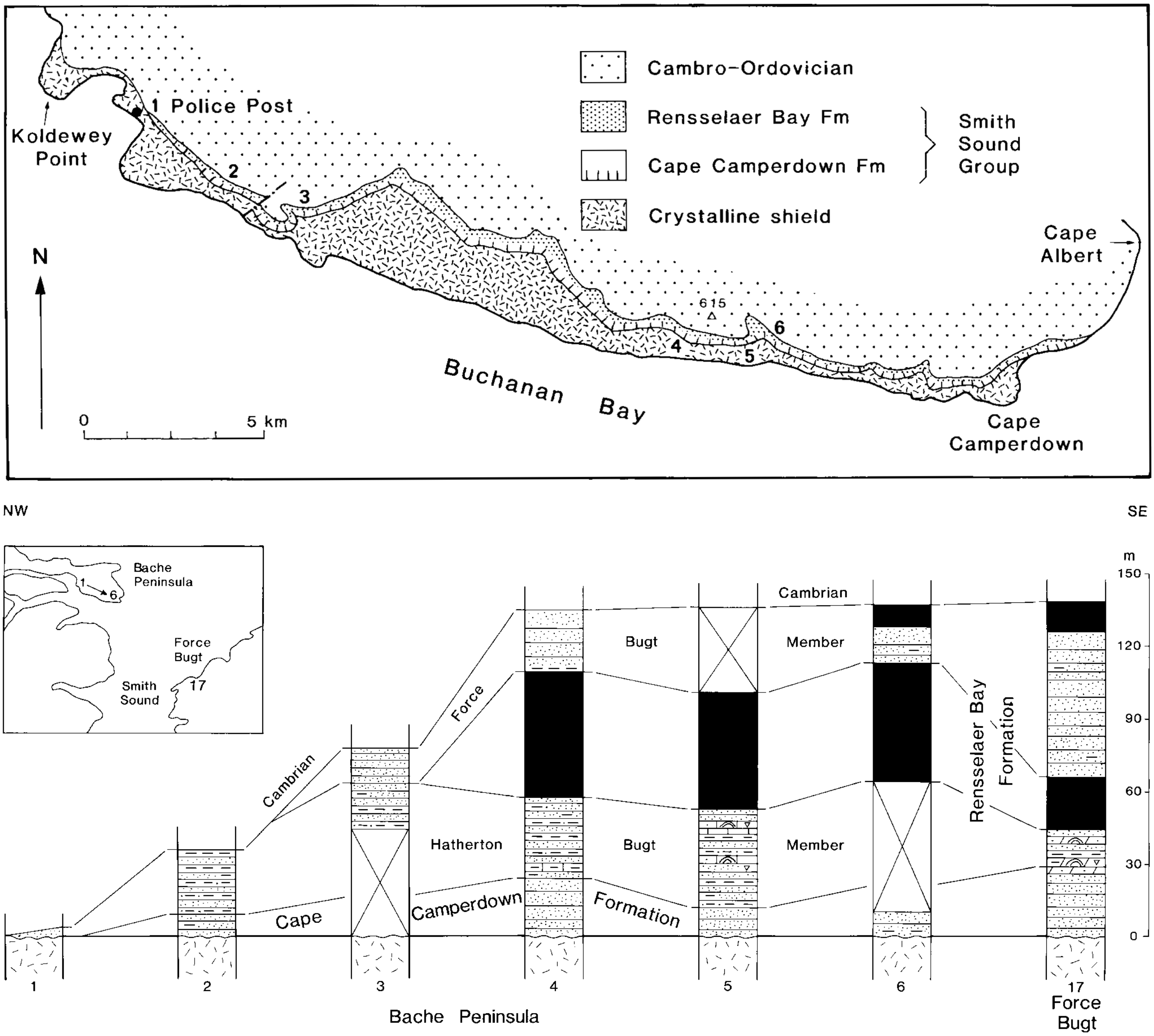


Fig. 15. Geological map and stratigraphic chart of southern Bache Peninsula, Canada. Sections 1 to 6 show westerly thinning and wedging out of the Smith Sound Group. Canadian geology is compiled from Christie (1967) and illustrated in Fig. 7; the Force Bugt section from Inglefield Land, Greenland, for comparison, is simplified from the log given in Fig. 42. Height of 615 is in metres. For regional location, see Fig. 2.

Distribution. Both sides of Smith Sound, viz. in Greenland, coastal, central and south-western Inglefield Land and northernmost Prudhoe Land; in Canada, on Bache Peninsula and a small outlier at MacMillan Glacier on the south side of Johan Peninsula (Fig. 2). Precise northern limit of the group in Inglefield Land is obscured by extensive scree.

Type area. The coast of south-western Inglefield Land between Rensselaer Bugt and Kap Alexander, Greenland (Fig. 2).

Thickness. Varies from a feather-edge in northern exposures in central Inglefield Land and western Bache Peninsula to a composite thickness of around 700 m (Figs 3, 12, 15).

Dominant lithology. A varicoloured sequence of sandstones and shales, including red beds, with subordinate carbonates, cut by basic sills (Fig. 3). Quartz arenites dominate with, in places, interbedded shales with distinct intervals of algal and stromatolitic dolomites that are variously arenaceous. Thick units of clean quartz arenites with pebbly sandstone and quartz-peb-

Fig. 16. Western side of Rensselaer Bugt showing locations of sections 7 and 8 through the Cape Camperdown (CC) and Rensselaer Bay (RB) Formations. Ps = Precambrian shield; C = Cambrian. Distance from foreground houses to base of section 8 is about l.5 km; sea-cliffs are about 300 m high. Dark shale-rich unit (arrowed) seen in detail view of section 8 is 15 m thick and about 120 m above the sea-ice. Sections are given below in Fig. 17.

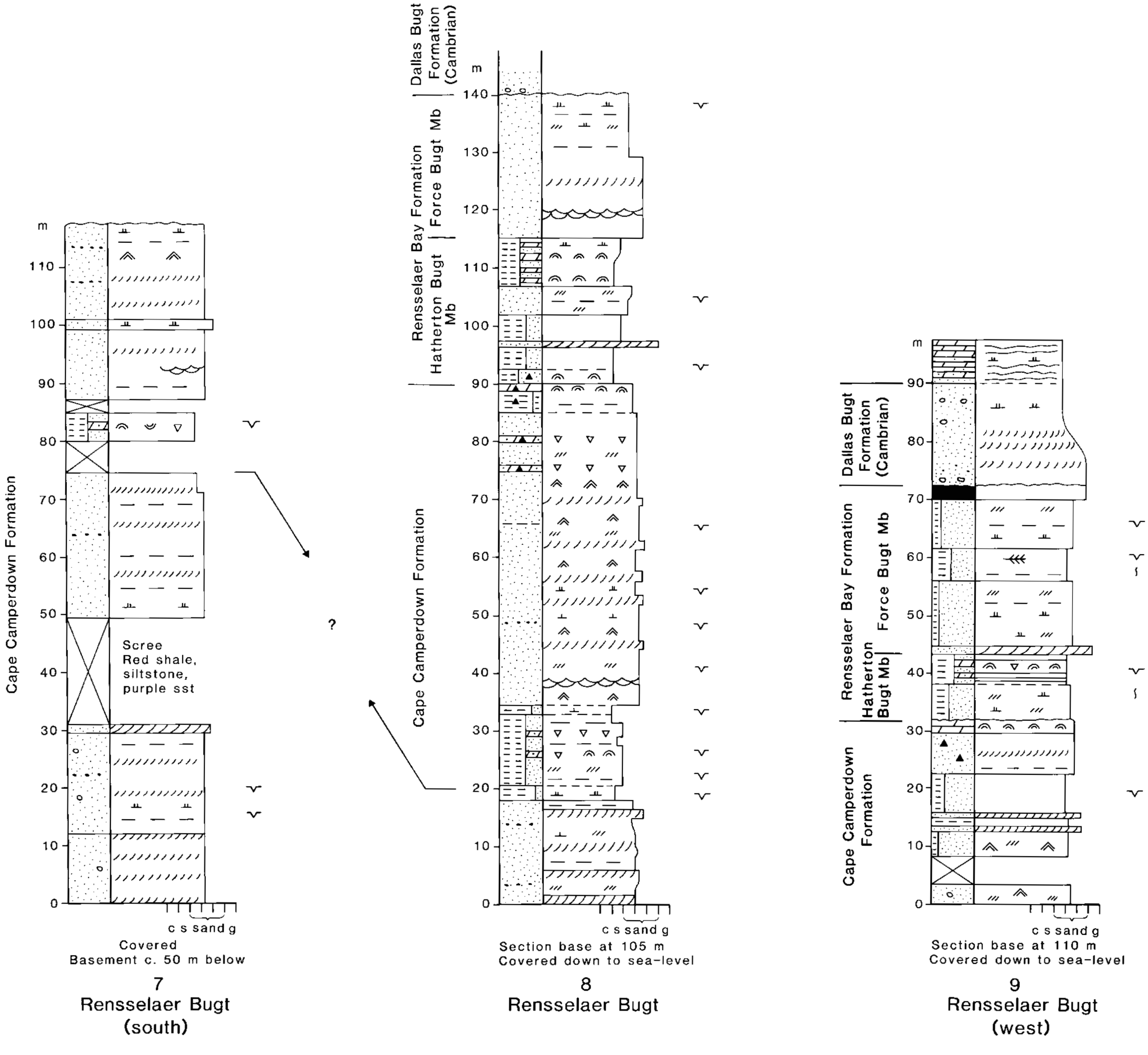
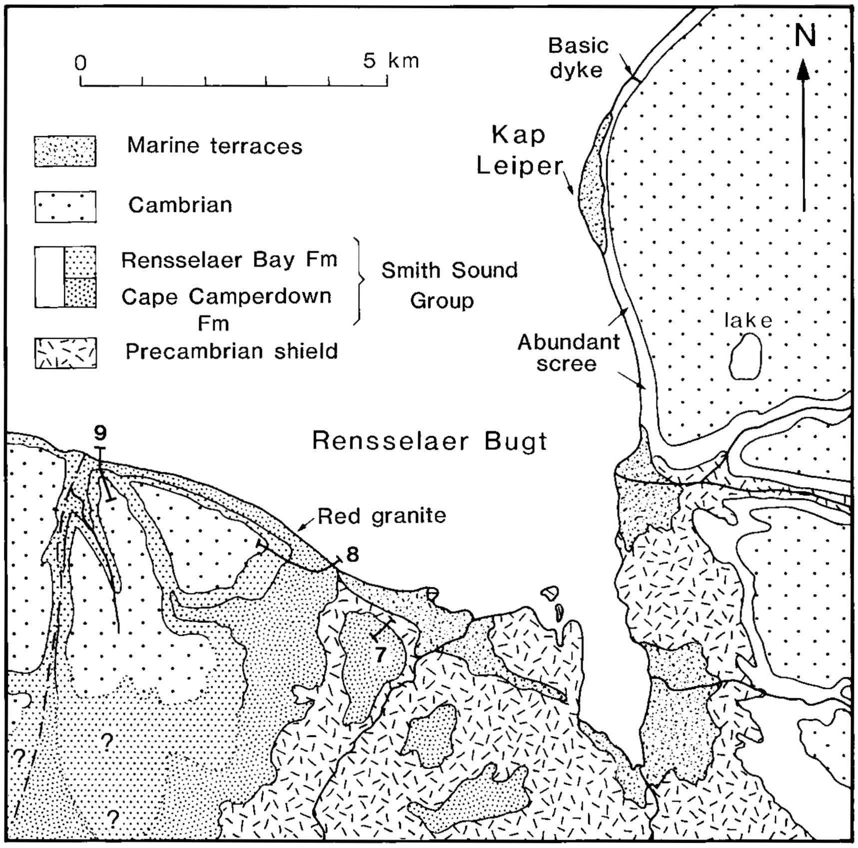


Fig. 17. Stratigraphic logs from Rensselaer Bugt showing the disconformity with the Cambrian. Section 8 is the type section for the Cape Camperdown and Rensselaer Bay Formations. Locations are shown on Figs 5A, 16 and 18.

Fig. 18. Geological map of the Rensselaer Bugt area, Inglefield Land, Greenland, showing locations of sections 7, 8 and 9. Map is drawn from an uncontrolled photomosaic. For location, see Fig. 2.



ble conglomerate characterise the lower and upper parts of the group in southern exposures.

Depositional environment. The Smith Sound Group was deposited in a stable, overall shallow shelf environment that ensured long-lasting conditions for shallow-water to subaerial deposition. Water-lain deposition probably ranged from marginally marine to supratidal and intermittently lacustrine. Southern exposures suggest progradation of the shoreline with uppermost strata indicating approaching fluvial deposition.

Fossils. Stromatolites, algal laminites.

Boundaries and correlation. The group directly overlies the crystalline shield (Figs 7, 9). In northern exposures it is disconformably overlain by Lower Cambrian clastics (Dallas Bugt Formation; Figs 7, 8), elsewhere by Quaternary deposits. Relationships to the Baffin Bay and Nares Strait Groups are not seen at present erosion level, but the Smith Sound Group almost certainly grades laterally into both these groups (Figs 3, 4, 120).

Geological age. Neohelikian. This age is based on the isotopic dating of dolerite sills that cut the upper strata of the group. The K-Ar whole-rock ages on basic sills from Inglefield Land are 1073 ± 40 and 1070 ± 40 Ma (Dawes *et al.*, 1973).

Subdivisions. The Smith Sound Group is divided into five formations: the Cape Camperdown, Pandora Havn, Kap Alexander, Rensselaer Bay and Sonntag Bugt Formations.

Cape Camperdown Formation

new formation

Composition. This formation includes basal strata of the Rensselaer Bay sandstone of Troelsen (1950a) as exposed at Rensselaer Bugt and environs and at Bache Peninsula. It should be noted that it does not incorporate southern exposures of either Troelsen's formation or the Rensselaer Bay Formation as used by Cowie (1961, 1971), Dawes (1976a, 1979a) and Peel *et al.* (1982). At Bache Peninsula it comprises sub-members A and B of the Camperdown Member of Christie (1967).

Name. After Cape Camperdown, south-eastern Bache Peninsula (Figs 2, 7, 15).

Fig. 19. Bedding characteristics of the Cape Camperdown Formation.
A: thin, cross-bedded sandstones with hammer arrowed as scale;
B: massive to laminated, sandstone with some channelling, overlain by thin- to medium-bedded sandstones (staff with 10 cm grid).
Coast, western Rensselaer Bugt.

Distribution. Coastal, central and south-western Inglefield Land between Force Bugt and Bancroft Bugt, and along the south coast of Bache Peninsula (Fig. 12). The formation may also occur east and south-east of Bancroft Bugt occupying hollows in the palaeosurface, as well as at the base of the scree-covered section in south-westernmost Inglefield Land.

Geomorphic expression and colour. Generally cliff-forming but at the base of sea-cliffs characteristically scree covered (Figs 5, 16). Purple to reddish unit with thinner darker purple, more recessive units.

Type and reference sections. The type section is on the west side of Rensselaer Bugt in the sea-cliffs (section 8, Figs 16, 17, 18); basal strata in contact with crystalline basement occur on a hill 1 km to the south (section 7, Figs 16, 17). Reference sections occur farther west in Rensselaer Bugt (section 9, Figs 5A, 17) and at Force Bugt (section 17, see Figs 41, 42) and along the south side of Bache Peninsula, for example sections 2, 4 and 5/6 (Fig. 15).

Thickness. The Cape Camperdown Formation shows marked thickness variations both locally and regionally (Fig. 12). At the type section it attains a thickness of about 190 m; on the eastern side of Rensselaer Bugt it varies from less than 50 m to around 150 m over a distance of a couple of kilometres, filling topographic lows in the eroded shield. To the south-west, coastal outcrops reveal a thinning so that at Force Bugt the formation is between 20 m and 30 m thick, probably petering out farther south. The formation also thins to the east and north-east, although exposures are generally scree covered and precise thicknesses obscured. In Canada on Bache Peninsula, it has a maximum thickness of 25 m, thinning and pinching out to the west near Koldewey Point (Fig. 15).

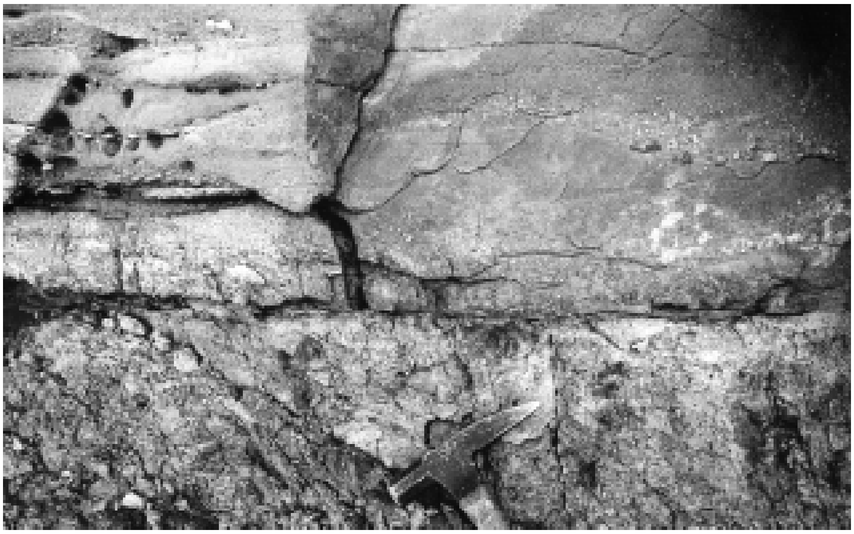


Fig. 20. Basal bed of the Cape Camperdown Formation (Smith Sound Group) on Precambrian shield at western Force Bugt. The granite substratum is severely weathered and rubbly; the conglomeratic sandstone contains quartz and pink feldspar granules, as well as granite clasts.

Lithology. Varicoloured thin- to thick-bedded sandstones with lesser amounts of siltstones and shales (Fig. 19). Some discrete shale-dominated units occur. Thin, green, jasper-rich arenaceous dolomite beds that are often brecciated characterise the upper part of the formation along with stromatolitic dolomite beds. The uppermost beds, where examined at Rensselaer Bugt and Force Bugt, are arenaceous dolomite with stromatolites, either in growth position or reworked to form a jasper-rich dolomite breccia.

The sandstones vary in colour from pink to purple, green, brown and buff; they are predominantly orthoquartzites but in many samples feldspar occurs, and in places at the base of the formation the rocks are subarkosic. Some pale green sandstones contain a sparse to abundant carbonate matrix. A green glauconite-bearing, fine conglomerate with well-rounded quartz and feldspar grains, rock fragments and a carbonate matrix occurs in contact with the crystalline basement at Force Bugt (Fig. 20). Glauconite occurs in basal beds at Bache Peninsula (Christie, 1967). The sandstones vary from fine to coarse grained and are generally fairly well sorted; some are characterised by very well-rounded quartz grains. Thin grit and quartz pebble layers occur and some are associated with the upper surfaces of sandstone beds. Many sandstones are characterised by green and red laminations (Fig. 19B); cross-bedding is common throughout. Cross-beds are low-angle mainly tabular type in sets up to 3 m; trough bedding also occurs in units up to 1 m thick. Some are catenary beds with truncated tops suggesting that many are the preserved bases of once thicker sets. Some channelling occurs locally and current ripples and symmetrical wave ripples are frequent.

The shale-rich units form dark purple recessive intervals that show considerable thickness and facies variation along strike. They are composed of interbedded red and green shales, siltstones and fine sandstones with pale arenaceous dolomite beds (Fig. 21). Some of the sandstones are calcareous and contain rip-up clasts of fine dolomite. Mudcracks are common.

Depositional environment. The formation represents shallow water to subaerial deposition of sand sheets with some intervals of low detrital input when stromatolites survived. Glauconite in basal beds is taken to mark an initial marine transgression. The truncated tops of large-scale cross beds suggest wind erosion and some of the sands are deemed aeolian. An ephemeral lake with periodic inundations by floods is a possible overall environment for the bulk of the formation (J. D. Collinson, personal communication, 1980).

Fossils. Stromatolites.

Boundaries and correlation. The formation overlies the crystalline shield and is followed disconformably by the Rensselaer Bay Formation. In central Inglefield Land and western Bache Peninsula, relationships to the Rensselaer Bay Formation are obscured, and the formation may be overstepped by the Cambrian Dallas Bugt Formation. At Rensselaer Bugt and Force Bugt the upper boundary is taken at the top of a sandstone unit topped by a stromatolitic dolomite bed (Fig. 22). Relationships to the Rensselaer Bay Formation south of Force Bugt are obscured by scree and the formation has not been identified over the structurally high basement around Hatherton Bugt.

Fig. 21. Thin, green arenaceous dolomite beds with irregular algal-laminated tops within purple shale and fine-grained sandstones. Reduction spots are prominent. Cape Camperdown Formation, western Rensselaer Bugt, section 8.

Correlation of the Cape Camperdown Formation with strata south of Force Bugt can only be surmised. The Pandora Havn and Kap Alexander Formations, which are also overlain by the Rensselaer Bay Formation, as well as one or more formations of the Nares Strait Group, may well contain coeval strata (Figs 12, 120). The Cape Camperdown Formation may contain strata as old as the basal rocks of the basinal section, viz. Northumberland Formation (Figs 11, 120).

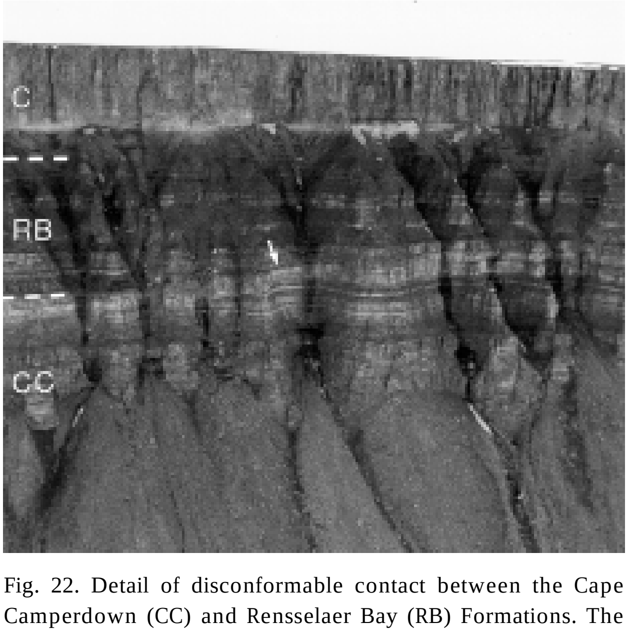


Fig. 22. Detail of disconformable contact between the Cape Camperdown (CC) and Rensselaer Bay (RB) Formations. The uppermost strata of CC is a transgressive sandstone topped by a stromatolite surface (arrowed). Lower beds of RB overlap onto the topographic high. C = Cambrian. Section height above scree is about 150 m. Sea-cliffs west side of Rensselaer Bugt.

Subdivisions. On Bache Peninsula, the strata that are now included in the Cape Camperdown Formation were subdivided by Christie (1967) into two units (submembers A and B) – a bipartite subdivision not recognised in Greenland. These units are not defined formally here.

Pandora Havn Formation

new formation

Composition. This formation comprises strata previously included in the Hatherton Member of the Rensselaer Bay Formation of Dawes (1976a) as exposed at McCormick Bugt.

Name. From Pandora Havn, the inner part of McCormick Bugt (Fig. 23).

Distribution. As yet only identified from the south side of McCormick Bugt. Profuse scree covering the lower part of the section in south-western Inglefield Land obscures recognition of a possible wider distribution.

Geomorphic expression and colour. A red to purple-weathering unit tending to recessivity and scree cover.

Type section. At sea level on the northern side of Crystal Palace Cliffs, McCormick Bugt (section 10, Figs 23, 24).

Thickness. At minimum 7.4 m. At the type section the base of the sequence is not exposed but position rela-

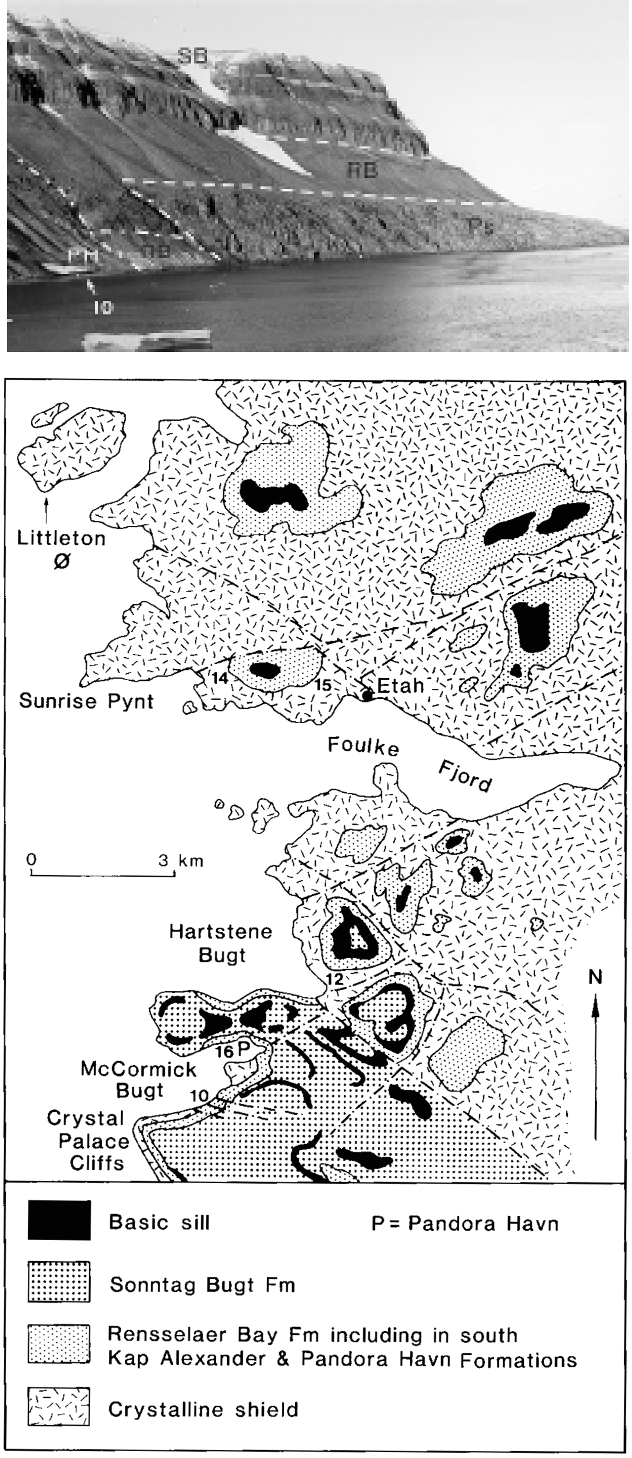


Fig. 23. Geology of the McCormick Bugt – Etah area, Greenland. Map showing the locations of sections 10, 12, 14, 15 and 16 is drawn from an uncontrolled photomosaic. The distinction between the Rensselaer Bay and Sonntag Bugt Formations, east of McCormick Bugt, is schematic. The view is south to Crystal Palace Cliffs showing basic sills within Sonntag Bugt Formation (SB) and the location of the Pandora Havn Formation (PH) in down-faulted section. Basal strata above Precambrian shield (Ps) hidden by scree. RB = Rensselaer Bay Formation. Summit of cliffs is at about 400 m. For location, see Fig. 2.

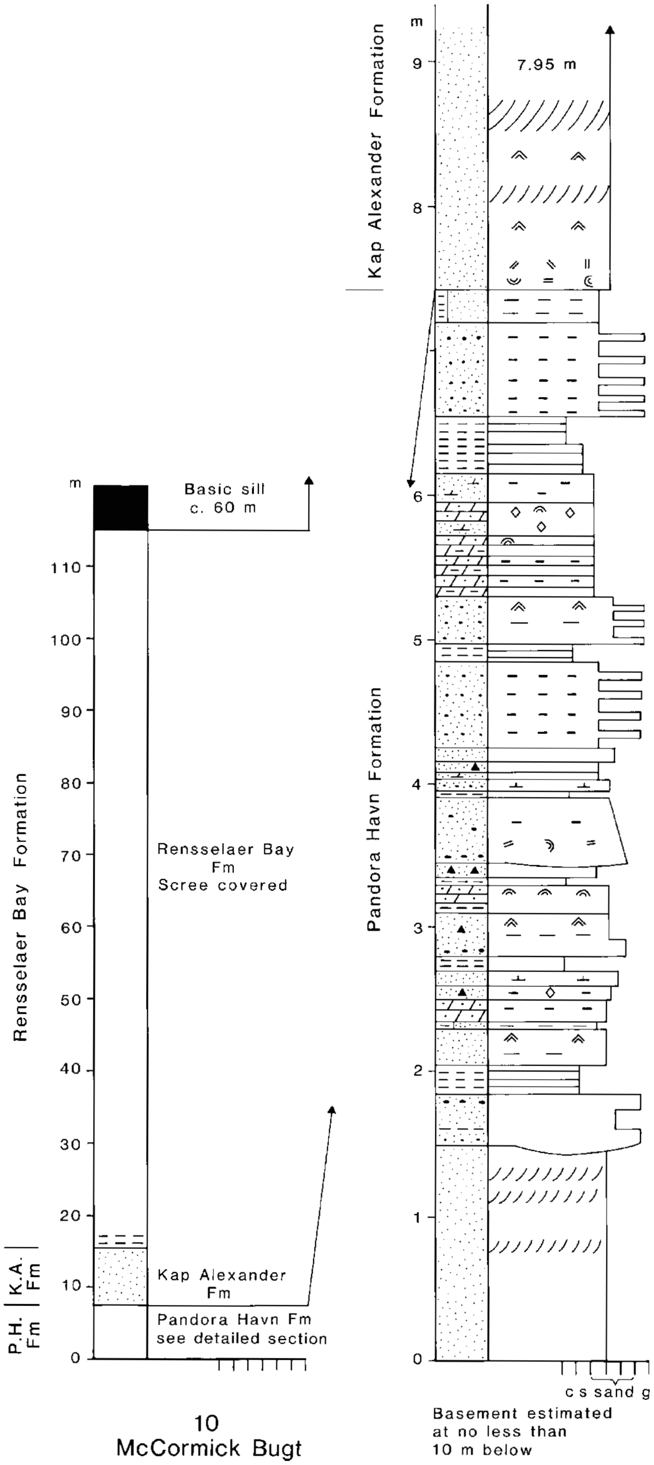


Fig. 24. Generalised section through the Pandora Havn, Kap Alexander and Rensselaer Bay Formations on the south side of McCormick Bugt, and stratigraphic log for the type section of the Pandora Havn Formation. For location, see Fig. 23.

Fig. 25. Bedding characteristics of the Pandora Havn Formation. Varicoloured, irregularly bedded sandstones and shales, with pale dolomitic beds, with slump beds (arrows) and ripple marks. McCormick Bugt, section 10.

tive to nearby crystalline basement outcrops suggests a maximum thickness of 20 m.

Lithology. A red bed unit composed of interbedded sandstones and shales with some dolomitic beds (Fig. 25). The sandstones have generally purple and mauve colours, both on weathered and fresh surfaces but some red, grey and greenish rocks occur. Streaky mottling is common. The sandstones are thin bedded, variously laminated, and many show prominent shale partings. Most beds are medium grained but finer sands, coarse-grained and granule beds also occur. Some of the latter contain polymict clasts, the largest of which are up to 3 cm long, composed of green silicified shale. Quartz sandstone, purple shale and pale dolomite clasts are smaller. Bedding is characteristically irregular with beds varying laterally and with channels common. Channel fill varies from poorly sorted, collapse material containing quartz sandstone pebbles to graded siltstone and sandstone. Many sandstones are cross-bedded with prominent ripple-marked surfaces, predominantly symmetrical wave ripples (Fig. 25).

Shales are usually well laminated and red and green. Green shales can show purple mottling in streaks. Shale ranges from lamellae and partings that are particularly common in some sandstones, to beds 40 cm thick. Beds often have irregular thicknesses due to encroachment by the flanking sandstones.

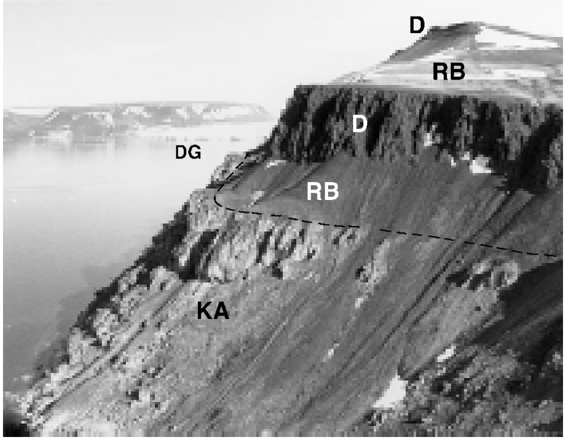
The third component of the lithology, dolomite, occurs in thin beds that often show irregular, even lenticular form. Typical rock is pink to pale green, fine-grained, showing some degree of lamination. Dolomites are variously arenaceous and argillaceous, and some contain white and green clasts of shale and dolomite. Small stromatolite domes occur in growth position at the upper surface of some beds but more commonly stromatolitic material occurs as rotated fragments and clasts. Some beds have a brecciated rubbly character. Ripple marks, mainly symmetrical, and mud-cracks occur on upper surfaces of some dolomite beds.

Depositional environment. From the restricted exposure, the environment is suggested to be supratidal possibly lacustrine but with active channelling suggesting some influence by streams. Some reworking of detrital material is evident, as well as intermittent detrital-poor intervals in which carbonate was precipitated and stromatolites grew.

Fossils. Stromatolites.

Boundaries and correlation. The formation is conformably overlain by the Kap Alexander Formation; its base is not seen but it is assumed to rest on the crystalline shield (Figs 12, 24).

The Pandora Havn Formation may be a correlative to part of the Cape Camperdown Formation to the north. It is thought to represent the northern feather-edge of a red bed sequence that in the basin in the south is defined as the Josephine Headland Formation of the Nares Strait Group (see Fig. 120). The nearest outcrops of that group are 35 km distant at Bamse Gletscher (see Fig. 64).



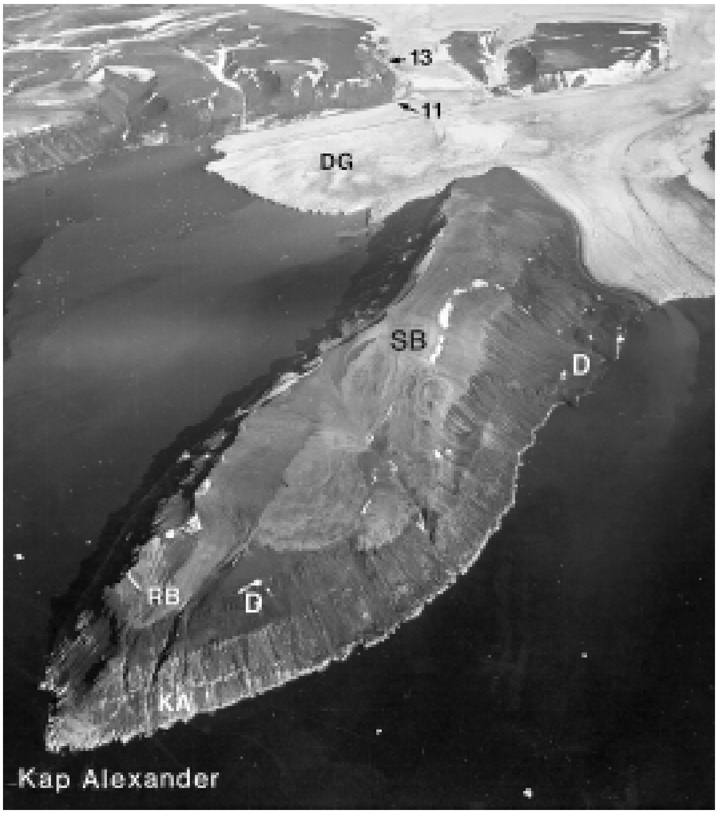


Fig. 26. Two views over Kap Alexander showing massive sandstones of the Kap Alexander Formation (KA, about 200 m thick) overlain by recessive Rensselaer Bay Formation (RB) with the Sonntag Bugt Formation (SB) forming pale strata at the summit around 500 m. The Kap Alexander Formation thins markedly across the basin margin overlapping onto crystalline basement at Dodge Gletscher (DG) and tapering out towards the north. D = Neohelikian dolerite sills. Sections 11 and 13, given in Figs 29 and 35, are located; for map location, see Fig. 27. Right photo: 543 B-NØ/2712, July 1950; Kort- og Matrikelstyrelsen, Denmark.

Kap Alexander Formation

new formation

Composition. This formation corresponds to the lower sandstone unit of Dawes (1976a) as exposed at Kap Alexander, sandstone formation A of Dawes (1979a) and the lower of three members of the Rensselaer Bay Formation of Peel *et al.* (1982) outcropping in the Kap Alexander – Storm Gletscher area. In south-western Inglefield Land up to 37 m of basal strata included by Dawes (1976a) in the Hatherton Member of the Rensselaer Bay Formation, are now referred to the Kap Alexander Formation.

Name. After Kap Alexander, a cape in Smith Sound and the westernmost point of Greenland (Figs 2, 26, 27).

Distribution. South-western Inglefield Land and northernmost Prudhoe Land between Hartstene Bugt and Sonntag Bugt (Fig. 12). Heavy scree cover farther north obscures its potentially wider extent below the recessive Rensselaer Bay Formation.

Geomorphic expression and overall colour. White to pale grey, resistant quartzitic unit forming in northern Prudhoe Land steep sections at the base of the sea cliffs (Fig. 26). Thin sections farther north have heavy scree cover.

Type and reference section. Well-exposed, accessible but relatively thin sections occur along the northern side of Dodge Gletscher. The type section is at the western end of this exposure (section 11, Figs 28, 29); reference sections exposing the contact with the overlying Rensselaer Bay Formation occur to the east (see Figs 34, 36). A poorly exposed reference section showing contact to the crystalline shield is exposed on the north side of Hartstene Bugt (section 12, Fig. 29). Thicker reference sections but with bases not exposed occur along the coast south of Kap Alexander.

Thickness. Thickest on the Kap Alexander peninsula where the formation is estimated at about 200 m (Fig. 12). The formation thins rapidly to the north over the basin margin so that to the north of Dodge Gletscher only 5 km distant it is 37 m thick, thinning to between 0 and 10 m in the McCormick Bugt – Hartstene Bugt area (Figs 26, 27).

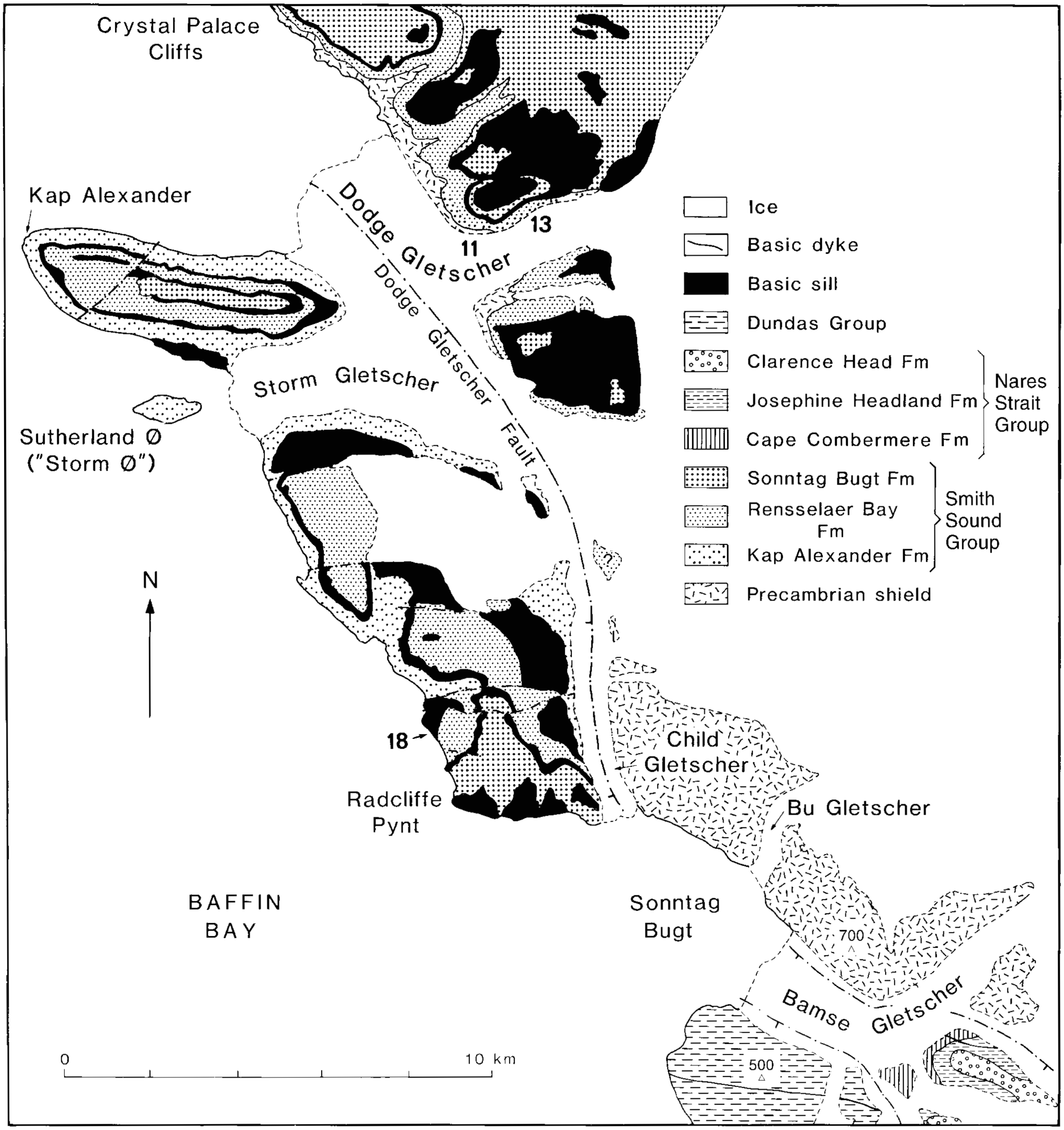


Fig. 27. Geological map of the Dodge Gletcher – Sonntag Bugt area, Greenland, showing the locations of sections 11, 13 and 18. The map covers the faulted northern margin of the Thule Basin, and shows the northernmost exposures in Greenland of the Nares Strait and Dundas Groups in coastal-parallel fault blocks (see also Figs 1, 5B). The Kap Alexander Formation of the Smith Sound Group (the assumed equivalent of the Clarence Head Formation of the Nares Strait Group) shows abrupt thickness variation. On the Kap Alexander peninsula (Fig. 26), the formation is at least 200 m thick; on the landward side of the Dodge Gletscher Fault the formation overlaps onto the Precambrian shield (Fig. 28), finally petering out farther north so that the Rensselaer Bay Formation overlies the shield (see Figs 9, 23, 38). The map is drawn from an uncontrolled photomosaic; an oblique photograph showing the same area is given in Fig. 1. Heights are approximate and in metres. For location, see Fig. 2.

Fig. 28. The type section of the Kap Alexander Formation (KA), on the north side of Dodge Gletscher, with dark shale beds conspicuous. The contact with the Precambrian shield (Ps) is poorly exposed. RB = Rensselaer Bay Formation with profuse scree, D = basic sill, SB = Sonntag Bugt Formation. Section 11, about 40 m thick, is given below in Fig. 29; for map location, see Fig. 27.

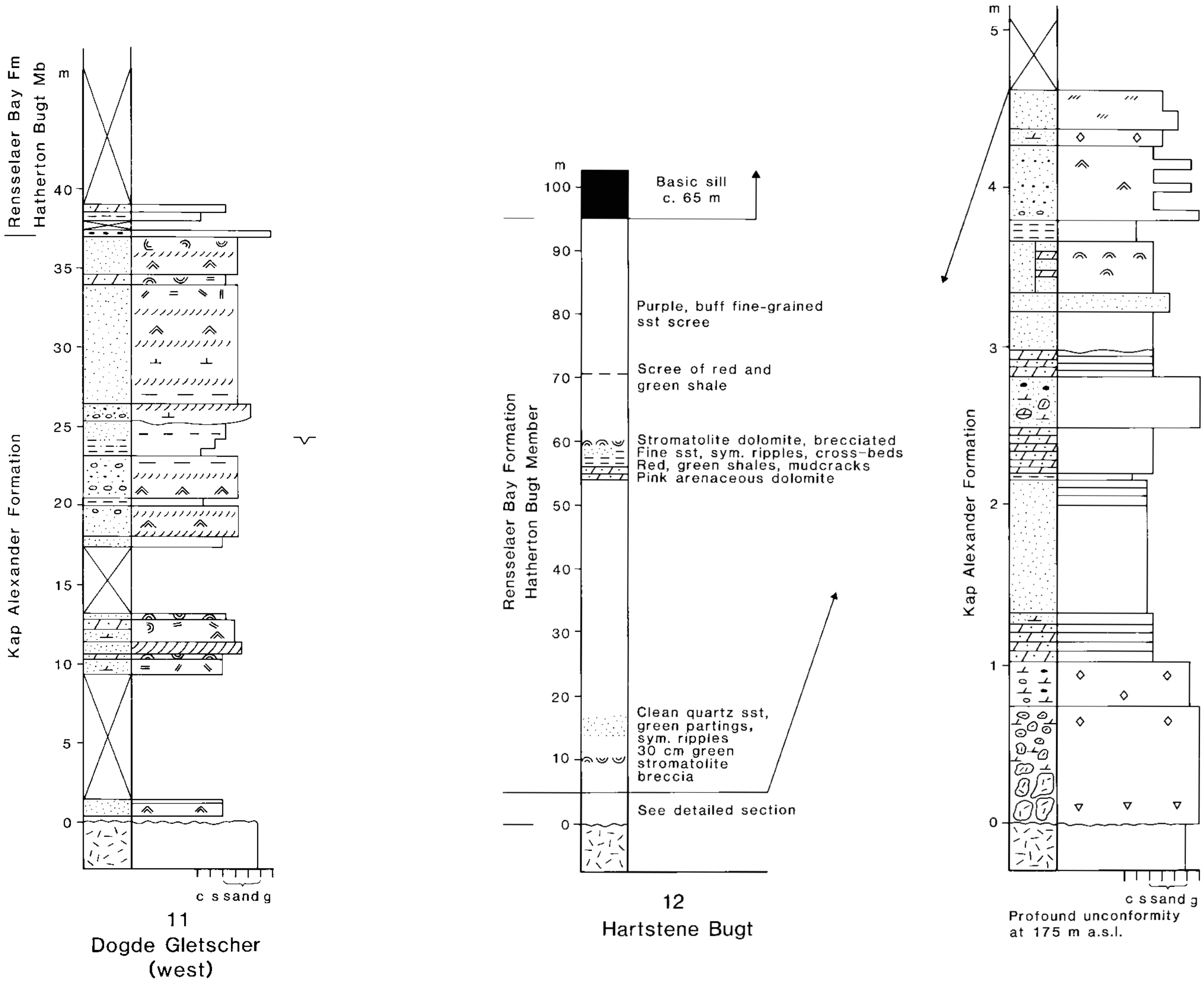


Fig. 29. Stratigraphic logs of the Kap Alexander Formation and generalised section of the Rensselaer Bay Formation. Section 11 is the type section at Dodge Gletscher located in Figs 27 and 28; section 12 is located in Fig. 23.

Fig. 30. Bedding characteristics of the Kap Alexander Formation. Massive, lenticular sandstone interleaved with finer grained beds that display low-angle cross-bedding. Hammer arrowed as scale. Coast, south of Storm Gletscher (Fig. 27).

Lithology. The formation is dominated by clean, white to grey and pale pink, medium-grained quartz sandstones that are generally medium to thick bedded and characterised by lenticular and cross-bedding (Fig. 30). The sandstones are well sorted with subrounded to well-rounded quartz grains with occasional feldspar; some have a 'sugary' quartzitic texture. Some beds show conspicuous quartz granules and there is a gradation to pebbly sandstone and conglomerate characterised by well-rounded quartz pebbles. Several coarse sandstone beds show channelled bases. A common association is medium to coarse sandstones that show thickness variation interbedded with finer grained, more fissile sandstone (Fig. 30). Tabular cross-bedding in sets generally less than a metre is common, and some beds show herringbone cross stratification. Wave and asymmetrical ripples occur.

Argillaceous material is restricted to thin lamellae and partings, and to very occasional thin, green to purple shale beds often interbedded with purple, fine-grained sandstones as at the type section (Figs 28, 29). These beds, together with areas of dark brown ferruginous sandstone, provide the only colour variation to the formation. The ferruginous material occurs in small spots and patches to lamellae that cause a distinct bedding-parallel banding, liesegang rings and irregular and

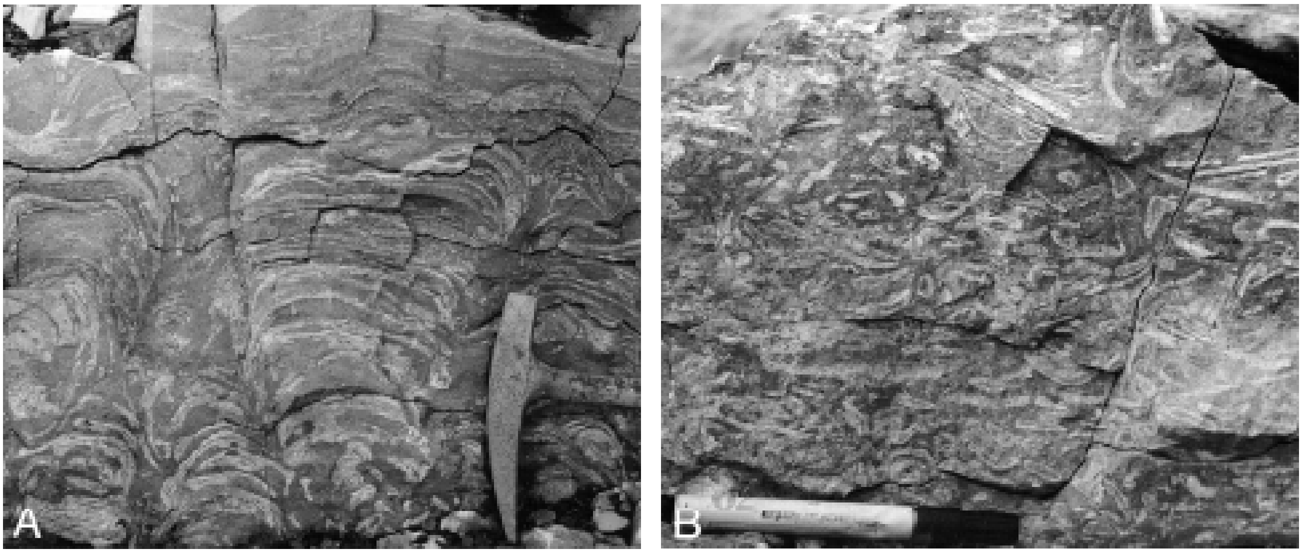


Fig. 31. Stromatolitic arenaceous dolomites of the Kap Alexander Formation. **A:** columnar stromatolites; **B:** breccia of stromatolite clasts; from respectively Dodge Gletscher sections L and M (Fig. 39). Hammer head is 17 cm, pen is 12 cm long.

discordant dark brown veins and ferruginous dykes up to two centimetres thick.

In the thin northern exposures some sandstones are calcareous and thin beds of pale green arenaceous dolomite occur. White stromatolites occur either in growth position or as resorted clasts and in flat-pebble conglomerates (Fig. 31). Several stromatolite conglomerate beds characterise the upper part of the formation at Dodge Gletscher (see Fig. 39).

At one section where the contact with the crystalline shield is exposed (section 12, Fig. 29), conglomeratic material including granitic fragments occur up to 3 m above the unconformity. The basal bed is a red stained breccio-conglomerate about 75 cm thick, clast-supported at the base, matrix-supported above, that is composed of green-weathered (?glauconite) granite boulders, cobbles and pebbles in a pale dolomitic matrix. The red granite below is heavily fractured and weathered, and is penetrated by veins of pink arenaceous dolomite.

Depositional environment. The clean, thick-bedded sandstones with prevalent cross-bedding, some of which is of herringbone type, are taken to indicate overall deposition on a shallow intertidal shelf. The thinner, northern strata containing stromatolitic dolomites showing frequent reworking suggest shallower water conditions, probably of the high tidal or supratidal zone.

Fossils. Stromatolites.

Boundaries and correlation. The lower boundary of the formation is only exposed in Inglefield Land, i.e. north of Kap Alexander where it is in contact with the crystalline shield. At McCormick Bugt the formation conformably overlies the Pandora Havn Formation, while to the east and north it overlaps onto the crystalline basement. The upper boundary, described later under the Rensselaer Bay Formation, is a disconformable contact with the Hatherton Bugt Member (see Figs 34, 39).

The formation may contain strata coeval with those of the Cape Camperdown Formation; to the south it is a supposed correlative of the Clarence Head Formation of the Nares Strait Group (Figs 11, 120).

Rensselaer Bay Formation

redefined

Composition. This redefinition entails a considerable reduction of stratigraphic range. The formation is now restricted to the middle part of the Rensselaer Bay sandstone of Troelsen (1950a) as exposed at Rensselaer Bugt and environs and at Bache Peninsula. It is represented by sub-members C and D of the Camperdown Member of Christie (1967) at Bache Peninsula, the Hatherton Member of Cowie (1961, 1971) in Inglefield Land south of Force Bugt but excluding basal strata between Hartstene Bugt and Dodge Gletscher (herein referred to the Pandora Havn and Kap Alexander Formations), and in northern Prudhoe Land, sandstone

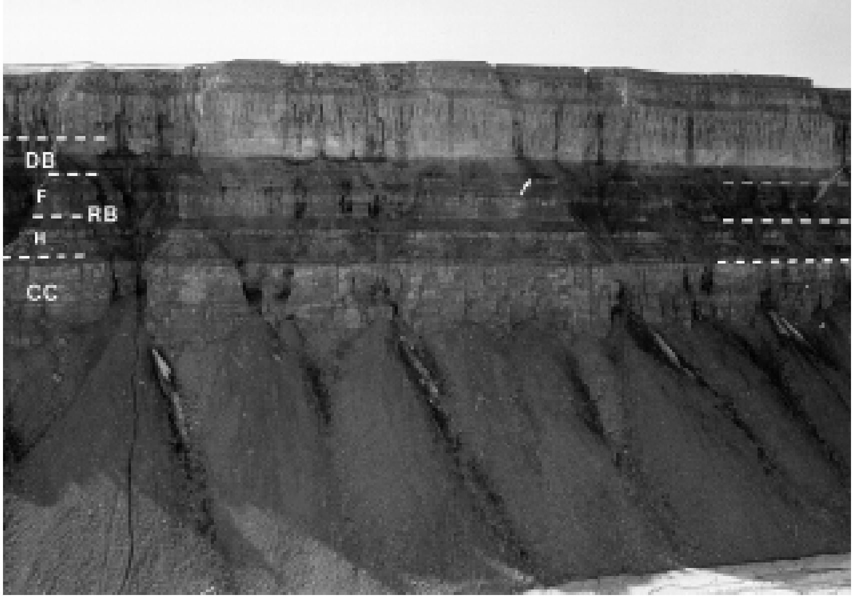


Fig. 32. Rensselaer Bay Formation (RB) in the sea-cliffs on the western side of Rensselaer Bugt showing the disconformity with the Palaeozoic. The dark layer marked by the arrow contains an erosional relict of basic sill under the red beds of the Cambrian Dallas Bugt Formation (DB). A section about 3 km to west (section 9, Fig. 17) has eroded basic sill at the unconformity; to the east (section 8, Figs 17, 33) it is absent. H = Hatherton Bugt Member, F = Force Bugt Member, CC = Cape Camperdown Formation. Cliffs about 300 m high with the sea-ice at bottom right.

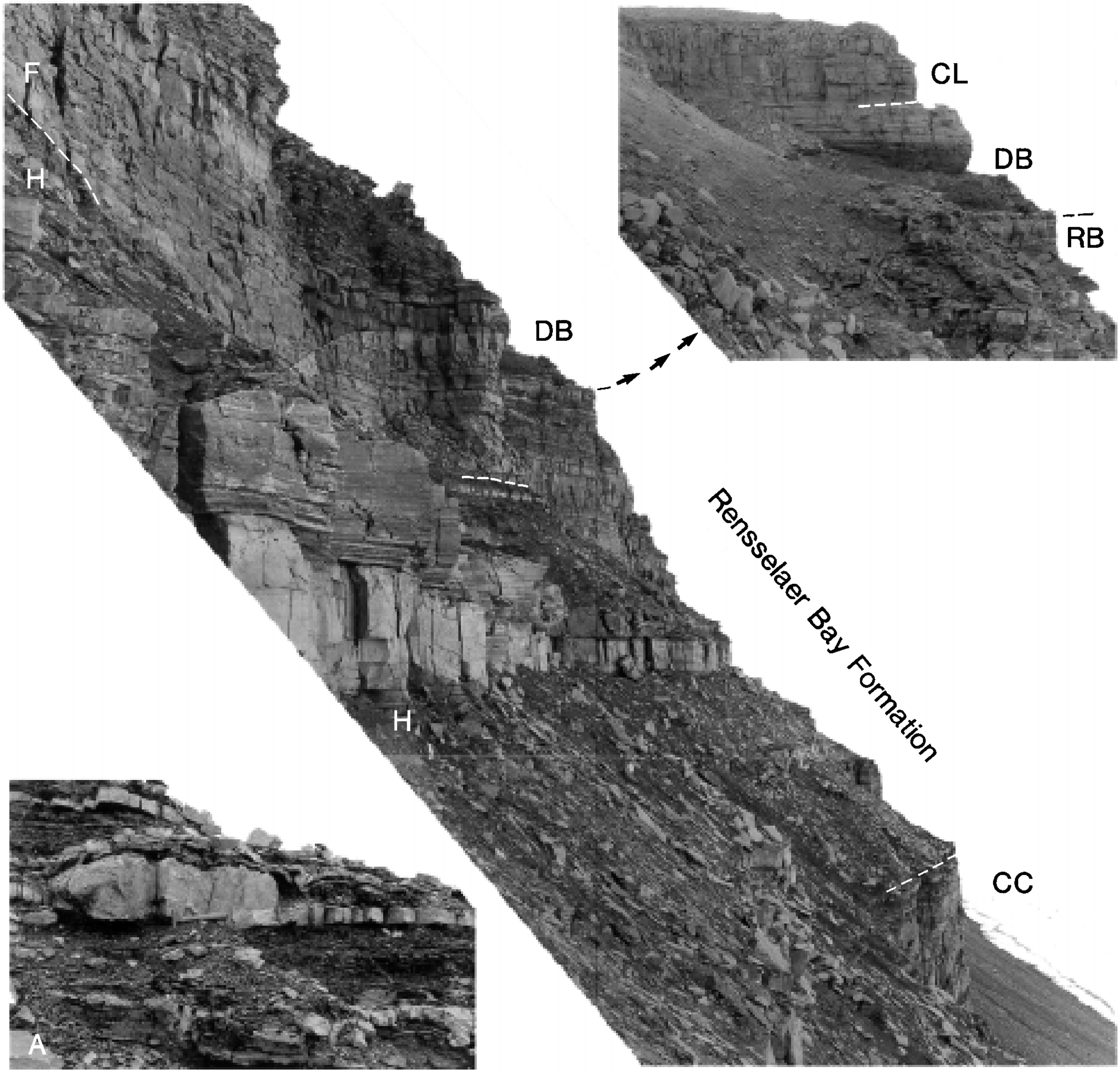


Fig. 33. Lithological characteristics of the Rensselaer Bay Formation (RB) at the type section (section 8, Fig. 17) with disconformities to the Cape Camperdown Formation (CC) and Cambrian Dallas Bugt Formation (DB). H = recessive Hatherton Bugt Member, F = cliff-forming Force Bugt Member, C = Cambrian Cape Leiper Formation. Pale resistant sandstone in the middle section is about 2 m thick. **Inset A:** from a strike section (section 9, Fig. 17) showing irregular and bulbous stromatolite beds of arenaceous dolomite within purple and green shales that is a typical lithology of the upper part of the Hatherton Bugt Member. Western Rensselaer Bugt.

formation B of Dawes (1979a) and the middle of three unnamed sandstone units of Dawes (1976a) and Peel *et al.* (1982).

Name. After Rensselaer Bugt, Inglefield Land, a prominent bay and the type locality of Troelsen's (1950a) Rensselaer Bay sandstone (Figs 2, 5A, 18).

Distribution. In Greenland, Inglefield Land and northernmost Prudhoe Land from the Bancroft Bugt area to Sonntag Bugt; in Canada at Bache Peninsula (Fig. 12). Its precise distribution in central Inglefield Land is unknown. A small outlier at MacMillan Glacier, west of Wade Point, (Frisch & Christie, 1982; Fig. 2), is referred to this formation.

Geomorphic expression and overall colour. A red and purple weathering sequence that, apart from basic sills,

Fig. 34. Unconformity between the Rensselaer Bay (RB) and Kap Alexander (KA) Formations; for stratigraphic detail see Fig. 39. Northern side of Dodge Gletscher; person on right as scale.

is recessive and very often scree covered, particularly where it directly overlies crystalline basement (Figs 7, 9, 32).

Type section. The type section is on the west side of Rensselaer Bugt in the sea-cliffs (section 8, Figs 16, 17); a reference section was measured farther west along the coast (section 9, Fig. 17). Other reference sections are the type and reference sections named for two members of the formation (Hatherton Bugt and Force Bugt Members; section 13, Fig. 35; section 17, Fig. 42).

Thickness. The formation reaches a maximum thickness of about 145 m in southernmost exposures at Radcliffe Pynt (Fig. 12). At Rensselaer Bugt it ranges from about 40 m to 70 m thick decreasing to zero towards the east and north-east; at Bache Peninsula it has a maximum thickness of about 65 m wedging out towards the west (Fig. 15).

Dominant lithology. A complex sequence of multicoloured, dominantly reddish sandstones and siltstones, with red and green shales and pale dolomitic rocks characterised by stromatolites (Fig. 33). The sandstone/shale ratio shows marked lateral variation, as is well seen in the cliffs on the west side of Rensselaer Bugt; vertically the formation is more sandy upwards. Shale, sandstone and dolomite characterise the lower and middle parts of the formation (Hatherton Bugt Member); sandstone with minor shale, the upper part (Force Bugt Member).

Depositional environment. The Rensselaer Bay Formation is taken to represent deposition in intertidal to supratidal conditions, possibly a large protected embayment. The passage from the mixed sandstone-shale-dolomite assemblage of the lower member to the siliciclastic upper sequence is taken to indicate shoreline progradation.

Fossils. Stromatolites, algal laminites.

Boundaries and correlation. In northern and southern exposures the Rensselaer Bay Formation disconformably overlies, respectively, the Cape Camperdown Formation and the Kap Alexander Formation (Figs 22, 34). Between Force Bugt and Etah, and west of Wade Point, it directly overlies crystalline rocks (Fig. 9). In Inglefield Land as far south as Force Bugt, and on Bache Peninsula, it is disconformably overlain by the Cambrian Dallas Bugt Formation (Figs 15, 32, 33); to the south it has a conformable contact with the overlying Sonntag Bugt Formation although commonly a basic sill follows the contact (Figs 9, 14). Although pertinent outcrop is missing, the formation is considered to be a lateral equivalent of strata of the Baffin Bay Group (Figs 11, 120).

Subdivisions. The formation is divided into two members: Hatherton Bugt and Force Bugt Members. These members are easily recognised in the cliff-sections at Bache Peninsula and between Rensselaer Bugt and Force Bugt but less evident farther south where the formation is poorly exposed.

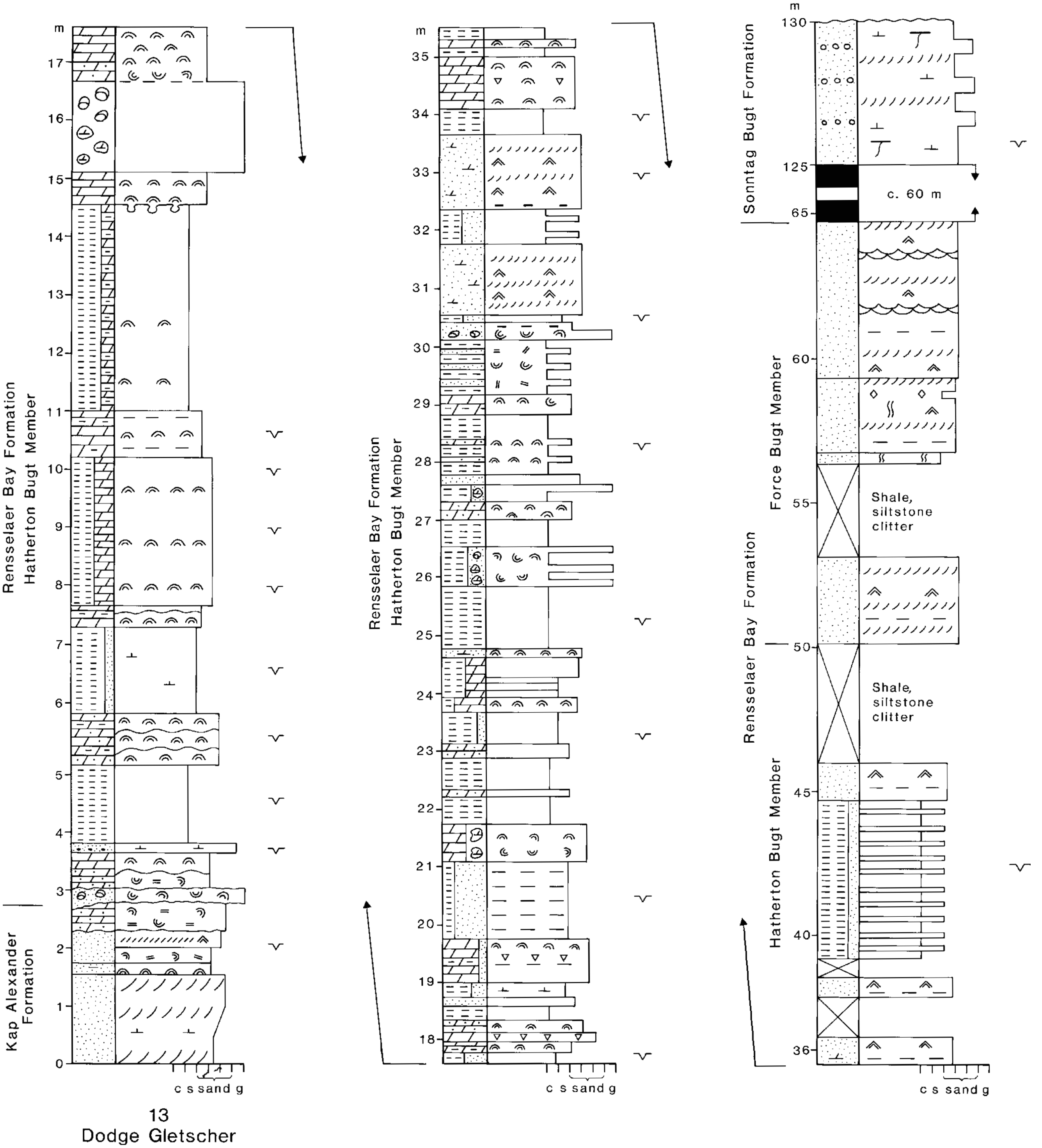
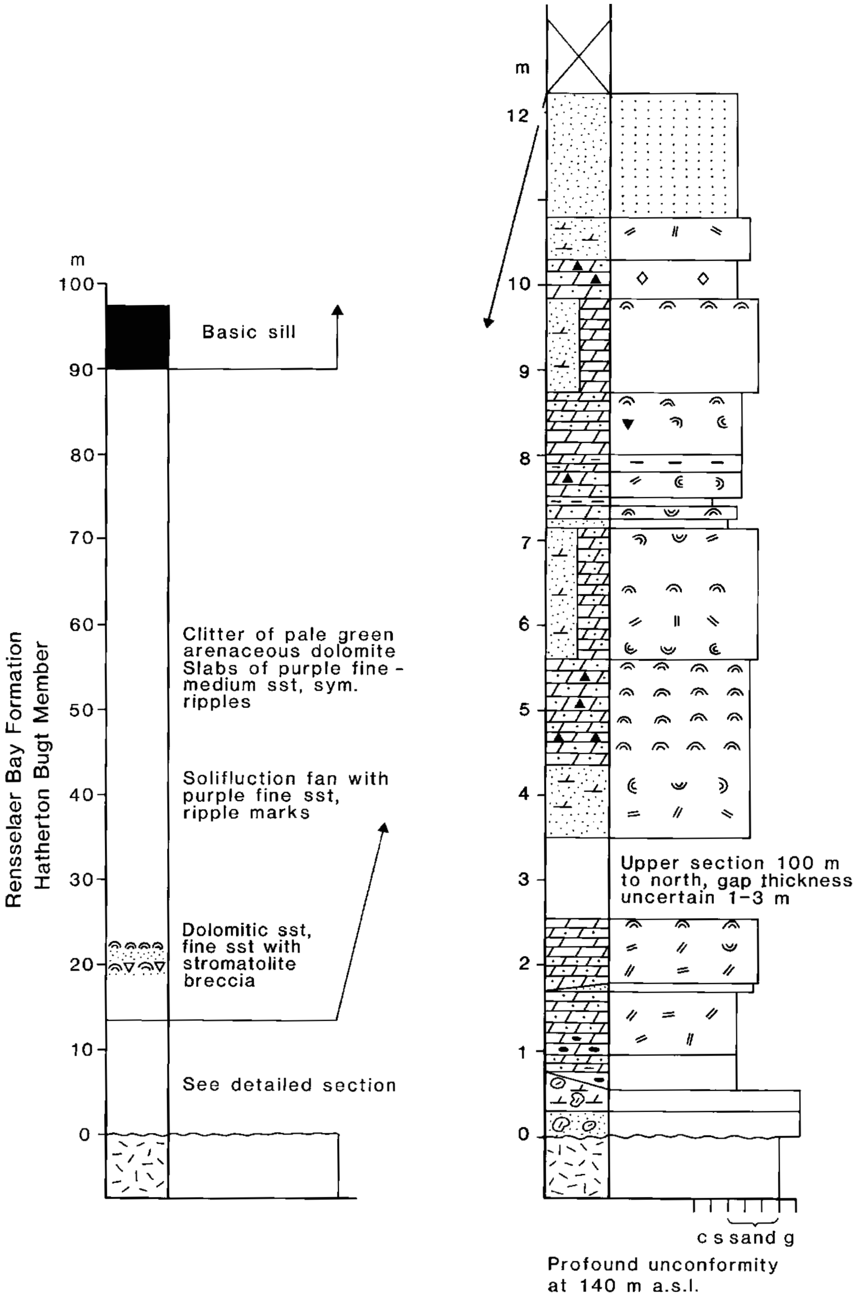
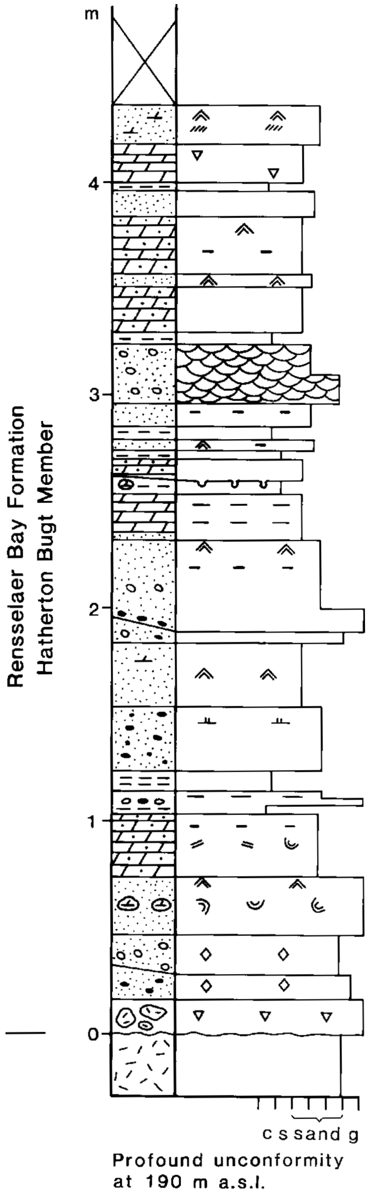


Fig. 35. Stratigraphic logs of the Rensselaer Bay and parts of the Kap Alexander and Sonntag Bugt Formations. Section 13 from the north side of Dodge Gletscher, the type section of the Hatherton Bugt Member of the Rensselaer Bay Formation, is located in Figs 27 and 36. Sections 14 and 15 through basal strata of the Hatherton Bugt Member are 3 km and 1 km respectively west of Etah; section 14 is the same locality as reported on by Cowie (1961; see Fig. 38). Section 16 is from the northern side of Pandora Havn. Sections 14, 15 and 16 are located in Fig. 23. Sections compiled from own data (15, 16) and joint measurement with B. O'Connor (13, 14). Note the varying scales of the sections.



14
Etah



15
Etah
(west)

Fig. 35 cont.

Fig. 35 cont. →
Section 16

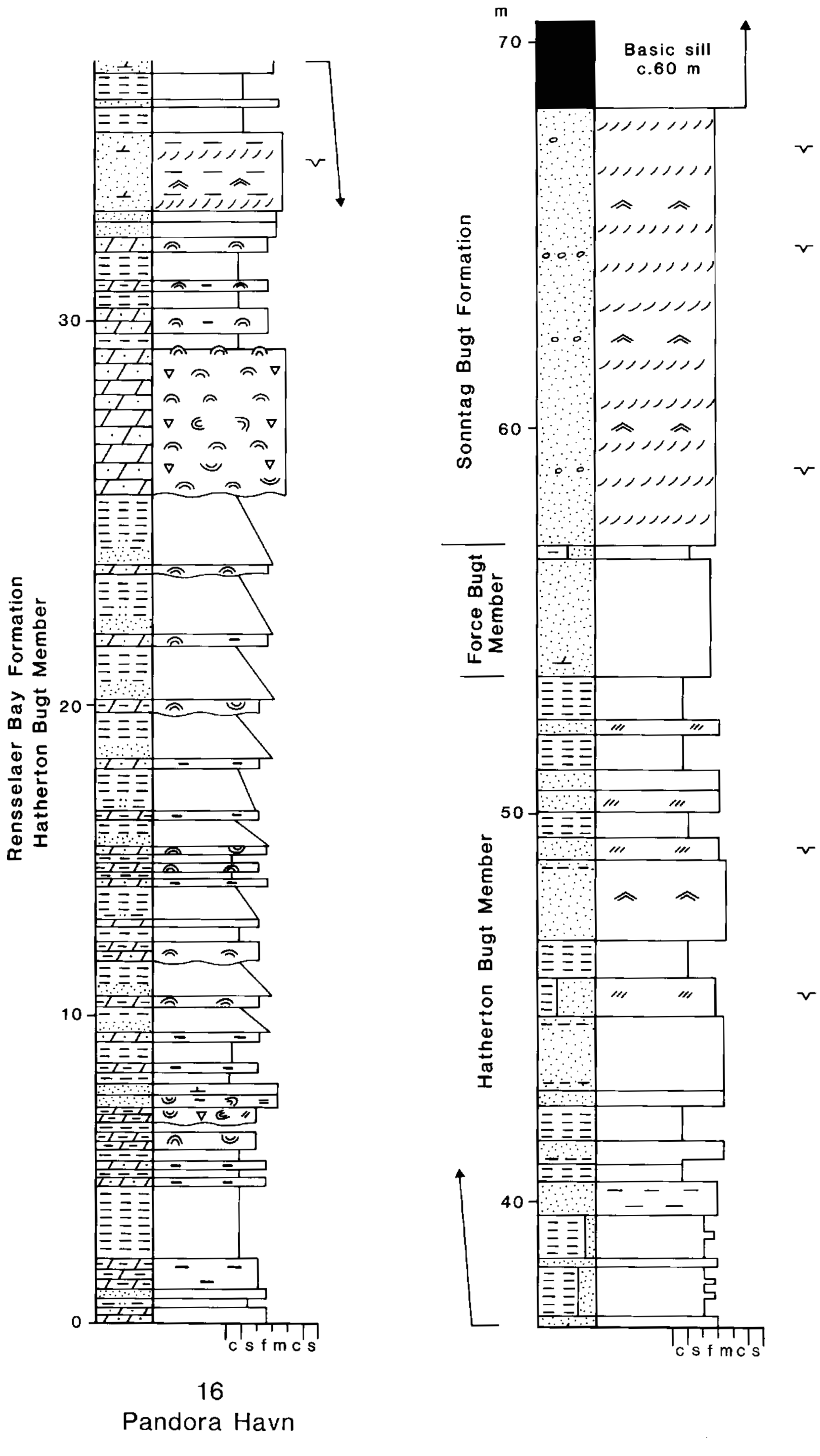


Fig. 35 cont.
Section 16, from the northern side of Pandora Havn, is located in Fig. 23.

Hatherton Bugt Member

new member

Composition. This member encompasses the lowermost strata of the redefined Rensselaer Bay Formation. It includes all but the uppermost strata of the Lower Beds of Cowie (1961) at Hatherton Bugt redefined by Cowie (1971) as the Hatherton Member (Fig. 9), all but the uppermost beds of the sandstone unit B of Dawes (1979a) in northern Prudhoe Land and submember C of the Camperdown Member of Christie (1967) at Bache Peninsula. It should be noted that it does not include the Hatherton Member as defined by Cowie (1971) at Kap Ingersoll or as exposed farther north in Inglefield Land, neither does it include the basal beds of that member as used by Dawes (1976a) in the McCormick Bugt area.

Fig. 36. The type section (foreground ridge) of the Hatherton Bugt Member of the Rensselaer Bay Formation (RB) on the north side of Dodge Gletscher. KA = Kap Alexander Formation, SB = Sonntag Bugt Formation, D = dolerite sill about 60 m thick. Section 13 is given in Fig. 35; for map location, see Fig. 27.

Name. After Hatherton Bugt, the broad bay in south-western Inglefield Land (Figs 2, 9).

Distribution. In Inglefield Land and northernmost Prudhoe Land between Bancroft Bugt area and Sonntag Bugt, at Bache Peninsula and west of Wade Point.

Geomorphic expression and overall colour. A purple to red predominantly recessive unit. Over large parts of south-westernmost Inglefield Land the member is scree-covered (Figs 9, 28; see also Koch, 1933, plate 1).

Type and reference sections. The type section is in the cliffs on the north side of Dodge Gletscher (section 13, Figs 35, 36). Sections measured by Cowie (1961) west of Etah (section 14, Fig. 35) and at Hatherton Bugt and re-examined during this study are poorly exposed; much better reference sections occur at Pandora Havn (section 16, Fig. 35), Rensselaer Bugt (sections 8, 9, Fig. 17), Force Bugt (section 17, Fig. 42) and Radcliffe Pynt (section 18, Fig. 45), although in the latter two sections the base is not seen. Reference sections through basal strata are west of Etah (e.g. section 15, Fig. 35). At Bache Peninsula the best reference section is situated about 7 km west of Cape Camperdown (section 5, Fig. 15).

Thickness. The member shows marked thickness variations. It is thickest in the south, about 130 m at Radcliffe Pynt (see Fig. 45) and thins markedly over the basin margin to under 60 m at the type section. In Hatherton Bugt the member is up to 100 m thick thinning to the north so that at Force Bugt it is between 10 and 20 m thick (see Fig. 42). At Bache Peninsula in eastern outcrops it is about 35 m thick, thinning out to a featheredge in the west (Fig. 15). To the west of Wade Point the section is topped by the present erosion surface and the member is only a few tens of metres thick (Frisch & Christie, 1982).

Lithology. Interbedded variously coloured mudstone, siltstone and mainly fine-grained sandstones, which in most sections are associated with thin beds of pale

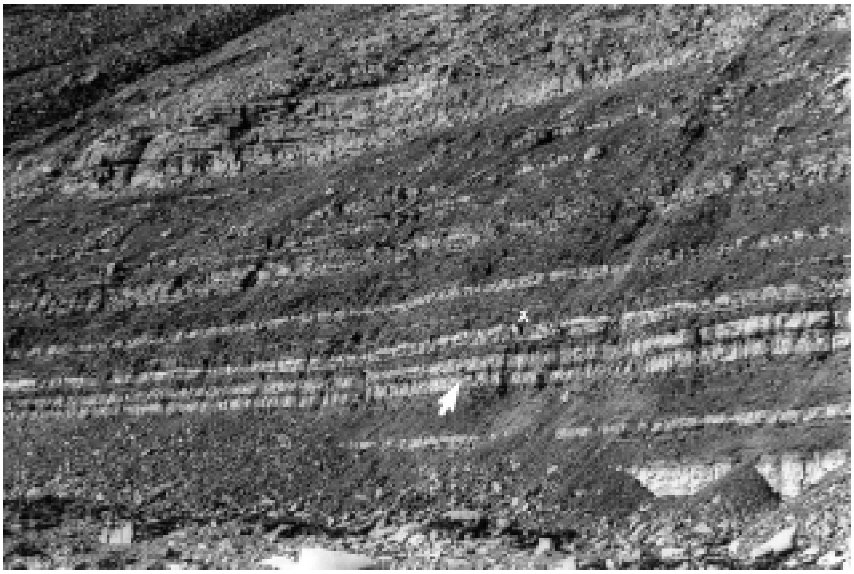


Fig. 37. Typical lithology of the Hatherton Bugt Member of the Rensselaer Bay Formation. Purple shales with thin arenaceous stromatolitic dolomite and breccia beds. Disturbed stromatolite bed at x; hammer arrowed as scale. Northern side of Pandora Havn, section 16.

dolomite and arenaceous dolomite (Figs 36, 37). The member shows marked lithological variation along strike; some sections show prominent sandstone intervals, elsewhere shales and arenaceous dolomite dominate. The basal beds, characterised by stromatolite-bearing sands and carbonates, show lateral variation governed in part by the nature of the substratum. In the Hatherton Bugt – Etah area, where the member directly overlies the crystalline basement, the basal strata, variously dolomitic, contain prominent granite components (Fig. 38). The actual contact is very often a diffuse zone; fractured and weathered granite with veins of dolomite passing upwards into a white to cream-coloured, often red stained, fine-grained dolomite or arenaceous dolomite that contains angular blocks of granite up to boulder size. Arenaceous dolomite up to 1 m above the diffuse zone can contain granite fragments; higher conglomeratic sandstone and dolomite beds contain polymictic clasts.

At Dodge Gletscher the basal strata are characterised by a silicified pink conglomerate up to 45 cm thick composed of stromatolite clasts and green siliceous pebbles set in a pink to green sandstone matrix. This may form the basal bed infilling the irregular surface of the top of the Kap Alexander Formation or it can be up to as much as 2 m above the contact (Fig. 39). The 2 m interval comprises a variety of predominantly purple, thin sandstone and arenaceous dolomite beds characterised by stromatolites either in growth position or resorted; in places a green shale bed, 35 cm thick to a feather-edge, forms the basal bed (Fig. 39).

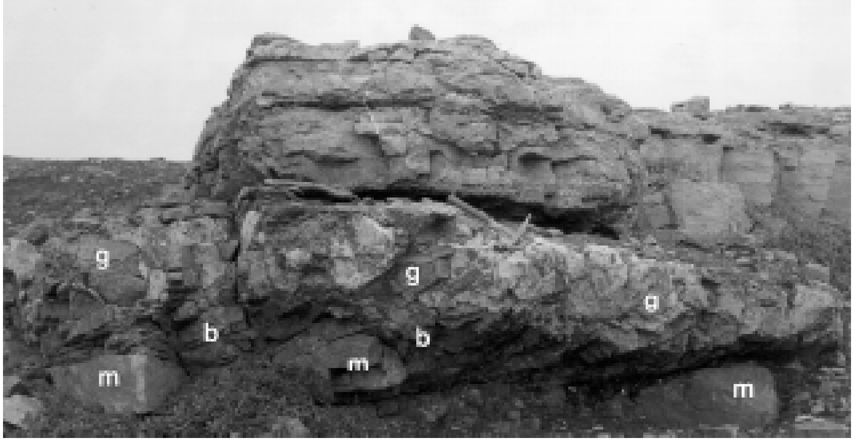


Fig. 38. The unconformity at the base of the Rensselaer Bay Formation (Hatherton Bugt Member) showing rubbly reworked crystalline basement (b) with massive gneiss (m) below, invaded by pale dolomite that contains angular gneiss blocks (g). Overlying beds are arenaceous dolomite with shale. West of Etah, section 14; cf. Cowie (1961, fig. 2).

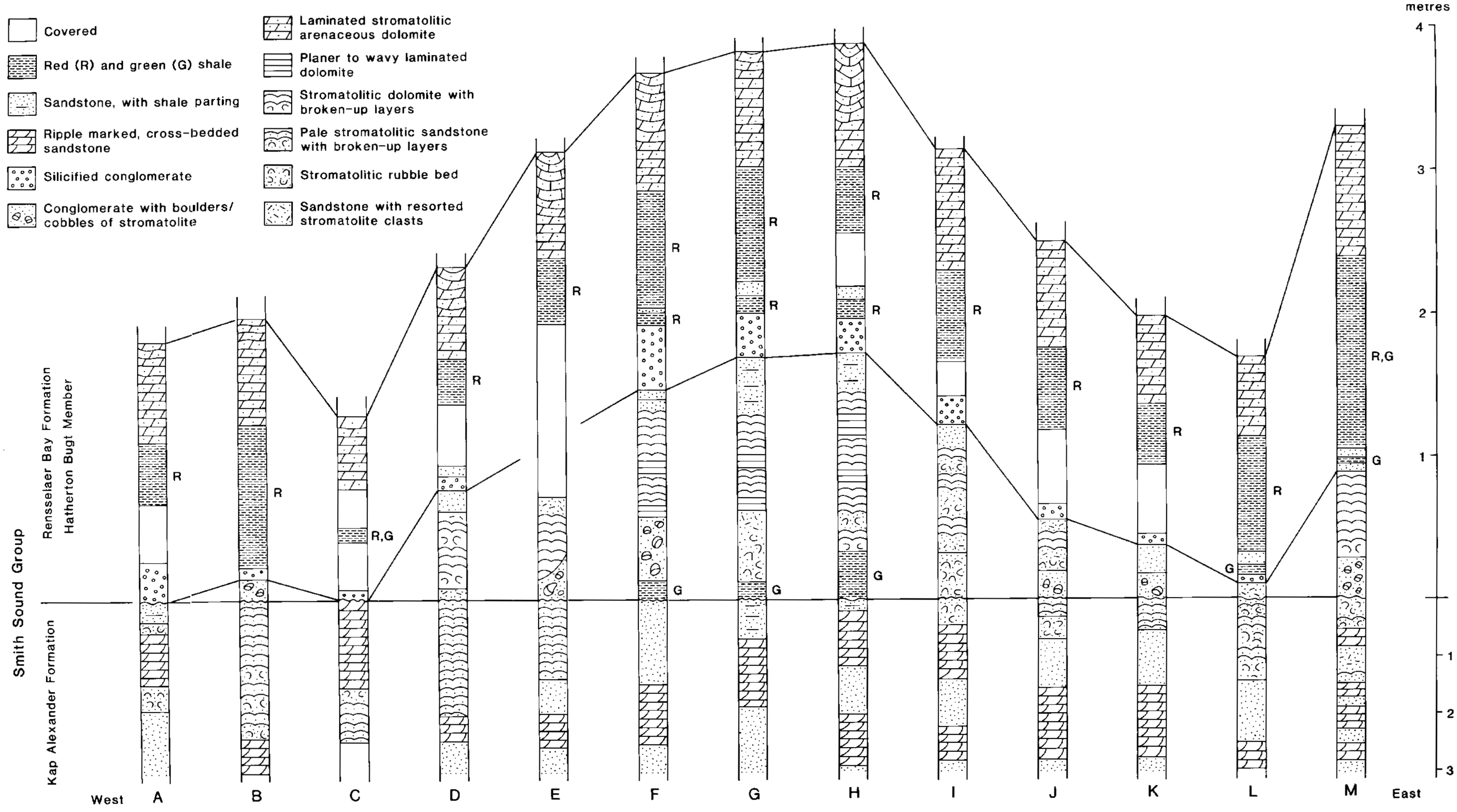


Fig. 39. Stratal variation at the unconformity between the Rensselaer Bay and Kap Alexander Formations at Dodge Gletscher (see Fig. 34). The 13 sections span about 400 m. Largest spacings are 100 and 47 m between respectively sections B & C, and A & B; shortest spacings are 10 and 12 m between sections H & I and I & J. Section M is the base of the type section for the Hatherton Bugt Member, section 13, Fig. 35. Note scale difference above and below the unconformity.

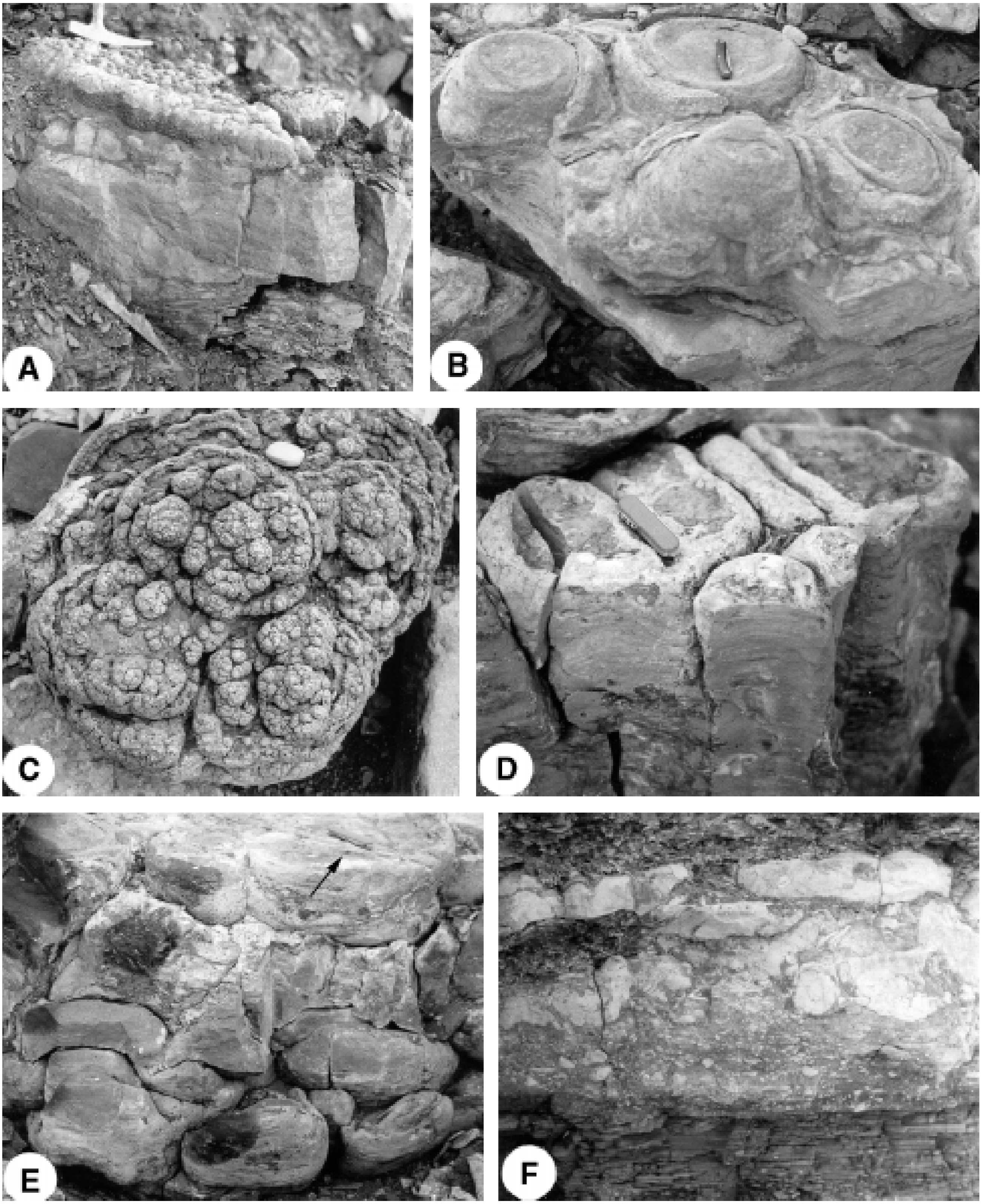


Fig. 40. Stromatolite forms in the Hatherton Bugt Member of the Rensselaer Bay Formation. **A:** arenaceous dolomite bed with bulbous base into shale capped by thin stromatolite bed; **B:** pudding-shaped domes with flat to concave surfaces; **C:** cauliflower dome; **D:** bulbous elephant-foot columns with concave tops; **E:** flat-topped bulbous domes separated by wavy laminated dolomite; **F:** breccia bed, 40 cm thick, with stromatolites in growth position at top, disturbed and rotated forms below and reworked clast breccia at base. Locations: **A**, Rensselaer Bugt, section 9; **B, D** and **E**, Dodge Gletscher, section 13; **C**, Force Bugt, section 17; **F**, Hartstene Bugt, section 12. Scales: Hammer head 17 cm, penknives 7–9 cm, eraser 4 cm.

The sandstones are purple, maroon, red, brown and buff, mainly fine-grained quartz arenites varying to calcarenites and arenaceous dolomite, and they are characteristically thin bedded. They are often flaggy with shale partings showing desiccation cracks. Some of the thicker beds up to 50 cm are cross-bedded. At Dodge Gletscher and elsewhere, distinct benches are formed of white to pale pink medium-grained sandstone characterised by well-rounded quartz grains, sometimes with a carbonate matrix and with in places festoon cross-bedding.

The shales and siltstones are typically red to purple with some green beds. They are interbedded on all scales with sandstone, and many discrete shale units contain thin silts and sand layers. Mudcracks are common. A common association is with thin dolomite beds. In places the strata are arranged in fining-up units up to 1.5 m thick, fine sandstone and siltstone passing upwards into shale that is overlain by stromatolitic dolomite.

The dolomites, pale green and pink and variously argillaceous and arenaceous, form planar to lenticular and irregular beds varying from a few centimetres to about 40 cm, rarely up to 90 cm. Discrete dolomite units interbedded with shale may represent single beds, but thick-bedded units up to 4 m occur in Hatherton Bugt and Pandora Havn. The base of the member at Etah is particularly dolomite rich. Generally, the dolomites show irregular internal structures, but both algal lamination, and columnar and domal stromatolites are common (Fig. 40). All gradations occur from stromatolites in growth position to completely disorganised breccio-conglomerates. Domal stromatolites are usually laterally linked, 10–30 cm in diameter; columnar stromatolites reach up to 40 cm in diameter.

Depositional environment. The alternation of siliciclastic and brecciated stromatolitic clastic carbonates is taken to represent deposition in a high-energy tidal flat or near-lagoonal or lacustrine environment. Carbonate precipitation and stromatolite growth were interrupted intermittently by floods with sand sheet transportation. According to Grey (1995), the internal structure of the stromatolites, together with an oncolitic habit, are consistent with formation in a closed system such as a lacustrine environment subject to seasonal influences. Some of the fining-upwards cycles noted in southern exposures may indicate channel-fill deposits.

Fossils. Stromatolites, algal laminites.

Boundaries and correlation. The lower boundary of the Hatherton Bugt Member is that of the formation; the upper boundary is with the Force Bugt Member. In places both contacts are followed by basic sills. At Dodge Gletscher the disconformable relationship to the Kap Alexander Formation is regarded as a shallow topographic unconformity (Fig. 34). The boundary to the Force Bugt Member is conformable but on a regional scale complicated and the two members are deemed to interdigitate. In many sections, for example at Rensselaer Bugt, the boundary is taken at the abrupt incoming of major sandstone units. Farther to the south the boundary is more arbitrarily drawn at the top of the last shale-siltstone-dolomite strata.

The relationship of the Hatherton Bugt Member to the strata of the central basin to the south is not exposed but the member is a possible lateral equivalent of the Robertson Fjord Formation of the Baffin Bay Group (Fig. 120).

Fig. 41. The type section of the Force Bugt Member (FB) of the Rensselaer Bay Formation at western Force Bugt. Arrows indicate traverse sites for section 17 given in Fig. 42. Dark rocks (s) are two basic sills, the upper of which is at the disconformity with the Cambrian (C). Ps = Precambrian shield, SS = Smith Sound Group, CC = Cape Camperdown Formation. Summit of cliffs about 300 m.

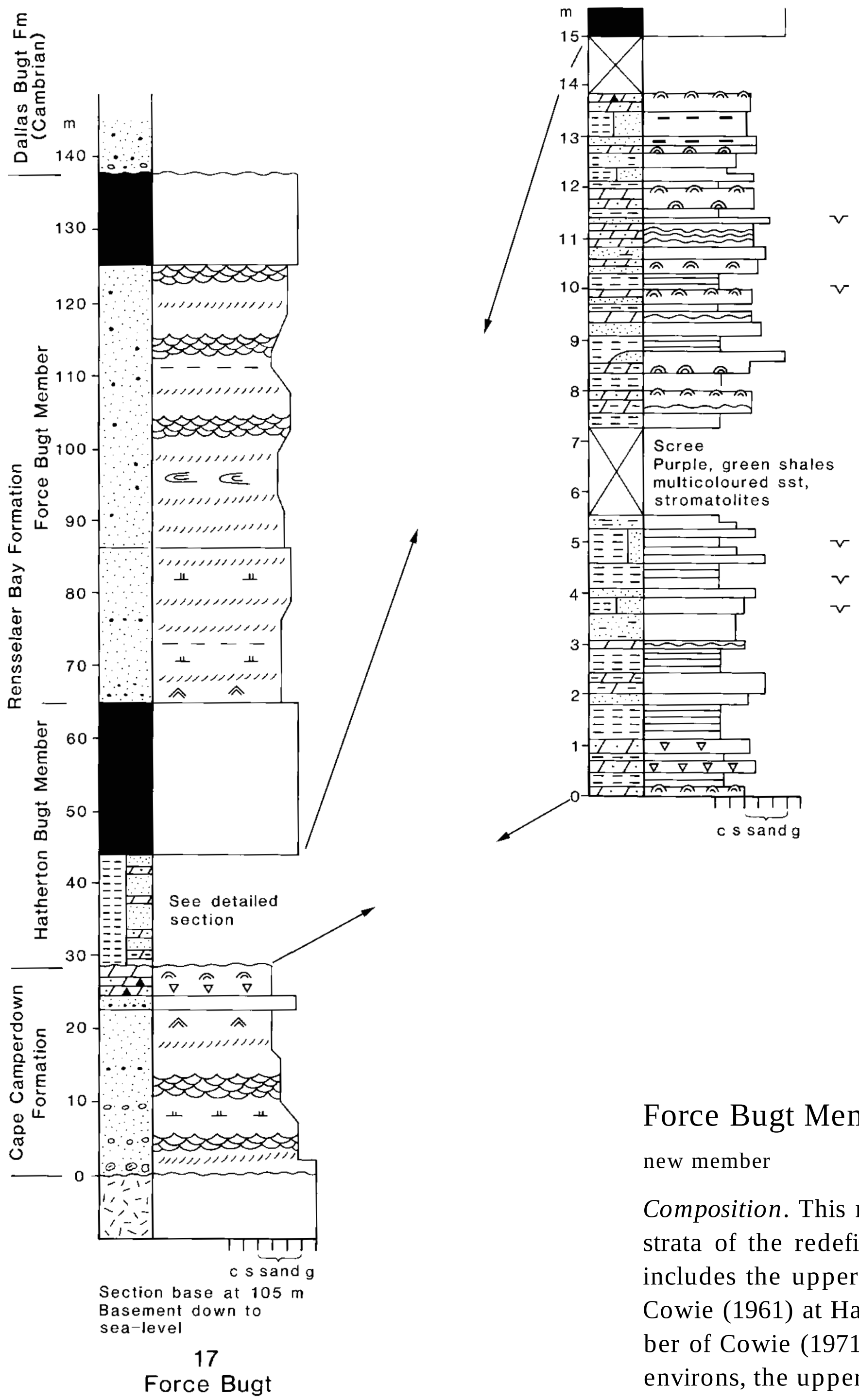


Fig. 42. Stratigraphic log of the Cape Camperdown and Rensselaer Bay Formations, western Force Bugt. This is the type section for the Force Bugt Member that is located in Fig. 41.

Force Bugt Member

new member

Composition. This member represents the uppermost strata of the redefined Rensselaer Bay Formation. It includes the uppermost strata of the 'Lower Beds' of Cowie (1961) at Hatherton Bugt, the Hatherton Member of Cowie (1971) as exposed at Kap Ingersoll and environs, the uppermost strata of the Hatherton Member as used by Dawes (1976a), and sub-member D of the Camperdown Member as described by Christie (1967) from Bache Peninsula.

Name. After Force Bugt, the broad bay in south-western Inglefield Land (Figs 2, 41).

Distribution. In Inglefield Land and northernmost Prudhoe Land between the area around Bancroft Bugt and Sonntag Bugt, and at Bache Peninsula.

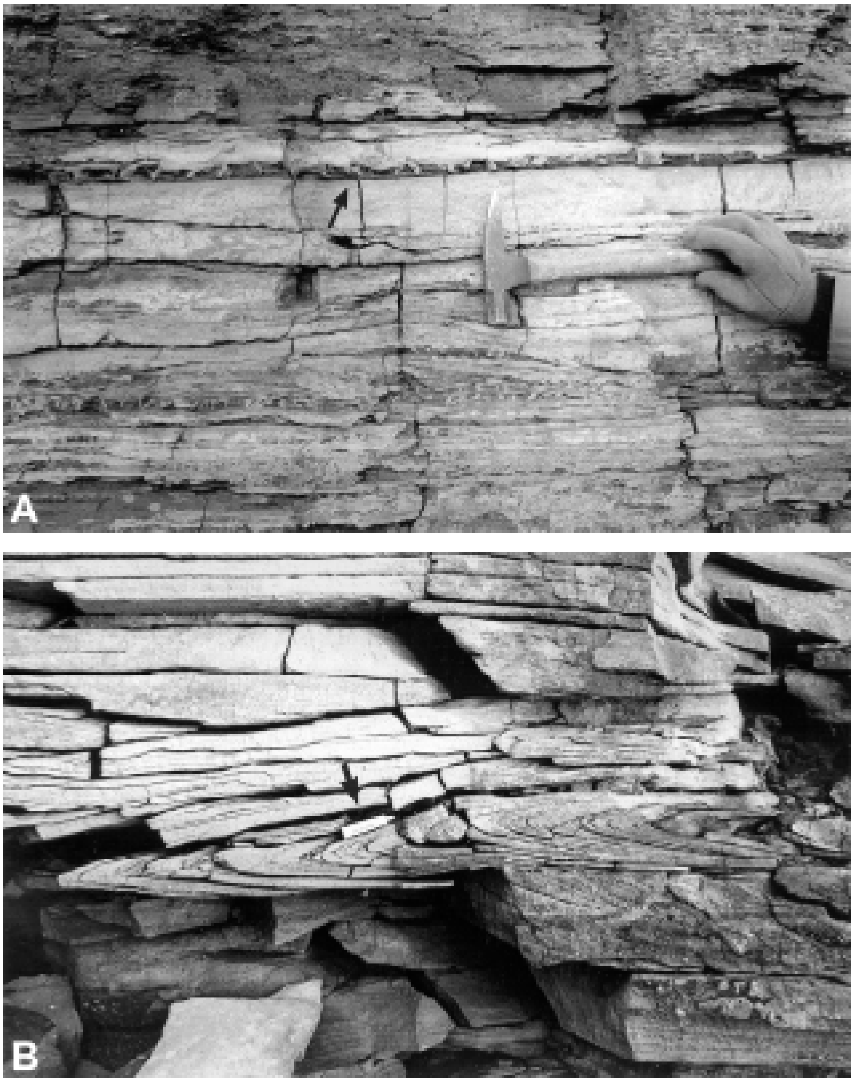


Fig. 43. Bedding characteristics of the Force Bugt Member of the Rensselaer Bay Formation.
A: thin-bedded sandstones with shale interbeds that may be discontinuous and severely disturbed by irregular sandstone infillings interpreted as diastasis cracks, e.g. thin shale bed arrowed. Western Rensselaer Bugt, section 9.
B: long-limbed recumbent fold developed from overturned cross-bedding. Current direction, left to right. Scale (arrowed), is almost 8 cm long. Western Force Bugt, section 17.

Fig. 44. Sea-cliffs of eastern Force Bugt showing the resistant cliff-forming Force Bugt Member (FB) of the Rensselaer Bay Formation and the hiatus with the Cambrian (C). The upper of two basic sills, marked on left, is cut out at the erosional disconformity; the lower sill (s) is visible through the scree that covers the recessive Hatherton Bugt Member. Height of the sea-cliffs is around 250 m, with the sea-ice at bottom left.

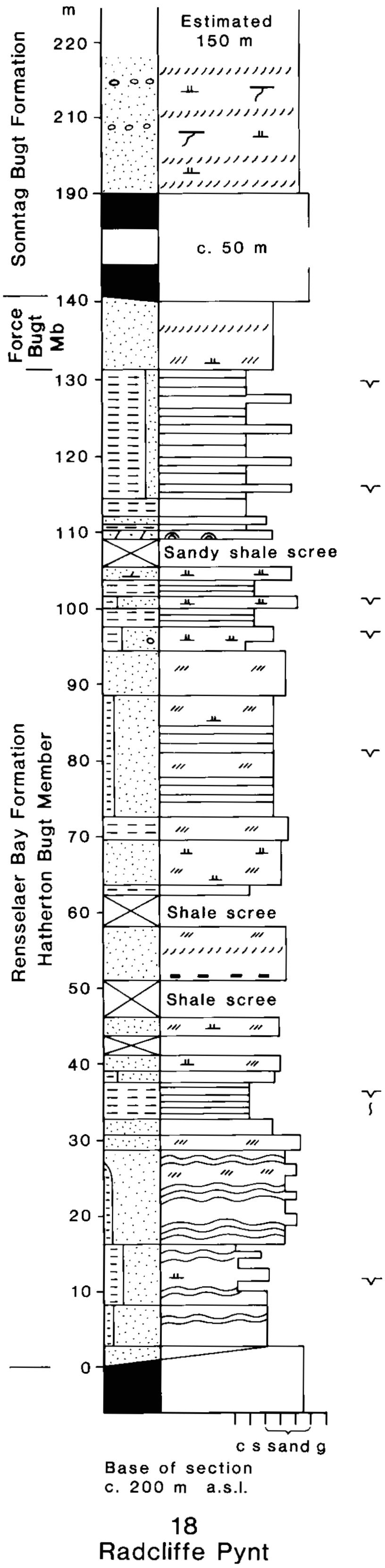


Fig. 45. Stratigraphic log of the Rensselaer Bay and Sonntag Bugt Formations; this is the type section for the latter formation. For location, see Figs 27 and 46.

Geomorphic expression and colour. Pale purple to buff, variously banded, with occasional darker more recessive units; locally cliff-forming but commonly with scree cover (Figs 32, 41).

Type and reference sections. The type section is in the sea-cliffs on the west side of Force Bugt (section 17, Figs 41, 42); reference sections are on the west side of Rensselaer Bugt (sections 8, 9, Fig. 17), at Dodge Gletscher (section 13, Fig. 35) and at Bache Peninsula, for example section 4 about 10 km west of Cape Camperdown (Fig. 15).

Thickness. True sediment thicknesses are obscured by basic sills. The member is thickest at Force Bugt – up to 60 m – thinning to the north and south. At Rensselaer Bugt it is about 25 m thick, at Radcliffe Pynt less than 5 m of strata can be referred to the member. At Bache Peninsula it has a maximum thickness of 30 m pinching out to the west.

Lithology. The main lithology is thin- to thick-bedded, clean to slightly ferruginous sandstones with local thin mudstone and siltstone beds (Fig. 43A). In Inglefield Land, argillaceous lithologies are best developed in northern sections. The sandstones vary in colour: purple, pink, brown, buff and white. Interbedded purple and pale sandstones give the unit a striped or banded appearance.

Sandstones are fine- to medium-grained quartz arenites with typically subangular to poorly rounded grains, with locally coarser beds grading to grits. Beds vary from planar to lenticular. Cross-bedding in planar sets up to 50 cm thick is common, with some herringbone and local trough cross-bedding, as well as overturned cross-bedding (Fig. 43B). Current ripples and symmetrical wave ripples are locally common; channels are seen at some levels.

Argillaceous material varies from shaly laminae and partings in sandstones to discrete planar to lenticular beds of shale, siltstone and sandy shale up to *c.* 30 cm thick. A common feature is the irregular nature of thin shale beds both in bed form and internal structure (Fig. 43A). Mudcracks and the mixing of sands and mud resemble the diastasis cracks of Cowan & James (1992).

Depositional environment. The strata of the Force Bugt Member, that are characterised by wave ripples and bimodal and overturned cross-bedding, are interpreted to represent an intertidal deposit reflecting shoreline progradation over the underlying carbonate-bearing sequence.

Fossils. None known.

Boundaries and correlation. The lower boundary of the Force Bugt Member is with the Hatherton Bugt Member; the upper boundary is that of the Rensselaer Bay Formation (see earlier). In many locations, for example on eastern Bache Peninsula and in Inglefield Land south-west of Rensselaer Bugt, the upper boundary of the Force Bugt Member is a basic sill. Between Rensselaer Bugt and Force Bugt the sill is discontinuous; it shows an irregular weathered top surface and is in places cut out by the overlying Cambrian Dallas Bugt Formation (Figs 17, 32, 44). The Force Bugt Member interdigitates with the Sonntag Bugt Formation in the Force Bugt area.

Sonntag Bugt Formation

new formation

Composition. The formation encompasses the uppermost part of the Rensselaer Bay sandstone of Troelsen (1950a) as exposed between Force Bugt and Dodge Gletscher, the Middle and Upper Sandstones of Cowie (1961), later referred by Cowie (1971) to the Sverdrup Member, sandstone formation C of Dawes (1979a), and the upper of three members at Storm Gletscher illustrated in Peel *et al.* (1982).

Name. After Sonntag Bugt, the prominent bay on the northern coast of Prudhoe Land (Figs 1, 2, 27).

Distribution. Inglefield Land and northernmost Prudhoe Land between Force Bugt and Sonntag Bugt (Fig. 12).

Geomorphic expression and overall colour. A brown, orange to buff weathering, cliff-forming unit, every-

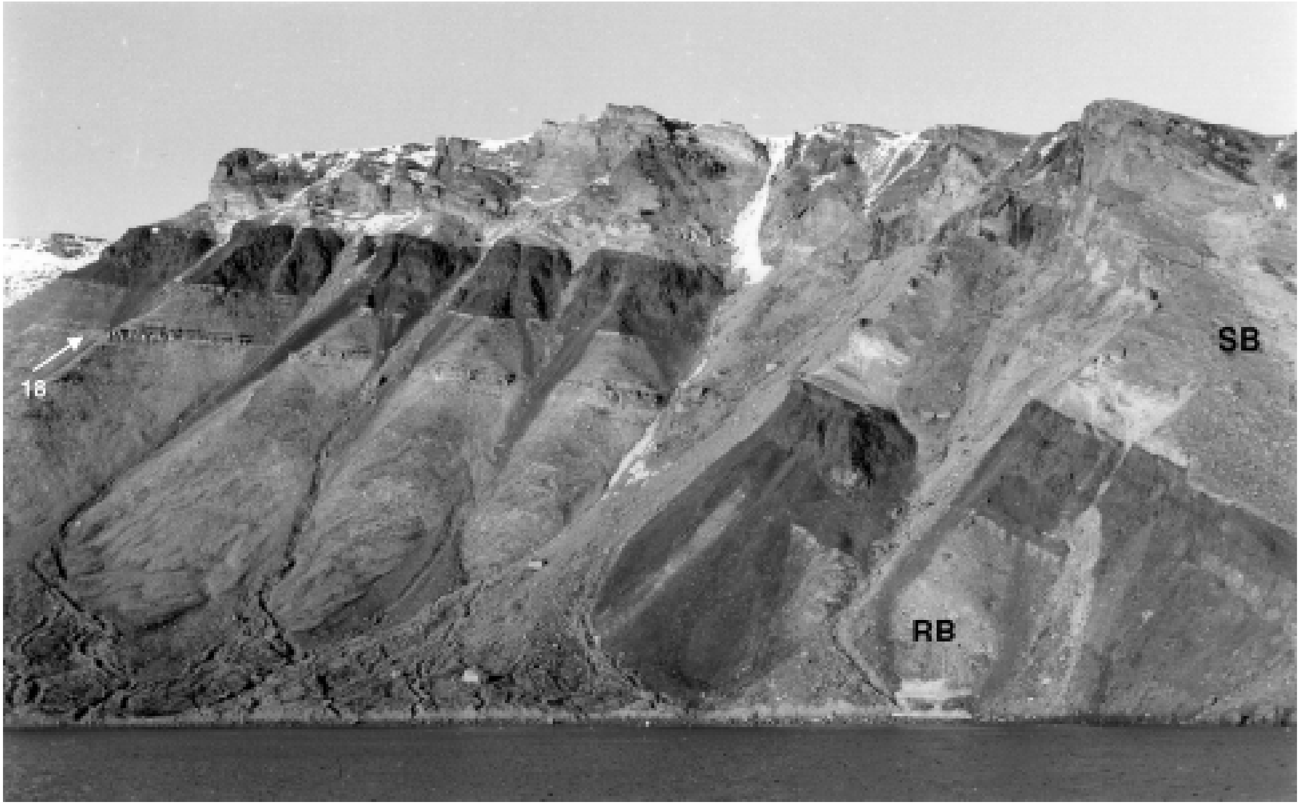


Fig. 46. Faulted sea-cliffs north of Radcliffe Pynt showing cliff-forming sandstones of the Sonntag Bugt Formation (SB) overlying the more recessive Rensselaer Bay Formation (RB); the contact is followed by a basic sill about 50 m thick. This is the type section for the Sonntag Bugt Formation (section 18, Fig. 45). For map location, see Fig. 27.

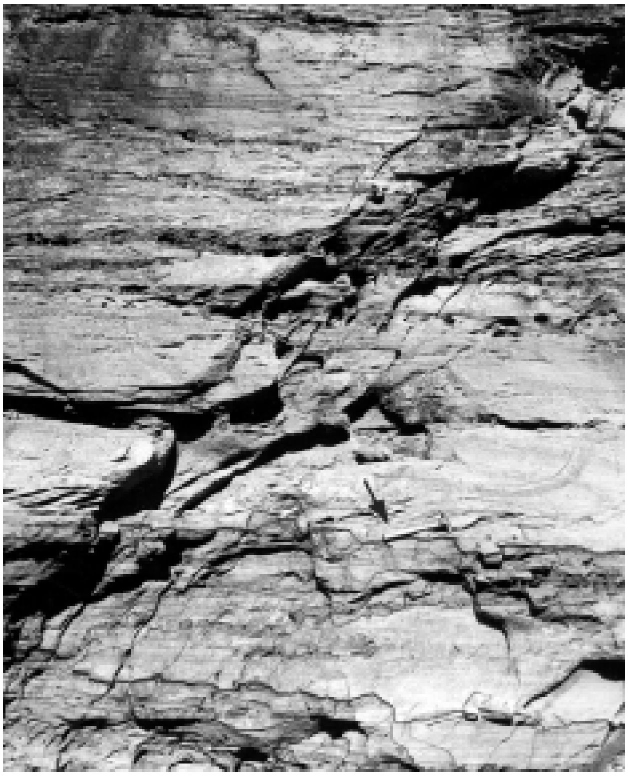


Fig. 47. Bedding characteristics of the Sonntag Bugt Formation. Medium to thick cross-bedded, variously laminated, ferruginous sandstones. Liesegang rings just right of hammer (arrowed). Coast, north of Radcliffe Pynt.

where associated with basaltic sills, as illustrated in the tiered landscape at Crystal Palace Cliffs (Fig. 23).

Type and reference sections. The type section is in the cliffs north of Radcliffe Pynt (section 18, Figs 45, 46); reference sections are at Dodge Gletscher, McCormick Bugt (sections 13, 16, Fig. 35) and in Hatherton Bugt (Fig. 9).

Thickness. Ranges from 15 to 180 m (Fig. 12). The formation is thickest in the south at Radcliffe Pynt and McCormick Bugt. Although the top of the formation over most of its outcrop is the present erosion surface, the southerly thickening is taken to be an original feature corresponding to the thickening shown by the underlying Kap Alexander and Rensselaer Bay Formations over the basin margin.

Lithology. Well-bedded, clean to ferruginous quartz arenites with cross-bedding and ripple marks common (Fig. 47). Fresh surfaces are cream, buff, grey or brown in colour; pale pink to purple hues appear due, at least in places, to contact metamorphism adjacent to basic intrusions. Orange to yellow weathering colours are very characteristic.

The quartz arenites are generally medium grained and well sorted with subangular to subrounded grains. Variations to fine sand and to coarse grit occur. Grit, fine conglomerate and pebbly conglomerate are characterised by very well-rounded quartz grains and pebbles, in combination with a much less rounded, finer grained matrix. Some sandstones are finely laminated; mudstone partings show desiccation cracks. Cross-bedding in tabular sets up to 30 cm is common; some cross beds are up to 60 cm thick.

In all sections examined, some intervals show dark brown, highly ferruginous veins and irregular partings that can reach a centimetre or more in thickness. These veins may show a random pattern but are oblique to bedding. They are characteristically composed of well-rounded quartz grains separated by iron oxide and may represent wind-blown sand infillings. Liesegang rings also occur (Fig. 47).

Depositional environment. The interpretation of the sedimentary environment is tentative; shallow water to subaerial deposition is suggested. The rudaceous incursions might represent a fluvial source and the sand infilling structures may be subaerial.

Fossils. None known.

Boundaries and correlation. Over much of its outcrop the Sonntag Bugt Formation is bounded at the base by a basic sill separating it from the Rensselaer Bay Formation, and at its top by the present erosion surface (Figs 9, 36, 46). Where preserved the sedimentary contact is conformable and fairly abrupt and drawn at the incoming of prominent buff-brown sandstones. In the Force Bugt area, the Sonntag Bugt Formation interdigitates with the Rensselaer Bay Formation, and both formations are overlain disconformably by the Cambrian Dallas Bugt Formation (Fig. 14).

Contact with the Baffin Bay Group is not exposed but the Sonntag Bugt Formation is taken to be a correlative of that group, more specifically of the Qaanaaq Formation (Figs 11, 120).

Nares Strait Group

The Nares Strait Group represents the oldest strata of the central basin fill of the Thule Basin (Figs 2, 4, 120). It is subdivided into five formations, viz. Northumberland, Cape Combermere, Josephine Headland, Barden Bugt and Clarence Head Formations, in which eight members are formally recognised.

Nares Strait Group

new group

Composition. Koch (1926, 1929a; *in* Dawes & Haller, 1979, plate 1) included strata now referred to this group in his lower red sandstone of the Thule Formation, although some strata on Northumberland Ø are part of his upper sandstone unit. Seen regionally the group is part of the Wolstenholme Formation of Davies *et al.* (1963, fig. 2), although *not* part of the succession in the type area and environs studied by these authors, Kurtz & Wales (1951) and Fernald & Horowitz (1964). The group equates with the lower two members (a and b) of the Wolstenholme Formation as described by Dawes (1975) from Northumberland Ø and encompasses units I, II, III and IV of that formation in Canada (Frisch *et al.,* 1978; Frisch & Christie, 1982). It embraces the lower four units of the Wolstenholme Formation as defined by Dawes *et al.* (1982a) from both sides of Nares Strait.

Name. After Nares Strait, the narrow seaway separating Ellesmere Island and Greenland (Figs 2, 10).

Distribution. In Greenland, Prudhoe Land south-east of Sonntag Bugt, western Steensby Land and Northumberland Ø; in Canada, in all main exposures south of Johan Peninsula, viz. both sides of Cadogan Inlet, Goding Bay, Cape Combermere and Clarence Head (Fig. 2).

Type area. North-western Northumberland Ø, Greenland (Fig. 48).

Thickness. The maximum composite thickness reaches 1200 m. Individual sections vary from about 950 m on Northumberland Ø to about 700 m in northern Prudhoe Land and at Clarence Head to around 450 m in western Steensby Land, thinning east to 200 m at Granville Fjord (Figs 3, 12).

Dominant lithology. The Nares Strait Group is dominated by siliciclastic strata, with one main formation of basaltic extrusive and intrusive rocks, although basic sills occur throughout (Fig. 3). In ascending stratigraphic order the main lithologies are: quartz arenites with subordinate siltstone and shale (with basic sills) followed by a volcanic – red bed sequence composed of lavas, agglomerate, tuffs, sills and various clastic rocks, overlain by varicoloured carbonate and clastic rocks containing volcaniclastic elements, and topped by massive, nearly pure quartz arenites (Fig. 49).

Depositional environment. The group is taken to represent shallow water deposition in alluvial plain, littoral and offshore environments, as well as a period of terrestrial volcanism manifested mainly by outpouring of plateau basalts. Based in part on the interpretations of Frisch & Christie (1982) and Jackson (1986) the following history is suggested: early sandstone-dominated and sandstone-shale sequences of supratidal to subtidal environments ranging from alluvium of meandering rivers to possible prodelta or offshore muds, gave way to marine sand deposition with thick, highly reworked quartz sands probably representing extensive offshore bars.

Fossils. Stromatolites, algal laminites.

Boundaries and correlation. The Nares Strait Group lies between the crystalline shield and the Baffin Bay Group (Figs 3, 12, 75, 77). In the north, lack of exposure prevents factual information on the relationship to the Smith Sound Group, but the Nares Strait Group is assumed to be limited northwards around Sonntag Bugt by basin margin faults (Figs 1, 27). Coeval sediments probably are represented in the basal strata of the Smith Sound Group, i.e. the Cape Camperdown, Pandora Havn and Kap Alexander Formations (Figs 3, 4, 120).

Geological age. Neohelikian; an age based on isotopic age determinations of basaltic rock from flows and sills from Canada and Greenland. A ^{207}Pb/^{206}Pb baddeleyite age of 1268 Ma from the major sill in the Cape Combermere Formation at Goding Bay (section 28, Fig. 58) is the most reliable age available (LeCheminant & Heaman, 1991). The six most reliable whole-rock K-Ar age determinations of basaltic rock from Robertson Fjord, Northumberland Ø, Clarence Head and Gale

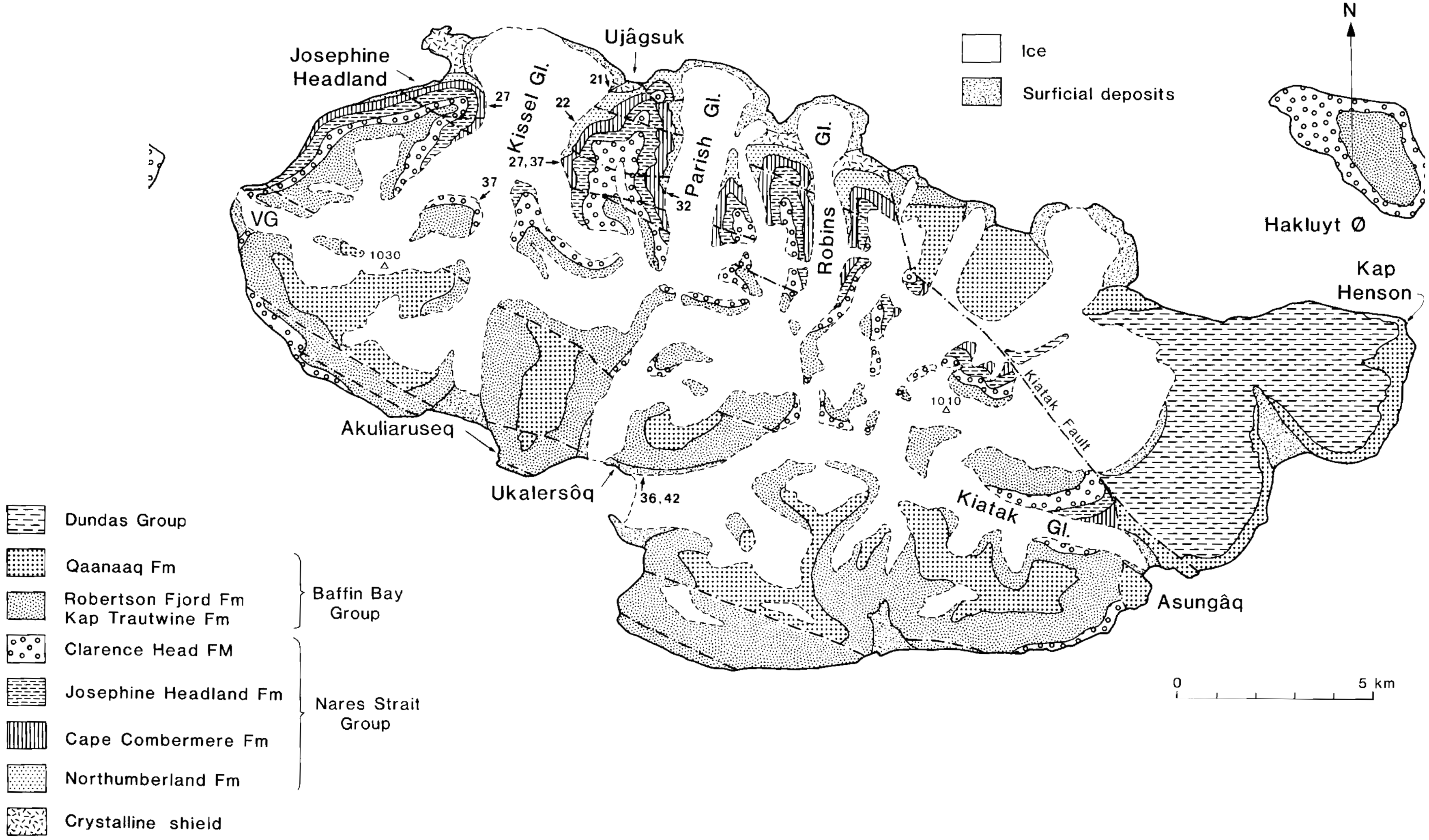


Fig. 48. Geological map of Northumberland Ø (Kiatak) and Hakluyt Ø, Greenland, showing the locations of sections 21, 22, 27, 32, 36, 37 and 42 (sections 27 and 37 are composite). Northumberland Ø proved to be a key area for the understanding of the Thule Basin stratigraphy. The island exposes a full section through the Nares Strait and Baffin Bay Groups, including the transition into the Dundas Group (Fig. 4). The north-western part of the island is the type area for the Nares Strait Group that represents the early siliciclastic-volcanic fill of the central basin. The initial recognition that the central basin succession also occurred in adjacent Canada, was based on the correlation between Northumberland Ø and Clarence Head on the coast of south-eastern Ellesmere Island. VG = Vestgletscher. Heights are in metres. For location, see Fig. 2.

Fig. 49. Nares Strait Group: Greenland and Canada. **A:** eastern side of Kissel Gletscher, Northumberland Ø; **B:** coast, south of Clarence Head, photo: T. Frisch. Ps = Precambrian crystalline shield, N = Northumberland Formation with basic sills, CC = Cape Combermere Formation, JH = Josephine Headland Formation with arrows marking dark carbonate bench of the Robins Gletscher Member, CH = Clarence Head Formation characterised by darker and banded strata in lower part. At Clarence Head, the Northumberland Formation is thin and in places tectonically cut out (see map, Fig. 75); on Northumberland Ø it is composed of the Kissel Gletscher (KG) and Kiatak (K) Members. The relief in both scenes is about 700 m. For location, see Figs 48 and 75.

Point fall in the range 1284 ± 37 and 1065 ± 73 Ma (Dawes *et al.*, 1973; Frisch & Christie, 1982; Dawes & Rex, 1986).

Subdivisions. The Nares Strait Group is subdivided into five formations: the Northumberland, Cape Combermere, Josephine Headland, Barden Bugt and Clarence Head Formations.

Northumberland Formation

new formation

Composition. The strata of this formation correspond to the basal unit of the Wolstenholme Formation as described on Northumberland Ø and in the Neqe–Siorapaluk area (Dawes, 1975, 1976a, b) and to units 1 to 10 as logged by Christie (1975) from Gale Point. It equates with unit I in the Clarence Head – Cape Combermere region as defined by Frisch *et al.* (1978) and

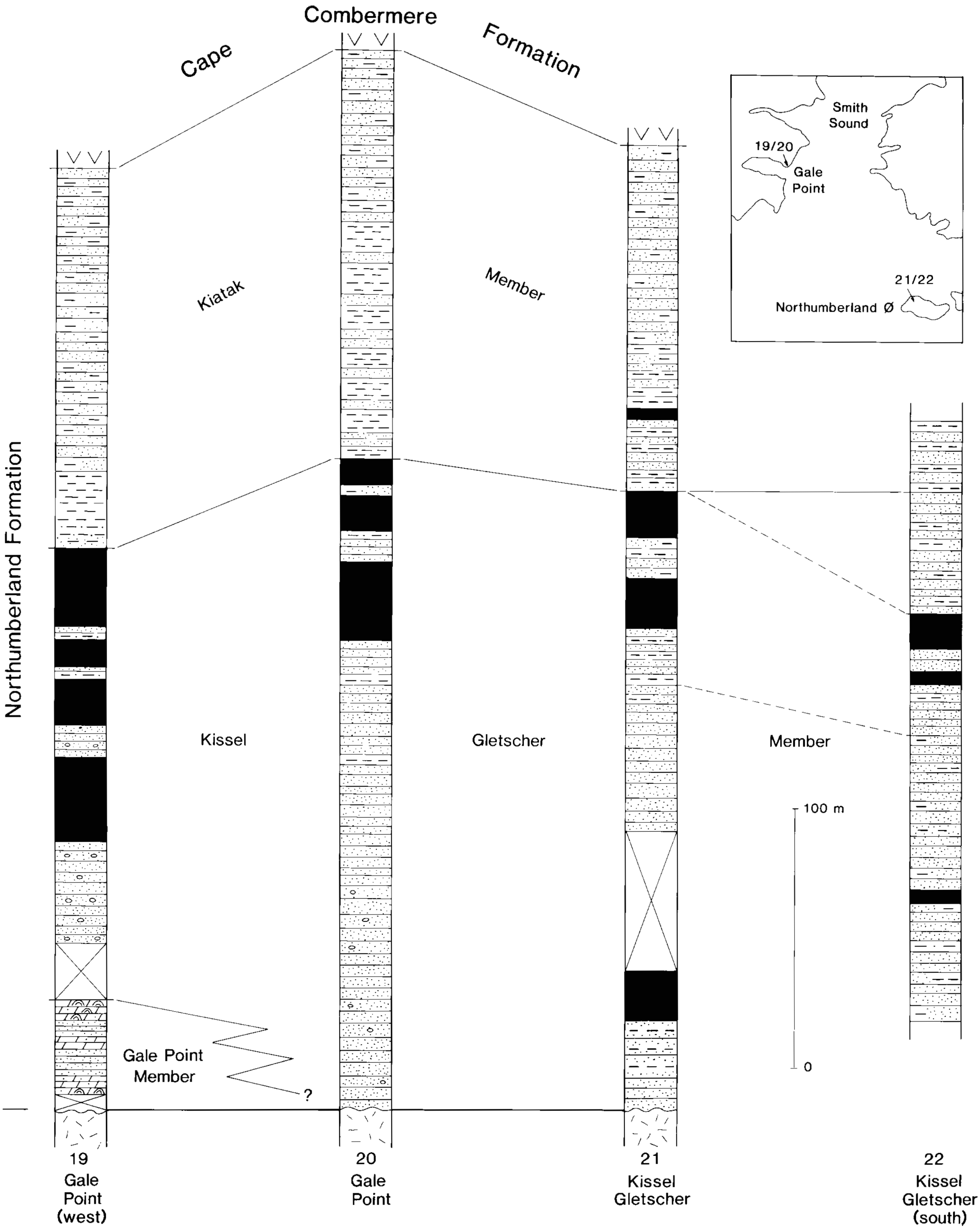


Fig. 50. Generalised sections of the Northumberland Formation from Northumberland Ø and Gale Point. Sections compiled from data in Frisch & Christie (1982; section 19), Christie (1975; section 20) and Jackson (1986; sections 21, 22); the latter with modification for thickness. Sections 21, the type section, and 22 are located in Fig. 48; Canadian sections are located in Fig. 54.

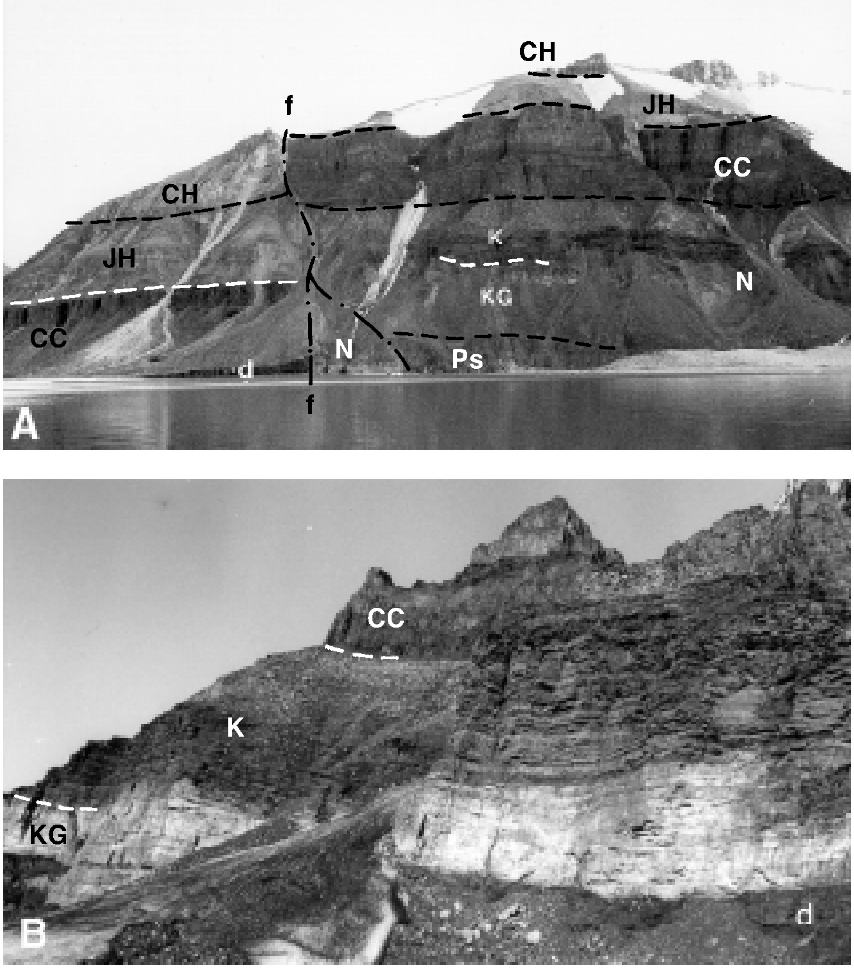


Fig. 51. Northumberland Formation (N) in the type area at western Ujâgsuk, Kissel Gletscher, Northumberland Ø. **A:** the type section above the cystalline shield (Ps) with moraine of Kissel Gletscher on the right; **B:** section to the south along Kissel Gletscher illustrating Kissel Gletscher (KG) and Kiatak (K) Members. CC = Cape Combermere Formation, JH = Josephine Headland Formation, CH = Clarence Head Formation, d = dolerite. Sections are given in Fig. 50; for map location, see Fig. 48.

Frisch & Christie (1982, fig. 2) but at Clarence Head includes the basal 15 m of strata of unit II, i.e. all sediments below the first major basaltic body. In the section at Clarence Head measured by Jackson (1986), the formation includes his unit 1 and the basal 60 m of unit 2. In the 6-unit scheme erected by Dawes *et al.* (1982a) for Ellesmere Island and Northumberland Ø, the strata correspond to the 'Basal Sandstone unit' (unit 1). However, it should be noted that at Gale Point, strata of overlying units, i.e. units 2 and 3 of Dawes *et al.* (1982a) and units II and III of Frisch & Christie (1982), are also referred to the Northumberland Formation, with the exception of a 39 m thick igneous unit that caps the section. This is regarded as the lowest strata of the Cape Combermere Formation.

Name. After Northumberland Ø, the middle and largest of three islands separating Murchison Sund and Hvalsund (Figs 2, 48).

Distribution. In Greenland, Prudhoe Land to the southeast of Diebitsch Gletscher, Northumberland Ø, and western Steensby Land; in Canada at Gale Point, south of Cadogan Inlet and at Clarence Head (Fig. 12). At Goding Bay the sections measured by Christie (1975), Frisch & Christie (1982) and Jackson (1986) are of strata stratigraphically higher than the Northumberland Formation. The one contact between Thule strata and crystalline shield in the area, north of Sparks Glacier, is interpreted as a fault boundary involving the Cape Combermere Formation (see Fig. 80).

Geomorphic expression and colour. Pale weathering, partly recessive and with resistant basic sills.

Type and reference sections. The type section is on the western side of Ujâgsuk, along Kissel Gletscher, Northumberland Ø (section 21, Figs 50, 51). (It should be noted that Jackson (1986) erroneously refers to the locality as 'Cadogan Glacier'.) Reference sections occur along Parish Gletscher and Robins Gletscher (e.g. fig. 7 *in* Dawes *et al.*, 1982a), at Barden Bugt (section 23, Fig. 52) and at Gale Point (sections 19, 20, Fig. 50).

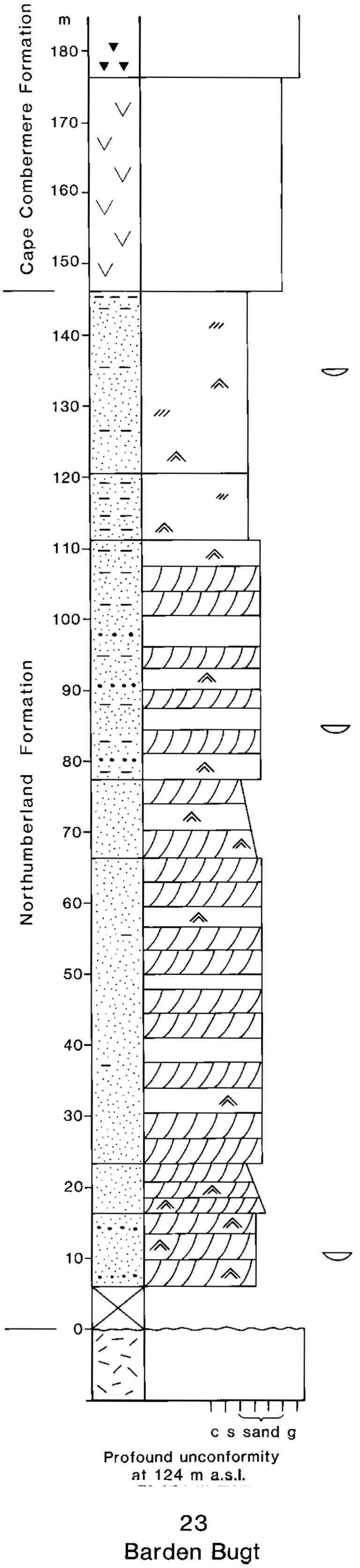


Fig. 52. Stratigraphic log of the Northumberland Formation from the south side of Barden Bugt; compiled mainly from data in O'Connor (1980). Section is located in Fig. 70.

Fig. 53. Basal strata of the Nares Strait Group. Thin-bedded, ripple-marked sandstones of the Northumberland Formation overlying biotite schists of the Precambrian shield. Only a thin weathering zone is present and no basal rudaceous rocks. East side of Bowdoin Fjord (Fig. 98).

Thickness. At Gale Point strata are between 265 and 350 m thick with up to 340 m on Northumberland Ø, thinning east to less than 50 m at Granville Fjord (Fig. 12). The thinnest section seen is in the Clarence Head – Cape Combermere area where between 10 and 75 m of strata are preserved, although tectonic disturbances have affected thicknesses (Frisch & Christie, 1982; Jackson, 1986; Figs 49B, 75).

Dominant lithology. Varicoloured sandstones, mainly quartz arenites, with red and green shale and siltstone units. At Gale Point additional lithologies in the lower part of the formation are calcareous sandstones and impure dolomites with stromatolites. Where examined basal beds rarely show rudaceous material (Fig. 53). Basic sills that both bifurcate and change stratigraphic level are prominent in the middle part; some basaltic bodies, for example the basic sill complex at Gale Point (Figs 54, 55), may contain effusive material.

Depositional environment. The formation is regarded

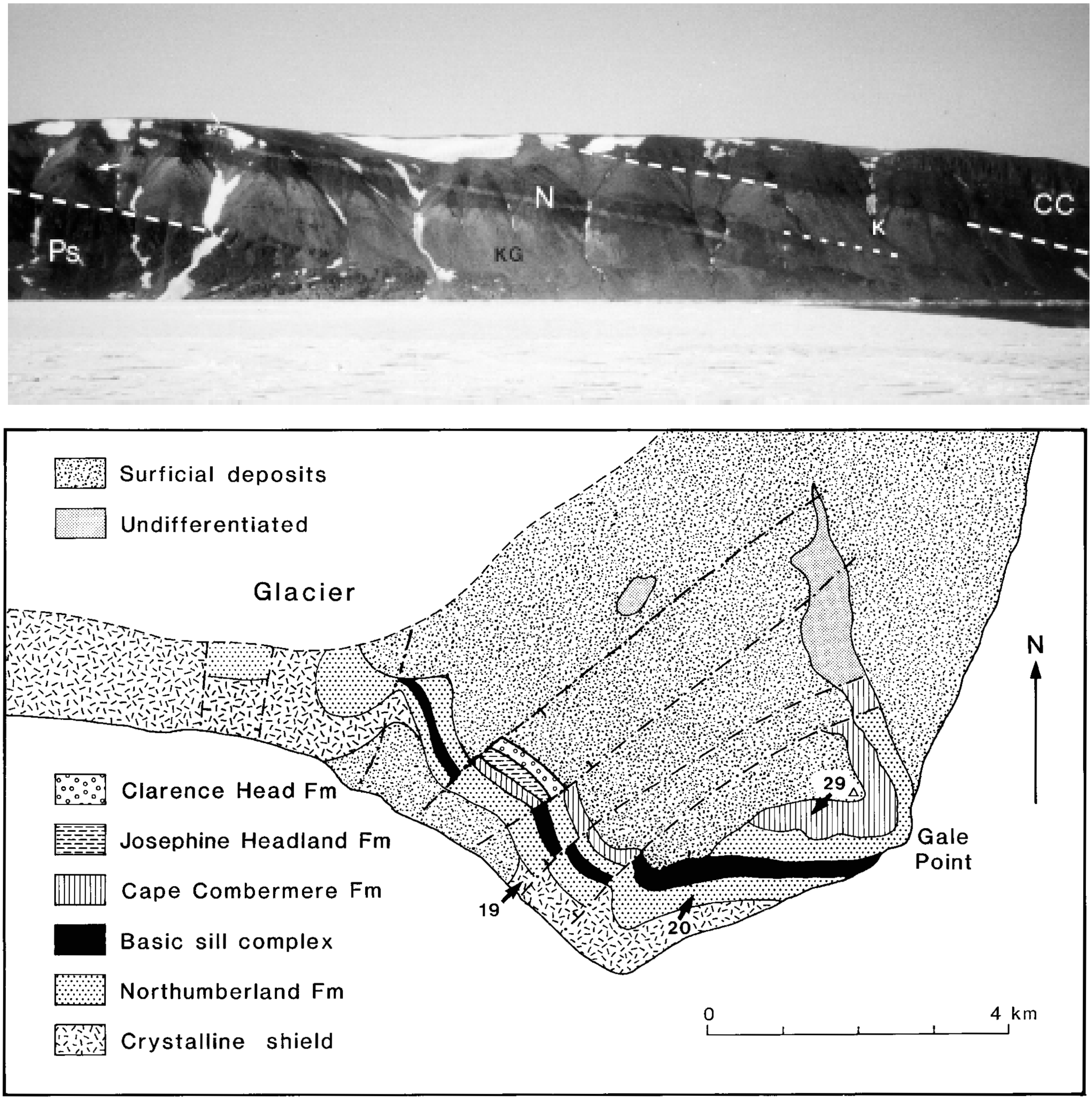


Fig. 54. Geology of the Gale Point area, Canada, showing the northernmost exposures of the Nares Strait Group overlying the Precambrian shield (Ps), and the location of sections 19, 20 and 29. Map and geology compiled from aerial photographs based on interpretation of data in Frisch & Christie (1982) and Frisch (1988); westernmost outcrops are reinterpreted as basal strata on shield rather than overlapping of the shield by ‘upper beds’ as in Frisch (1988). The photographic view of the coast south-west of Gale Point shows the Northumberland Formation (N) with dark basaltic units overlain by the Cape Combermere Formation (CC). The Kissel Gletscher (KG) and Kiatak (K) Members are shown. The dark rocks arrowed on left may represent dolomitic strata that farther west form the Gale Point Member of section 19 (see Fig. 50). The triangle marks summit at about 410 m a.s.l. Photo: G. D. Jackson. For location, see Fig. 2.

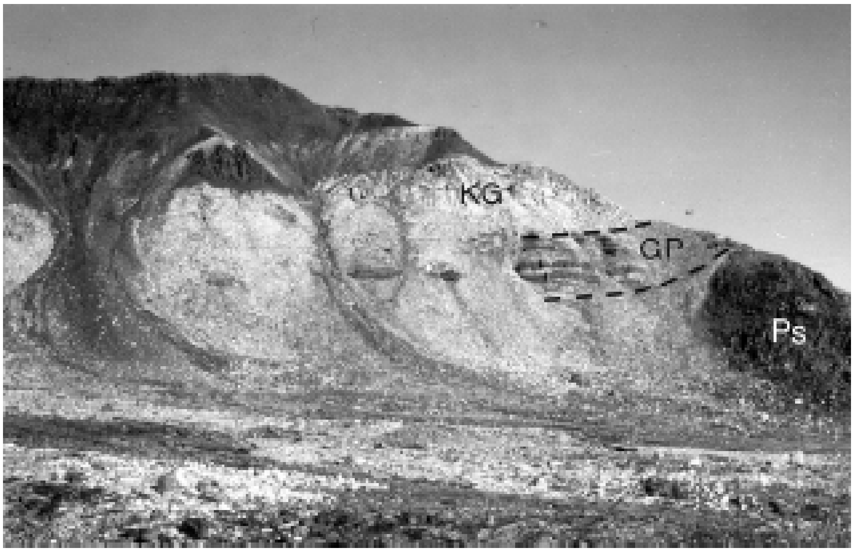


Fig. 55. Section west of Gale Point showing the Gale Point (GP) and Kissel Gletscher (KG) Members of the Northumberland Formation overlying the Precambrian shield (Ps). The dark basaltic units capping the hill form a sill complex (see Fig. 54) that may contain effusive rocks. This is the base of the type section of the Gale Point Member; section 19, Fig. 50; for map location see Fig. 54. Photo: T. Frisch.

as a mixture of subtidal to supratidal deposits; low-energy environments with stromatolites gave way to intertidal and floodplain deposits, reverting finally to shallow shelf deposition.

Fossils. Stromatolites.

Boundaries and correlation. The formation rests on crystalline rocks of the shield and it is overlain by the Cape Combermere Formation (Figs 49, 50, 51). The contact to the overlying formation is often with igneous rock but a regional conformable relationship is inferred. At Clarence Head the contact with crystalline basement is tectonised and Frisch & Christie (1982) regard the lower boundary as a fault (Figs 49B, 75).

There is no visible correlation with the Smith Sound Group of the northern platform but coeval strata may be present in the basal part of the Cape Camperdown Formation (Figs 11, 120).

Subdivisions. Where the formation is thickest, three members are recognised. The Kissel Gletscher and Kiatak Members are present on both sides of Nares Strait; the Gale Point Member appears to be restricted to Ellesmere Island.

Gale Point Member

new member

Composition. This member corresponds to unit I of Frisch & Christie (1982) as exposed west of Gale Point. A small outcrop at MacMillan Glacier some 40 km to the north, provisionally correlated with the Gale Point section by these authors, is referred to the Rensselaer Bay Formation (Smith Sound Group).

Name. After Gale Point at the northern entrance of Cadogan Inlet (Figs 2, 54).

Distribution. West of Gale Point. The member cannot be recognised in the section logged by Christie (1975) in the sea-cliffs immediately south-west of Gale Point (section 20, Fig. 50), although photographic interpretation suggests that dark dolomitic rocks, characteristic of the member, occur nearby (Fig. 54).

Geomorphic expression and colour. Pale weathering, moderately recessive and poorly exposed.

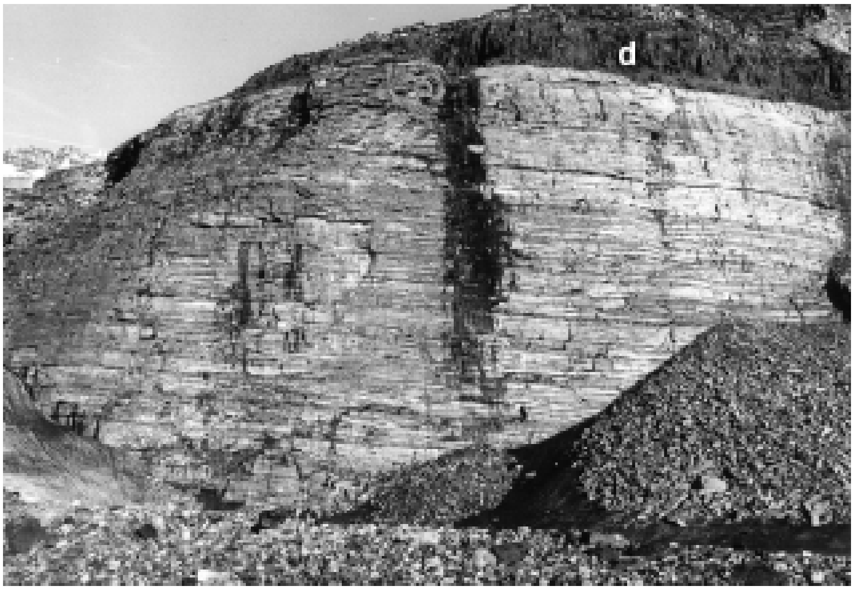
Type section. West of Gale Point (section 19, Figs 50, 55).

Thickness. Up to 40 m.

Lithology. The main lithologies are dolomitic sandstone, subarkose and stromatolitic dolomite. The sandstones are thin bedded, white, buff or pale green in colour, with cross-bedding and occasional ripple marks. The dolomites, which alternate with the sandstones in the bulk of the member, contain chert clasts, have shale and sandy partings and display domal stromatolites.

Depositional environment. Deposition was probably in an overall supratidal environment in which carbonate precipitation and algal growth were periodically

Fig. 56. Thin- to medium-bedded mottled sandstones in the upper part of the Kissel Gletscher Member of the Northumberland Formation. Low-angle cross-bedding is depicted by colour variation. A basaltic sill (d) caps about 60 m of strata. Eastern side of Kissel Gletscher, Northumberland Ø.



stifled by influx of detrital material. According to Frisch & Christie (1982) the lack of interstitial clastics, relatively steep walls and absence of lateral linkage favour the stromatolites having formed in a rapidly subsiding or sediment starved region, such as a lagoon or supradeltaic lake.

Fossils. Domal stromatolites up to 15 cm high (see Frisch & Christie, 1982; fig. 14).

Boundaries and correlation. The upper and lower contacts are poorly exposed, but the Gale Point Member probably directly overlies crystalline basement and in the type section it has a conformable contact with the Kissel Gletscher Member above (Fig. 55). The relationship to the Kissel Gletscher Member away from the type section is unknown; possibly the two members interdigitate.

Kissel Gletscher Member

new member

Composition. This member corresponds to the basal strata of unit 1 of Northumberland Ø of Dawes (1976b) and is grossly equivalent to sub-units 1A and 1B as described by Jackson (1986). At Gale Point it comprises units 1 to 7 of Christie (1975) and all but the uppermost 25 m of unit II of Frisch & Christie (1982).

Name. After Kissel Gletscher, north-west Northumberland Ø (Figs 2, 48).

Distribution. Northumberland Ø, western Steensby Land, Gale Point, Cape Combermere and probably Prudhoe Land. The light-coloured lower part of the thin and faulted section at Clarence Head (Frisch & Christie, 1982, fig. 5) is referred to this member (Fig. 49B).

Geomorphic expression and colour. Buff to orange weathering, partly recessive with distinct cliff-forming beds and resistant basic sills mainly in the upper part (Figs 49A, 54).

Type and reference sections. The type section is the same as for the formation, viz. western side of Ujâsuk, along Kissel Gletscher, Northumberland Ø (section 21, Figs 50, 51). Reference sections are at Gale Point (sections 19, 20, Fig. 50).

Thickness. About 200 m at Kissel Gletscher and Gale Point, thinning to the south and east; at Kap Trautwine about 70 m. Jackson (1986) records a southward thickening of 36 m over about 1.5 km in the upper beds at Kissel Gletscher (Fig. 50).

Lithology. The member is typified by planar, generally medium-bedded, fine- to medium-grained, massive to laminated multicoloured quartz arenites characterised by varying degrees of mottling (Fig. 56). Some units are distinctly thin bedded and platy (~ 10 cm), others thick to very thick bedded. Lenticular beds characterise some outcrops. Cross-bedding and symmetrical ripple marks occur throughout; at Kissel Gletscher some units are characterised by strong bimodal cross-beds (Jackson, 1986). At the base of some beds there are scours, as well as occasional, thin, coarse to very coarse layers commonly showing minor channels. At Gale Point sandstones are locally conglomeratic with quartz granules and pebbles, occasionally subangular, occurring in small diffuse concentrations. In the upper part of the member mud flakes are common in some beds. At Kissel Gletscher and Barden Bugt upward-fining cycles up to a couple of metres occur.

Thin interbeds of green, red and purple shale occur sporadically and these show profuse mudcracks. Shale increases in abundance in the upper part, and in the upper 20 m Jackson (1986) describes wavy to lumpy beds containing shale chips and balls.

The arenites are composed of rounded to subrounded, locally subangular, quartz that often shows dusty borders; some rocks approach subarkose. Sericite may be present interstitially and in some rocks forms a sparse matrix, very occasionally with carbonate.

Much of the Kissel Gletscher Member is composed of pale sandstones – grey, pink, pale green, buff and even white – but particularly in the lower part units vary from purple and maroon to orange and brownish colours. Reduction spots and irregular colour patterns are common. Reduction of iron is a widespread feature and it appears to have taken place on a large scale; some pale sandstones contain only small relict patches of red coloration.

On Northumberland Ø and at Gale Point the uppermost part of the member contains prominent igneous bodies up to 30 m thick, and in the Gale Point west section igneous rocks form at least 50% of the member (section 19, Fig. 50). Where examined in Greenland the basaltic rocks are sills. At Gale Point, Christie (1975) suggests that some may be effusive; Frisch & Christie (1982) state that at least three of the four igneous bodies in the Gale Point west section are sills.

Depositional environment. The Kissel Gletscher Member probably represents a marine transgression and the incoming of major detrital sedimentation that terminated the protected low-energy environment of the Gale Point Member. Bimodal cross-beds indicate a tidal environment. According to Jackson (1986) the nature and abundance of compound cross-beds suggest deposition in sand ridges and waves in a shallow shelf, while the incoming of shale in the upper part may represent relatively protected deposition behind a barrier island or in a lagoon.

Fossils. None known.

Boundaries. The lower boundary is the formational boundary except in the Gale Point west section where the member is underlain by the Gale Point Member. Where basaltic material is absent the upper boundary to the Kiatak Member is gradational and taken at the incoming of abundant thin red beds; it is often seen as a distinct colour change (Fig. 51). At Gale Point and in places on Northumberland Ø the uppermost rock is basalt taken to be intrusive.

Kiatak Member

new member

Composition. On Northumberland Ø the Kiatak Member corresponds to the middle and upper strata of unit 1 of Dawes (1976b), being equivalent to sub-units 1C and 1D as described by Jackson (1986). At Gale Point it comprises units 8–10 of Christie (1975), and the upper 25 m of unit II and all but the upper igneous part of unit III of Frisch & Christie (1982).

Name. After Kiatak, the Eskimo name for Northumberland Ø (Figs 2, 48).

Distribution. Northumberland Ø, western Steensby Land and Gale Point. The red beds in the upper part of the faulted section at Clarence Head may belong to the member.

Geomorphic expression and colour. A generally recessive unit, with lower part dark weathering and locally cliff-forming; upper part is pale weathering and often scree covered (Fig. 51).

Type and reference sections. The type section is the same as for the formation, i.e. western side of Ujâgsuk, along Kissel Gletscher (section 21, Figs 50, 51). Reference sections are at Gale Point (sections 19, 20, Fig. 50).

Thickness. In Greenland up to about 135 m; at Gale Point between 85 and 210 m of strata are referred to the member.

Lithology. The member is an interbedded sandstone-siltstone-shale sequence. In Greenland it shows variable lithology. The lower part is composed of purple, red to brownish red, very thin- to medium-bedded sandstones, with red and green siltstone and shale (Fig. 51); the upper part contains much less argillaceous material and fewer red beds. In the upper part sandstones are mainly buff to pale pink, in places white, and they are planar to lenticular, medium to thick bedded. There are also some pink sandstone beds in the lower part of the member; these have an irregular, rather lenticular form. At Gale Point the member is dominated by fine-grained lithologies: interbedded, red, green and buff, often banded variably silty and micaceous sandstone, siltstone and shale.

The sandstones are fine to medium grained, composed of subrounded to subangular quartz with up to 10% feldspar and with mica flakes and disseminated hematite. They are often finely laminated and frequently have green shale partings that show mudcracks. Cross-bedding and ripple marks occur but they vary markedly in frequency at different levels of the member. Some sandstone beds contain intraformational conglomerates with shale flakes and clasts.

In Greenland purple and green shale beds are up to 35 cm thick, usually containing thin sandstone and siltstone horizons. Jackson (1986) notes that some red and green beds are composed of mud balls 6 cm in diameter. At Gale Point shale and siltstone form thicker beds; in the western section Frisch & Christie (1982) report a 20 m unit of green shale.

Depositional environment. This sandstone-siltstone-shale succession is thought to represent a complex of intertidal to supratidal deposits, more specifically to a flood plain environment. According to Jackson (1986) basal strata contain beach deposits, while the lower part of the member in the type section is dominated by meandering stream channel and overbank deposits formed in a low-energy environment. The uppermost strata of relatively clean sands are taken to represent intertidal shelf deposition.

Fossils. None known.

Boundaries. The lower boundary of the member is generally with sill rock of the Kissel Gletscher Member; on Northumberland Ø, as described above, where a sedimentary contact is preserved, it is gradational. The upper boundary is that of the formation, viz. sharp contact with igneous rock of the Cape Combermere Formation.

Cape Combermere Formation

new formation

Composition. Volcanic strata with interbedded red beds, first recognised on Ellesmere Island, form part of Christie's (1962a, b) 'little disturbed formation 2'; in Greenland on Northumberland Ø the strata were placed by Dawes (1975) as part of the lowest member of the Wolstenholme Formation being later defined as unit 2 (Dawes, 1976b). The formation equates with unit II of the Wolstenholme Formation of Frisch *et al.* (1978) and Frisch & Christie (1982) as described between Clarence Head and Goding Bay, although at Clarence Head basal sediments beneath the first major igneous body (12–15 m thick) are herein referred to the Northumberland Formation. In the 6-unit scheme erected by Dawes *et al.* (1982a) the formation equates with the 'Basalt – Red Bed unit' except that only the uppermost 39 m of the section west of Gale Point described by Frisch & Christie (1982, fig. 2) are included in this formation, the underlying strata of units 1, 2 and 3 being referred to the Northumberland Formation. In the section measured by Christie (1975) farther east at Gale Point, the formation corresponds to units 11 to 19.

Name. After Cape Combermere, the prominent eastern cape of Smith Bay (Figs 2, 57).

Distribution. In Greenland, Prudhoe Land south-east of Sonntag Bugt, Northumberland Ø and western Steensby Land; in Canada, in all main sections between Gale Point and Clarence Head that expose the lower Nares Strait Group (Fig. 12).

Geomorphic expression and colour. Dark-weathering cliff-forming unit differentiated into dark grey to black precipitous cliffs (igneous rocks) punctuated by purple to brown recessive intervals (sediments).

Type and reference sections. The type section is at Cape Combermere (section 26, Figs 57, 58); good reference sections occur on Northumberland Ø (section 27, Fig. 58, and at Robins Gletscher), and at Clarence Head, Goding Bay and at Gale Point (sections 24, 25, 28, 29, Fig. 58).

Thickness. Basaltic sills, the largest of which is nearly 140 m thick, form an uncertain and varying thickness. Although all sills may not be contemporaneous and coeval with the extrusive strata (i.e. sills occur in the

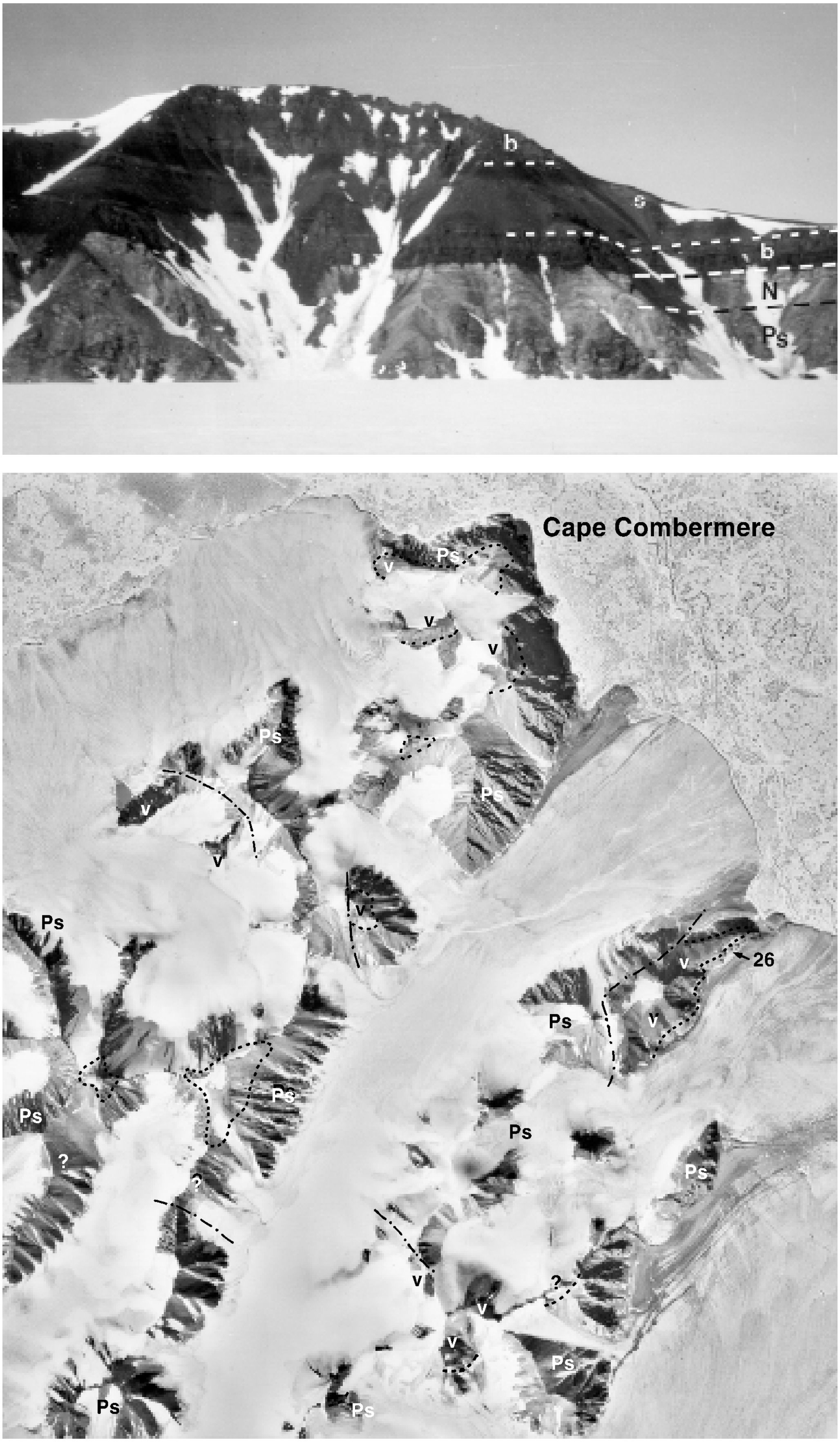


Fig. 57. Geology of the Cape Combermere area, Canada, showing the location of the type section of the Cape Combermere Formation (section 26).
Coastal view, above: Dark Cape Combermere Formation capping cliffs with sedimentary member (s) separating lower and upper basalt members (b). Height of section above the glacier is about 300 m. Section 26, given in Fig. 58, was measured on the lower slopes on the right. Photo: W. C. Morgan.
Aerial view, below: small outliers of Northumberland Formation (light coloured) and Cape Combermere Formation (dark, also marked v) on the Precambrian shield (Ps). Compilation and interpretation are by the author from data supplied by T. Frisch. East–west field of view is about 10 km; highest nunatak is above 760 m. A ground view of this nunatak country is given in Fig. 13B. Photo: E31-124, National Air Photo Library, Ottawa.
For location, see Fig. 2.

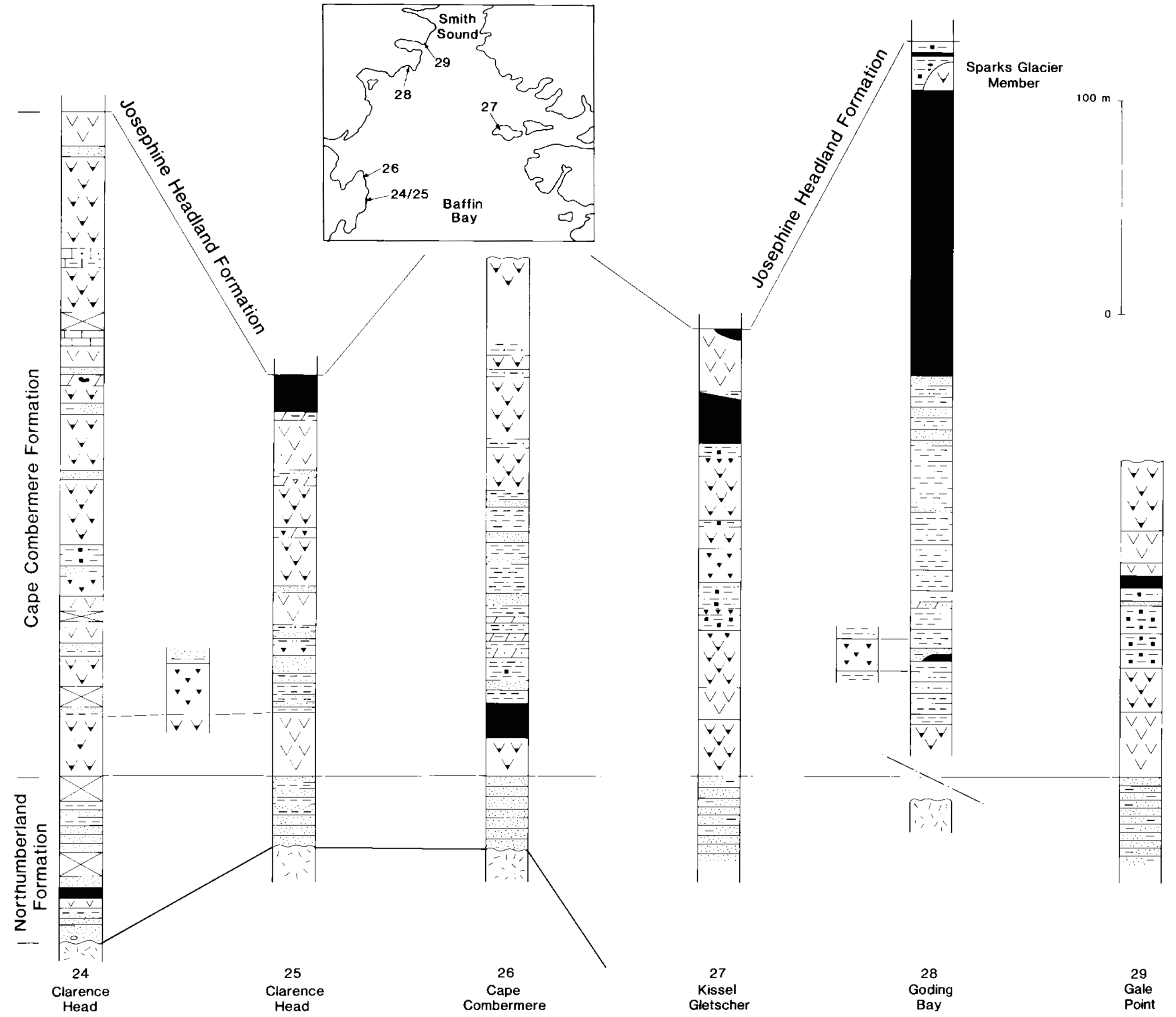


Fig. 58. Generalised sections of the Cape Combermere Formation. Canadian geology compiled from following sources: section 24 from Jackson (1986), sections 25, 26, 28 and 29 from data in Christie (1975) with some modification in section 28 from Frisch & Christie (1982) and Jackson (1986). Section 27 is a composite section from both sides of Kissel Gletscher. Dykes and low-angle sills are not shown. Part sections illustrate volcanic breccia units in nearby sections. Section locations: 24 and 25, Fig. 75; 26, Fig. 57; 27, Fig. 48; 28, Fig. 80; 29, Fig. 54.

overlying Baffin Bay Group and younger strata), thicknesses given here include all concordant sheets of basalt. So defined the formation varies in thickness from more than 340 m at Goding Bay (base not seen) and 310 m at Clarence Head to about 200 m on Northumberland Ø to less than 100 m in Prudhoe Land (Fig. 12). At Bowdoin Fjord and Granville Fjord a single basic sheet of uncertain origin with a minimum thickness of 15 m is taken to represent the distal edge of the formation in the east (see Figs 87, 98).

The thickness difference of 120 m between sections spaced about 1 km apart at Clarence Head (sections 24, 25, Fig. 58) may not reflect true stratal variation. These sections, as elsewhere, include precipitous units the thicknesses of which are estimates (Frisch & Christie, 1982, p. 3; R. L. Christie, personal communication, 1975).

Lithology. The formation consists of a complex suite of effusive, hypabyssal and pyroclastic basaltic rocks with interbedded water-lain volcaniclastic and clastic sediments and subordinate siliciclastic carbonate rocks.

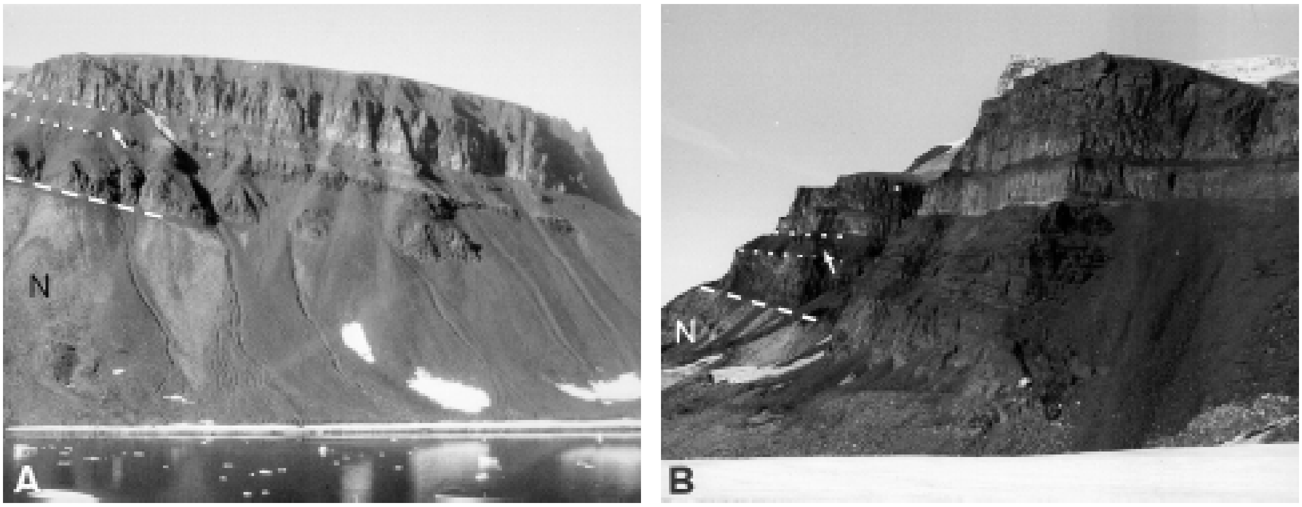


Fig. 59. Cape Combermere Formation, Canada and Greenland, illustrating lower and upper resistant basalt units separated by bedded volcaniclastic unit (arrowed). N = Northumberland Formation. **A:** Gale Point seen from the south, photo: K. W. Christie; **B:** eastern Kissel Gletscher, Northumberland Ø, viewed to the north. For location, see Figs 48 and 54.

Throughout much of its exposure the formation shows a tripartite division: a varied unit of recessive sandstone, siltstone and shale with diverse volcanic, pyroclastic and volcaniclastic rocks separates upper and lower massive units of lava and sill rock (Figs 57, 59, 71). At Clarence Head the formation is composed of at least 12 basaltic bodies separated rather regularly by sediments (Fig. 58).

Igneous rocks generally constitute between 60 and 80% of the formation. At Goding Bay igneous and sedimentary rocks make up about equal volumes of the incompletely exposed section. Pyroclastic rocks are a notable component of main Greenland exposures and at Gale Point; in contrast such rocks are less common at Clarence Head and Cape Combermere and they have not been recognised in the section at Goding Bay studied by Frisch & Christie (1982) and Jackson (1986).

Distinguishing between flows and sills can be extremely difficult, particularly where contacts with host rock are not exposed. Based on the complete sections effusives appear to dominate over intrusives. Observations taken at face value can be conflicting; thus at a single locality good amygdaloidal texture may suggest a flow top, elsewhere basalt of the same body can appear to be intrusive. Such relationships are taken to indicate the near-surface origin of some of the sills with perhaps lava being intruded down-slope into older strata.

Lavas and sills. Flow and sill rock are very similar in appearance, weathering dark grey to greenish-grey. Some lavas have a purplish hue on fresh surfaces and commonly a purplish-brown, even reddish, weathering colour. Some have red tops. All flows examined show some degree of vesicular or amygdaloidal structure. Confirmed sill rock, with chilled contacts, may also contain amygdules. Petrographically both lava and sill rock are similar; microporphyritic, sub-ophitic clinopyroxene basalt with or without olivine as a phenocryst phase. Olivine typically shows alteration to semi-opaque oxides. Textures may be hyalo-ophitic, intersertal or intergranular; the lavas show a wider range of textural variation than the sills with transitions to vesicular basalt and in places with stellate aggregates of feldspar laths.

Individual sills range from less than a metre thick to the gabbro at Goding Bay 130 to 140 m thick (Frisch & Christie, 1982; Jackson, 1986). This sill has baked the adjacent sediment; it shows columnar jointing throughout suggesting that it represents a single cooling unit. Many sills are between 10 and 25 m thick. Flows range from 2 m thick to the 43 m flow near the top of section 24 at Clarence Head (Fig. 58).

Typical flows are characterised by heterogeneous tops that show upward increasing abundance and size of vesicles and amygdules or the presence of a fragmental or brecciated zone. Vesicular basalt also occurs at the base of some flows but appears impersistent along strike. Amygdules are more common than crystal-free vesicles; mineral infillings are calcite, siderite, zeolites and silica minerals; the latter often shows spherulitic texture. Some lavas are locally vuggy and they can contain reddish-brown agates; at Robertson Fjord, Robins Gletscher and Gale Point agates are up

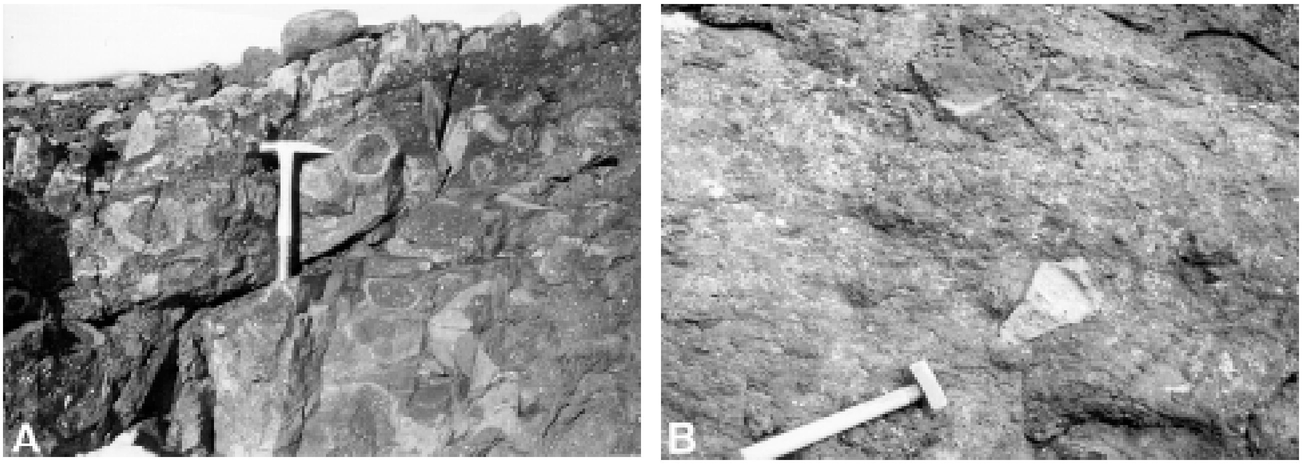


Fig. 60. Volcanic agglomerates with carbonate-rich matrices from the Cape Combermere Formation. **A:** bombs of amygdaloidal basalt containing tuffaceous fragments with rims of concentric carbonate laminae. Clarence Head, section 25, photo: R. L. Christie; **B:** subangular to rounded fragments of varying composition and up to several decimetres in size. Josephine Headland, section 27.

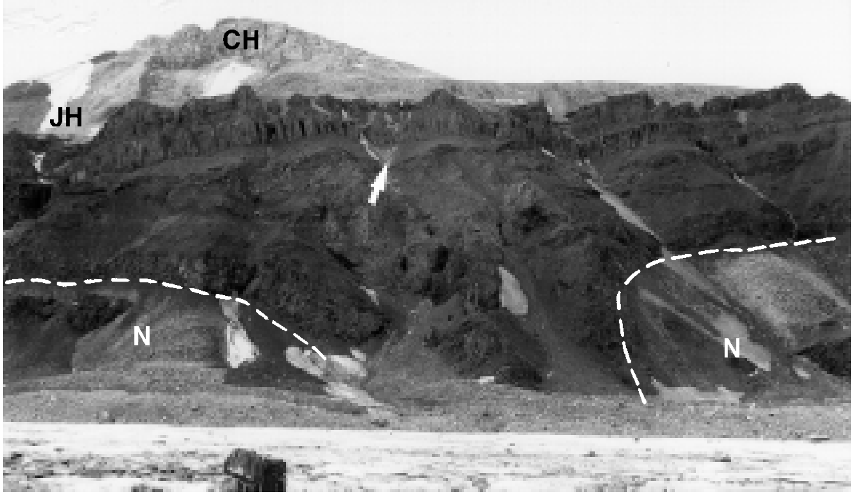
to 10 × 30 cm in size. Some vugs contain ornamental quality chalcedony and quartz crystals.

The fragmental flow tops have a rubbly to blocky appearance and are commonly brecciated and agglomeratic; some tops have tuffaceous material between blocks. Such rocks commonly are enriched in carbonate, both in the matrix or cavity-fill and in small irregular veins. Flow-top breccia may contain a variety of pyroclast composition, volcanic as well as volcaniclastic. Pillow-like structures have been recognised at several localities, for example at Clarence Head and on Northumberland Ø; loose material from Robins Gletscher shows the unmistakable chilled dense to glassy margins characteristic of water-lain pillow lava. Flows display a variable degree of vertical columnar jointing but it is not a particularly conspicuous feature.

Volcanic breccia and agglomerate. Discrete units of pyroclastic rocks up to 25 m thick occur; the thickest are in the lower part of the formation (Fig. 58). Breccias are dark grey to purplish-red weathering and cliff-forming and contain a variety of angular to rounded volcanic and sediment enclaves. At Kissel Gletscher these are composed of diverse basaltic rocks, many of which are vesicular and carbonate-rich, pumice, some light coloured to brownish altered volcanic rocks, some of which are quartz porphyries, yellow and red quartzite and baked siltstone, together with volcaniclastic rocks that are characterised by angular to subrounded quartz grains. Phenocrysts of quartz and feldspar in the porphyries may be badly corroded in an altered fine-grained cryptocrystalline matrix.

Enclave sizes are centimetre to metre scales. Vol-

Fig. 61. A volcanic vent in the Cape Combermere Formation on the western side of Robins Gletscher, Northumberland Ø. For location, see Fig. 48. The vent feeds the lower part of the formation since the sedimentary unit (arrowed) and the uppermost columnar-jointed basalt continue uninterrupted above the vent. N = Northumberland Formation with basalt sills, JH = Josephine Headland Formation, CH = Clarence Head Formation. Height of basalt section at vent about 300 m.



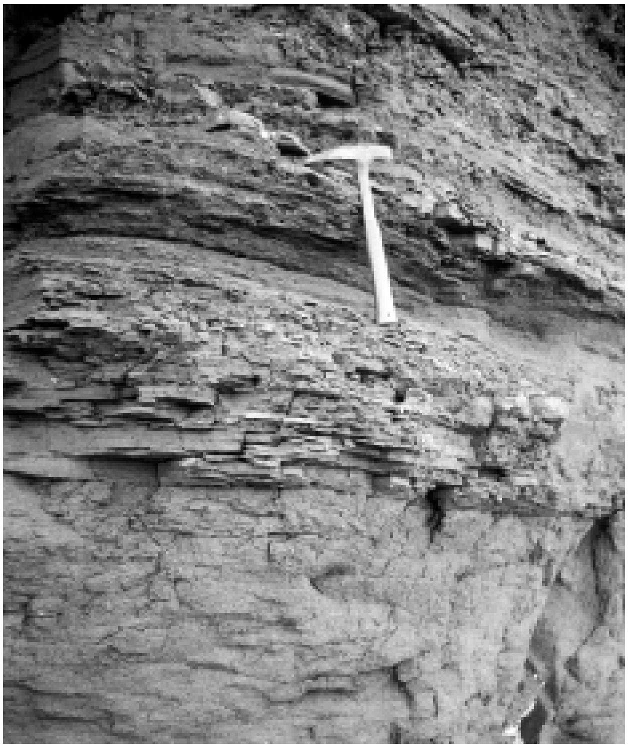


Fig. 62. Bedding characteristics of clastic and volcaniclastic sediments of the Cape Combermere Formation at Barden Bugt (Fig. 70). Red to brown, interbedded fine to very coarse sands with occasional pebble beds. Photo: B. O'Connor.

canic bombs are smooth-surfaced and pitted, mainly composed of black to dark grey amydaloidal basalt with calcite fillings. Some show distinct rimming. At Clarence Head, a 3 m thick carbonate-matrix agglomerate has volcanic bombs up to 25 cm that have well developed rims of carbonate (Fig. 60). At Robins Gletscher an irregular mass of rubbly agglomerate, composed mainly of rounded to subrounded basalt blocks up to 50 cm long, occurs in association with a possible volcanic feeder (Fig. 61).

Sedimentary rocks. Sediments are of wide diversity dominated by sandstone-siltstone-shale sequences with minor carbonate and volcaniclastic rocks. Volcaniclastic rocks are best developed on Northumberland Ø and at Gale Point where they characterise the middle unit of the formation; in more eastern outcrops and in southern sections in Ellesmere Island, sediment packages apparently contain less pyroclastic material. For example, at Cape Combermere only "a few centimetres of basaltic tuff" have been noted (Frisch & Christie, 1982, p. 7).

Clastic rocks are characteristically red to brown, thin-bedded and recessive, dominantly fine to medium grained and often have hematitic laminae. At the type section at Clarence Head, clastic rocks form interflow packages up to 15 m thick of arkosic sandstones, commonly with red or green shale partings, interbedded with shale and siltstone. Ripple marks and desiccation cracks occur; cross-beds are very rare. Buff, orange and green sandstones occur occasionally; Jackson (1986) mentions fining-up sequences in the basal strata. At Goding Bay a 160 m section contains conspicuous red shale units and is topped by a dark, concretionary shale unit (see below, Sparks Glacier Member). Christie (1975) noted coarse-grained, green glauconitic sandstones in upper strata at Goding Bay, while at Cape Combermere grading from red sandstone to fine-grained silts in 20 cm beds was noted by W. C. Morgan (personal communication, 1990).

In eastern outcrops, e.g. in Prudhoe Land and western Steensby Land, coarser clastic material comes in, and red to brown and purple interbedded fine to coarse sandstones with occasional pebble beds, have minor red siltstone and shale (Fig. 62). Mudcracks are common, ripple marks and cross beds rare. Reduction mottling and fish-eye spots occur in some places. At Barden Bugt the sandstones have angular to subrounded quartz and occasional feldspar grains in a carbonate-rich matrix.

Carbonate strata form a minor lithology occurring as thin, brownish, less often green and grey-weathering thin limestone or dolomite beds that are variously laminated, fragmented, arenaceous and argillaceous. Jackson (1986) noted limestone-clast granule conglomerate beds, cryptalgal laminites and gypsum nodules at Clarence Head.

Volcaniclastic strata are concentrated within a very distinctive, deep red and maroon to tan succession up to 25 m thick on Northumberland Ø and up to 38 m at Gale Point (Figs 58, 59). Main rock types are fine-grained, variably silty sandstone, siltstone and shale with lithic tuff, tuff breccia and ash flow units. The silty sandstones have rounded to angular quartz grains in a very fine-grained siliciclastic matrix with occasional microscopic volcanic clasts. The rocks are irregularly thin bedded and commonly severe fracturing obscures bedding. Desiccation cracks occur on the muddy tops of some beds.

Sandstones and shales grade into lithic tuffs with increase of rock fragments, which are generally up to 5 mm in size, but occasionally larger. Fragments are fine grained and mostly volcanic but some are shale or quartzite. Main volcanic types are basaltic, quartz porphyry and glass, with some elongated carbonate-rich clasts. A similar clast suite is found in tuff breccia which forms discrete beds on Northumberland Ø. Clasts are angular to subrounded and normally below 3 cm in length.

Some chocolate-brown strata on Northumberland Ø are characterised by accretionary lapilli which are rounded to slightly ellipsoidal, generaly less than 1 cm in diameter. Normally the lapilli are densely scattered throughout the rock, but particularly in upper parts of beds; however, isolated spheroids also occur. They are characterised by a thin, dense outer shell of ash around an unstructured central part that corresponds to the tuff matrix. The spheroids are identical to rim-type lapilli described as indicative of ash-flow deposits by Schumacher & Schmincke (1991). At Clarence Head the upper parts of thin beds are described by Jackson (1986) as being "full of small spherical bodies (pisolites or concretions?)". These have an internal structure very similar to the Northumberland Ø lapilli (G. D. Jackson, personal communication, 1992).

Volcanic and sedimentary environments. The Cape Combermere Formation represents rift volcanicity in the axial parts of the basin, with contemporaneous sedimentary deposition in shallow water to terrestrial environments.

The similar chemistry of flows and sills suggests that both effusive and hypabyssal basalts belong to the same magmatic regime: a continental flood basalt province. Chemical analyses of Canadian material judged nearest to original composition fall mainly in the tholeiitic field in alkali-silica and AFM diagrams (Frisch & Christie, 1982); Greenland results plot similarly. However, some lavas tend towards andesites, and, the presence in Greenland of pyroclastic rocks with quartz porphyry clasts indicates that rock types other than 'typical' plateau tholeiitic basalts occur.

The flows, some with reddish weathering tops, are typical terrestrial effusives while local pillow structure indicates proximity of a shoreline. The sills, commonly amygdaloidal, are regarded as near-surface intrusions, an interpretation supported by dual contact relationships (extrusive-intrusive) shown by the same basaltic body. The rim-type accretionary lapilli in bedded tuffs are typical proximal deposits indicating a nearby source (within a few kilometres). One vent or feeder has been recognised on Northumberland Ø (Fig. 61).

Biogenic carbonates associated with the interflow sequences indicate prolonged association of lava extrusion and intermittent shallow water. Fining-upward cycles in lower strata suggest early fluvial deposition (Jackson, 1986) while marine conditions are thought to have prevailed in at least one area of Ellesmere Island at the end of deposition of the formation (see Sparks Glacier Member below).

Fossils. Algal laminites.

Boundaries. The Cape Combermere Formation overlies the Northumberland Formation and is overlain by the Josephine Headland Formation, and in Greenland, in eastern outcrops, by the Barden Bugt Formation (Figs 49, 58, 71).

In most outcrops lower and upper boundaries are sharp involving igneous rock, either lava or sill. On a regional scale such contacts are conformable; locally and in detail discordant relationships exist. The lower boundary is transgressive reaching different levels of the underlying Northumberland Formation; at Robins Gletscher it plunges inwards towards a vent structure. The upper boundary consistently marks the same stratigraphic level. Where the upper contact involves igneous rock in contact with the Josephine Headland Formation, the contact in detail may be very irregular (see later under Robins Gletscher Member). Where the boundary is a sediment-sediment contact, as at Goding Bay, it is conformable and well defined.

Subdivision. A regional tripartite subdivision is mentioned under *Lithology*. The similarity of sections at Cape Combermere, Gale Point and main exposures in Greenland is striking, and direct correlation is suggested between upper and lower basalt units and the middle sedimentary unit (Figs 57, 59, 61, 71). At Gale Point and Northumberland Ø, the middle unit is characterised by tuffaceous rocks. With stratigraphic logging, aided by unit by unit geochemistry, detailed regional correlation of flows may well be achieved. Pending such investigations the tripartite subdivision is not formalised. Only a peculiar concretionary shale unit, forming the uppermost strata, is separated out and described here as a formal member.

Sparks Glacier Member

new member

Composition. This member corresponds to the uppermost subunit of unit II of Frisch *et al.* (1978) and Frisch & Christie (1982) and of unit 2 of Jackson (1986), as exposed at Goding Bay, equating with unit 12 in the section measured by Christie (1975).

Fig. 63. Contact of the Cape Combermere Formation (CC) with the Josephine Headland Formation (JH). **A:** Clarence Head, calcite-veined basalt overlain by brown dolomites of the Robins Gletscher Member; **B:** Goding Bay, black shales with concretions and basaltic components of the Sparks Glacier Member (SG) overlying a diabase sill (d) and being overlain by the Robins Gletscher Member (scree covered) and interbedded sandstones and shales of the Cape Dunsterville Member. Photos: T. Frisch.

Name. After Sparks Glacier, a broad glacier reaching the sea at the head of Goding Bay (Figs 1, 2, 80).

Distribution. In all sections at Goding Bay exposing the uppermost part of the Cape Combermere Formation.

Geomorphic expression and colour. Dark weathering, generally recessive, with more resistant ribs of basaltic material (Fig. 63).

Type section. The type section is that measured by Jackson (1986) at the head of Goding Bay, close to the sections studied by Christie (1975) and Frisch & Christie (1982) (section 28, Figs 58, 80).

Thickness. Complete stratal thickness varies from 12 to 23 m. Where encroached by effusive basalt, the thickness is reduced to 9 m.

Lithology. A complex unit of sedimentary and igneous rocks dominated by dark shale. The sediments are laminated to very thin bedded, mostly black to dark green-grey to olivine green shale, slate and fine-grained siltstone. Minor, reddish quartz arenite and tuffaceous rocks are cross-bedded. Shales in the upper part of the member have a reddish hue. Rare siliceous stromatolitic dolomites are recorded by Jackson (1986).

Numerous thin basalt layers, both sills and flows, between 10 and 30 cm thick but occasionally thicker, occur parallel with bedding; Jackson (1986) also notes small dykelets. The igneous bodies often show altered margins.

Peculiar to the member are abundant iron-rich siliceous concretions, 25–30 cm in diameter, that occur mainly in the shales but also in the tuffs. These vary from spheroidal and ellipsoidal to nodular in form, are coarser grained and greener in colour than their host, and are composed of siliceous material with siderite, chlorite and hematite.

Fossils. Rare stromatolites.

Depositional environment. The presence of hematite and siderite in siliceous concretions in the black shale indicates oxidizing conditions during shallow water sedimentation. Jackson (1986), noting rare turbidite-like quartz arenite beds, suggests an origin as prodelta or offshore muds, with the associated tuffs and basaltic elements as the effects of landward volcanism in the west.

Boundaries. The lower boundary of the Sparks Glacier Member is generally planar and abrupt defined by the intrusive contact of the 130–140 m thick basic sill (Fig. 63B). This body has caused conspicuous baking of the basal strata. At one section seen by Jackson (1986), the member has a transgressive contact to a basaltic flow and only the upper part of the member is present. The upper boundary of the member is everywhere that of the formation, viz. a conformable contact with the Josephine Headland Formation (Robins Gletscher Member, Fig. 63A).

The Sparks Glacier Member, with shales and rare stromatolitic dolomites, shows a link to the overlying Josephine Headland Formation and its positioning within that formation is arguable. However, the member is placed in the Cape Combermere Formation on account of its intimate association with basalt flows, a practise also followed by Frisch & Christie (1982) and Jackson (1986).

Josephine Headland Formation

new formation

Composition. The formation equates with the uppermost part of the lower member of the Wolstenholme Formation as described by Dawes (1975) and on Northumberland Ø subsequently defined as unit 3 (Dawes, 1976b). It corresponds to unit III of the Wolstenholme Formation as defined on Ellesmere Island by Frisch *et al.* (1978) and Frisch & Christie (1982), but with the exception of Gale Point where the greater part of that unit is referred to the Northumberland Formation. In the 6-unit division pertaining to both sides of Nares Strait, the formation corresponds to the 'Dolomite–Shale unit' (Dawes *et al.*, 1982a) with the exception of the therein described strata from Gale Point.

Name. After Josephine Headland, a prominent coastal mountain in north-western Northumberland Ø (Figs 2, 48, 77).

Distribution. In Greenland, Prudhoe Land between Sonntag Bugt and Morris Jesup Gletscher, and Northumberland Ø; in Canada, in the main outcrop areas between Cadogan Inlet and Clarence Head (Fig. 12). The formation is deemed present north of Cadogan Inlet in a down-faulted block (Fig. 54) but it not represented in the sections measured farther east by Christie (1975) and Frisch & Christie (1982).

Fig. 64. Nunatak on the south side of Bamse Gletscher, northern Prudhoe Land showing the recessive Josephine Headland Formation (JH) with the intertonguing, cliff-forming unit (arrowed) as the Bamse Gletscher Member of the Barden Bugt Formation. Subdivision of Clarence Head Formation (CH) into lower thinner bedded and upper cliff-forming units is apparent. The sedimentary section, about 450 m thick, is cut by a late Hadrynian basic dyke (d). CC = Cape Combermere Formation. For regional view, see Fig. 1; for map location, see Fig. 27.

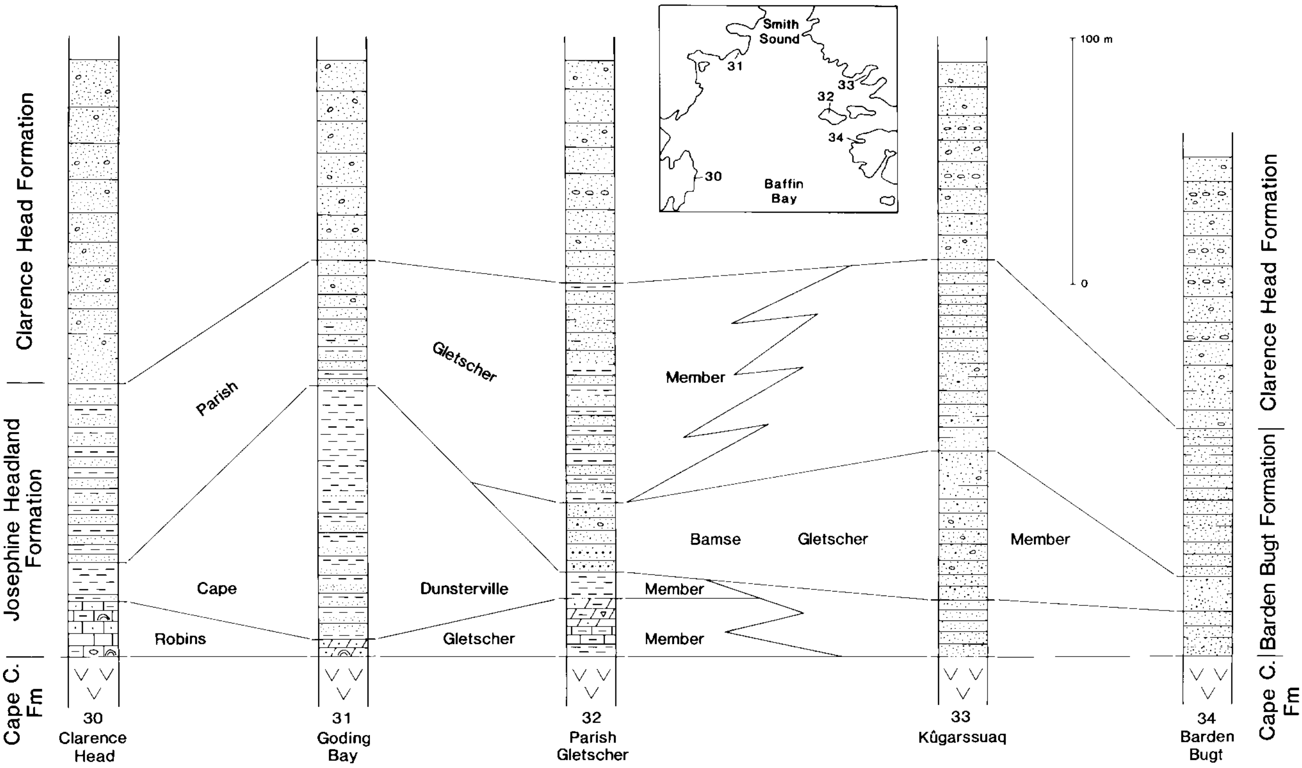


Fig. 65. Generalised sections of the Josephine Headland, Barden Bugt and Clarence Head Formations. Sections 30 and 31 are compiled from Jackson (1986); sections 33 and 34 partly based on data in O'Connor (1980). A stratigraphic log of section 32, the type section of the Josephine Headland Formation, is given in Fig. 66. Section locations: 30, Fig. 75; 31, Fig. 80; 32, Fig. 48; 33, Fig. 83; 34, Fig. 70.

Geomorphic expression and colour. A pale reddish weathering, generally recessive unit, often poorly exposed, with some prominent resistant benches (Figs 49, 64).

Type and reference sections. The type section is on the west side of Parish Gletscher, Northumberland Ø (section 32, Figs 65, 66); reference sections are at Clarence Head and Goding Bay (sections 30, 31, Fig. 65), cliffs on both sides of Kissel Gletscher (Figs 48, 49A) and at Bamse Gletscher (Fig. 64).

Thickness. Ranges from about 107 m at Clarence Head to 160 m at Goding Bay, possibly a little more in northern Prudhoe Land (Fig. 12).

Dominant lithology. Wide lithological variation exemplified by three members (Fig. 65). From base upwards main rock types are: limestone, dolomite and shale with a minor volcaniclastic bed, interbedded sandstone and shale with prominent red shale units and alternating sandstone-shale sequence with possible volcaniclastic elements.

Depositional environment. The Josephine Headland Formation marks a marine transgression across the volcanic landscape of the Cape Combermere Formation. A shallow shelf is seen as the overall depositional environment, basal carbonates being deposited initially when the input of detrital clastics was at a minimum, followed by clastic-dominated intertidal to fluvially influenced supratidal deposits (Jackson, 1986). Nearby volcanic activity prevailed for at least part of the time interval recorded by the formation.

Fossils. Stromatolites and algal laminites in basal beds.

Boundaries and correlation. The Josephine Headland Formation overlies, apparently conformably, strata of the Cape Combermere Formation; in places the contact is with a basic sill referred to that formation (Fig. 58). It is overlain conformably by the Clarence Head Formation and in Greenland the formation interdigitates with the Barden Bugt Formation (Figs 64, 65).

The relationship to strata of the Smith Sound Group is not exposed but the Pandora Havn Formation of that group is a possible correlative to the Josephine Headland Formation over the basin margin (Fig. 120).

Subdivisions. The Josephine Headland Formation is subdivided into three formal units: from below, the Robins Gletscher, Cape Dunsterville and Parish Gletscher Members.

Robins Gletscher Member

new member

Composition. The member equates with the lower subunit of the Dolomite-Shale unit of the Wolstenholme Formation as described from Clarence Head, Goding Bay and Northumberland Ø by Dawes *et al.* (1982a), and with sub-unit 3A of Jackson (1986).

Name. After Robins Gletscher, northern Northumberland Ø (Figs 2, 48).

Distribution. Same as the formation although its presence in northern Prudhoe Land, south-east of Bamse Gletscher, has not been ascertained.

Geomorphic expression and overall colour. Rather dark, brownish-weathering, resistant unit often forming a small bench (Fig. 49).

Type and reference sections. The type section of the Robins Gletscher Member is the same as for the formation at Parish Gletscher (section 32, Figs. 65, 66); reference sections are on both sides of Kissel Gletscher (Figs 48, 49A) and at Clarence Head and Goding Bay (sections 30, 31, Fig. 65).

Thickness. Variable in both Greenland and Canada: 5–6 m at Goding Bay, 9–22 m at Clarence Head and 20–35 m on Northumberland Ø. Thickness at Bamse Gletscher is obscured by scree.

Lithology. Thin- to medium-bedded, variously laminated, cryptocrystalline dolomite and limestone, with red and green shale with arenaceous carbonates and subordinate fine-grained sandstone. Shale usually forms interbeds with much thicker carbonate beds but in the type section red shale forms a discrete unit up to 5 m thick containing rare 3–6 cm thick limestone beds (Fig. 67). Both at Clarence Head and Northumberland Ø the carbonates in the upper part are variously argillaceous and siliceous with occasional thin sandstone beds.

The carbonates are typically brown to reddish brown weathering; some limestones weather light grey to

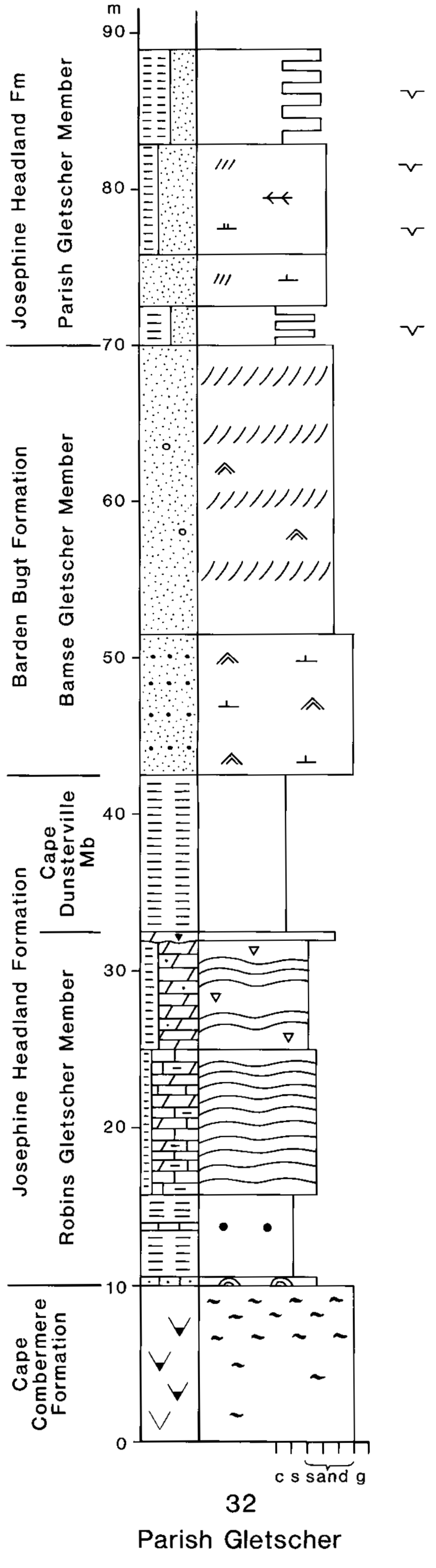


Fig. 66. Stratigraphic log of lower part of Josephine Headland Formation at Parish Gletscher, Northumberland Ø. For location, see Fig. 48.

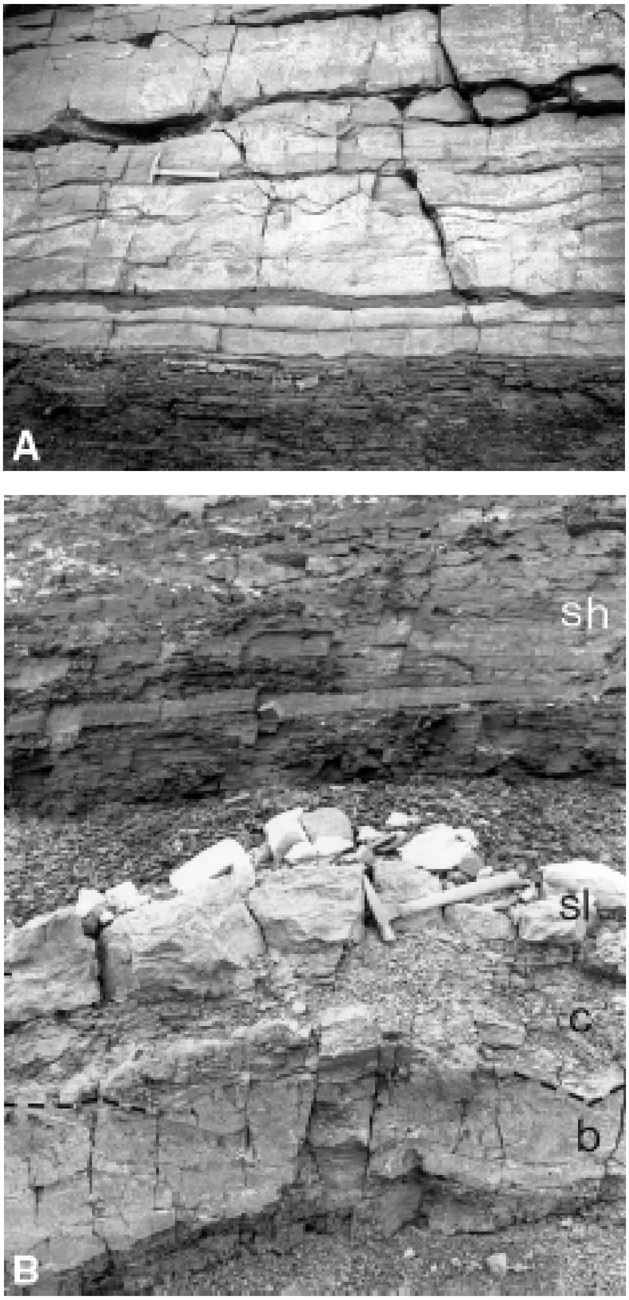


Fig. 67. Robins Gletscher Member of the Josephine Headland Formation, west side of Parish Gletscher, Northumberland Ø. **A:** brown dolomite with thin interbeds of red shale, some of which are preserved as wavy laminations; **B:** carbonate-rich rubbly material (c), stromatolitic limestone (sl) and maroon shales (sh) overlying basalt (b) of the Cape Combermere Formation.

green grey. Red to brown shaly partings show mudcracks and Jackson (1986) mentions tepee structures 15 cm high. Wavy bedding and thin lamination are common and, in the lower part particularly, algal laminites occur together with low-relief, laterally linked stromatolite columns. Some carbonates are oolitic and pisolitic. Some thin carbonate breccia and conglomerate beds contain siltstone and shale clasts with occasional volcanic pebbles.

The basal bed is commonly a stromatolitic carbonate; red to maroon shales locally underlie it, and in some localities a thin carbonate-rich breccia or conglomerate occurs at the contact. At Robins Gletscher such carbonate breccia rock contains subangular to angular, commonly irregular inclusions of basalt and cryptocrystalline quartz up to 2 cm long; at Clarence Head the carbonate granule conglomerate is only some 10 cm thick. In the type section basal red shales are very arenaceous, at intervals containing rounded quartz with some feldspar grains. Some show tuffaceous components: rounded to elongated granules to irregular fragments of cryptocrystalline quartz and glass up to 2 mm long set in a brown streaky matrix.

A breccia bed about 40 cm thick caps the Robins Gletscher Member at the type section (Fig. 66). In addition to angular sedimentary clasts the breccia contains what appears to be volcanic debris. The bed has a very irregular, scoured contact to the underlying dolomite and is taken to represent a flow breccia.

Depositional environment. The banks of low amplitude stromatolitic carbonates characterising the Robins Gletscher Member are taken to record the initial deposition of a marine transgression when the supply of terrigenous clastic material was at a minimum. Noting the presence of overlying beach deposits, Jackson (1986) interpreted the carbonates to represent intertidal to supratidal environments. Pyroclastic elements indicate contemporaneous volcanism nearby.

Fossils. Stromatolites, algal laminites.

Boundaries. The lower boundary of the Robins Gletscher Member is that of the formation. Where the member is in contact with sediments of the Cape Combermere Formation, as for example at Goding Bay, the boundary is conformable, planar and sharp; in contact with effusive rocks the contact may be sinuous to very irregular with the lower surface of the basal carbonate mirroring the top of the underlying flow (Figs 67, 68). In places in contact with intrusive rock there has been mixing of carbonate and basalt due to carbonate remobilisation. The upper boundary is conformable and drawn above the last carbonate or argillaceous dolomite bed, or, as at the type section at Parish Gletscher, above a volcanic breccia bed.

Fig. 68. Detail of stromatolitic dolomite of the Robins Gletscher Member of the Josephine Headland Formation in contact with vesicular basalt (b) of the underlying Cape Combermere Formation. Irregular cuspate contact has dark inclusions within the carbonate. West side of Robins Gletscher, Northumberland Ø. Hand-lens as scale.

Cape Dunsterville Member

new member

Composition. This member corresponds to beds in the lower to middle part of the Dolomite–Shale unit of the Wolstenholme Formation as defined by Dawes *et al.* (1982a) from Clarence Head, Goding Bay and Northumberland Ø; in Ellesmere Island it equates with subunit 3B of Jackson (1986).

Name. After Cape Dunsterville, the southern part of the peninsula limiting Goding Bay eastwards (Figs 1, 2, 80).

Distribution. On Northumberland Ø and at Bamse Gletscher in Greenland; at Clarence Head and Goding Bay in Canada. Its presence in Prudhoe Land, south-east of Bamse Gletscher, is not ascertained.

Geomorphic expression and colour. A pale red weathering, rather recessive unit, with main shale units commonly scree covered.

Type and reference sections. The type section is at Goding Bay (section 31, Figs 65, 80); thinner reference sections are at Clarence Head and Parish Gletscher (sections 30, 32, Fig. 65).

Thickness. Thinner in Greenland, varying from 5–10 m on Northumberland Ø to 15 m at Clarence Head and 102 m at Goding Bay.

Lithology. Thinly bedded, multicoloured sandstones and shales with units of reddish coloured shale (Fig. 63B). In Canada at Goding Bay, brownish red shale forms the upper half of the member while at Clarence Head and on Northumberland Ø shales predominate. Thus at Clarence Head a red shale unit 12 m thick dominates the 15 m section while on Northumberland Ø the member is mainly in shale (Fig. 65).

At the thickest development of the Cape Dunsterville Member at Goding Bay, Jackson (1986) describes a 7 m thick basal coarsening-upwards cycle involving green shale beds that decrease in thickness upwards from 80 cm to 2 cm, interbedded with thin to medium size beds of grey green, planar to wavy-bedded, in places cross-bedded subarkose. The middle 44 m of the member are dominated by fining-upward cycles of red-green sandstone (in beds 1 m to 60 cm thick) and red shale (7 m to less than 1 m thick). Basal sandstones have sharp contacts and display shallow channels; mudcracks occur on top surfaces of sandstone and shale beds. Cross-bedding and symmetrical ripple marks are common. Some sandstones contain carbonate-rich lamellae and shale fragments. Shale beds contain sandstone clasts, and Frisch & Christie (1982) mention hematitic mud or sand balls up to 3 cm in diameter.

Possible ball and pillow structures occur in the interbedded sandstone-shale section at Bamse Gletscher where certain shales of deep brownish-red colour contain rounded to disc-shaped sandstone concretions, the largest of which reach 10 cm in diameter. These balls and discs are fine to very fine grained and where sectioned are of siliceous dolomite. Some of the purplish-green sandstones at Bamse Gletscher are glauconite-bearing and carbonate-cemented, typically with subangular quartz grains.

Depositional environment. The Cape Dunsterville Member is taken to represent deposition in an overall shore zone environment with encroaching fluvial deposition. Basal coarsening-upwards strata overlain by fining-upwards cycles, fully developed at Goding Bay, are interpreted by Jackson (1986) as regressive beach deposits and meandering stream and overbank deposits, respectively, with the upper red argillites as vertical accretion muds.

Fossils. None known.

Boundaries. The conformable lower and upper boundaries are well demarcated. The lower contact is with the Robins Gletscher Member; the upper contact in Canada is with the Parish Gletscher Member. As a function of the interdigitation between the Josephine Headland and Barden Bugt Formations, in Greenland the Cape Dunsterville Member is overlain by the Bamse Gletscher Member (Fig. 65). The contact is drawn where red shales are abruptly overlain by the resistant sandstones of the Bamse Gletscher Member.

Parish Gletscher Member

new member

Composition. This member corresponds to the uppermost part of the Dolomite–Shale unit of the Wolstenholme Formation of Dawes *et al.* (1982a) from Northumberland Ø and Ellesmere Island (except Gale Point). At Clarence Head and Goding Bay it equates with subunit 3C of Jackson (1986); at Cape Dunsterville with unit 1 of Christie (1975).

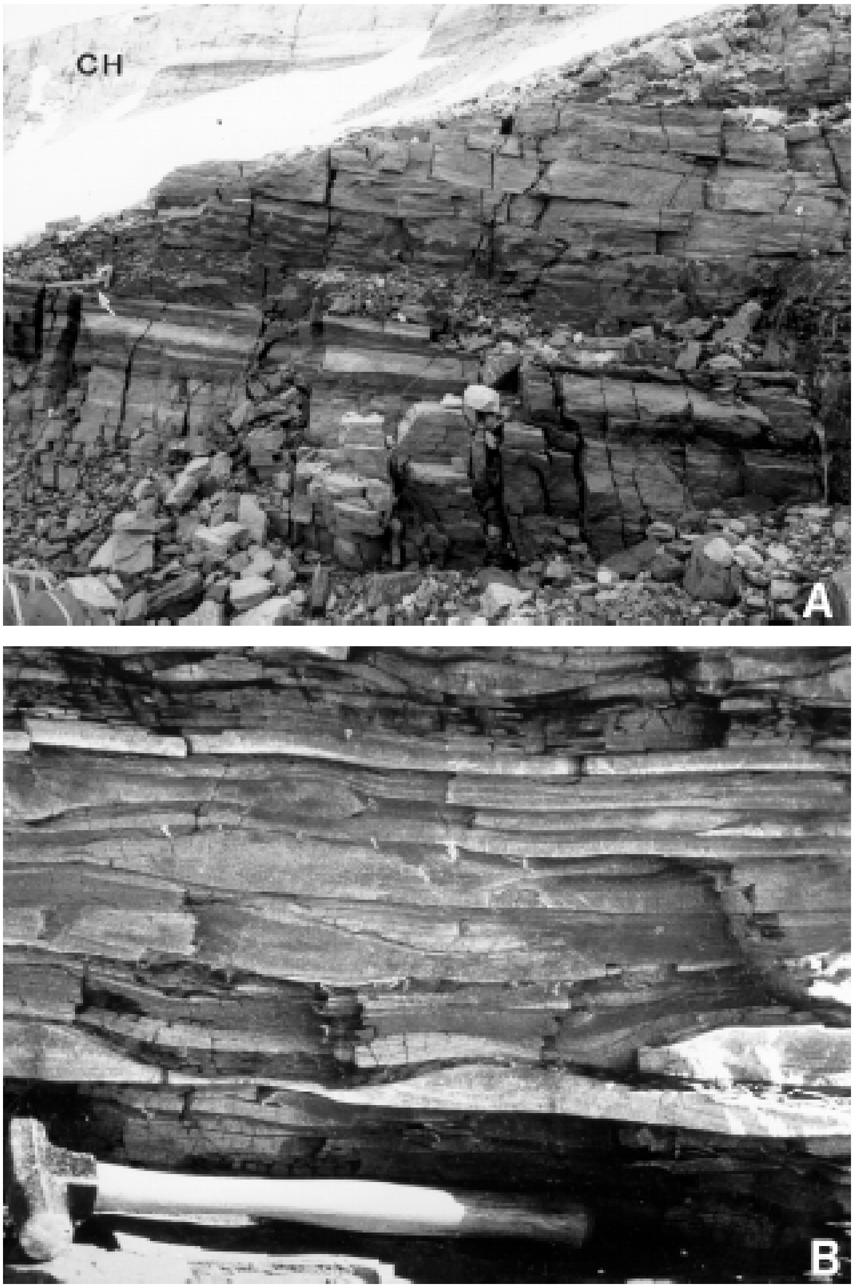


Fig. 69. Bedding characteristics of the Parish Gletscher Member of the Josephine Headland Formation.
A: variously mottled and laminated sandstone interbedded with shales on the western side of Parish Gletscher, Northumberland Ø; hammer (arrowed) as scale. Clarence Head Formation (CH) in background;
B: lenticular bedded, variously laminated sandstones with thin shale intercalations. The lenticular bedding is of probable wave ripple origin. Clarence Head. Photo: T. Frisch.

Name. After Parish Gletscher, northern Northumberland Ø (Figs 2, 48).

Distribution. Northumberland Ø and northern Prudhoe Land, and in all sections of the Josephine Headland Formation in Ellesmere Island.

Geomorphic expression and colour. A pale reddish-weathering, generally recessive unit with moderate scree cover.

Type and reference sections. The type section is that of the formation at Parish Gletscher (section 32, Figs 65, 66); reference sections are on both sides of Kissel Gletscher (Figs 48, 49A) and at Clarence Head and Goding Bay (sections 30, 31, Fig. 65).

Thickness. From 50–75 m in Canada to 90 m, possibly more, in Greenland.

Lithology. The main lithology is multicoloured, thin- to medium-bedded, alternating sandstones and shales; at one section in Parish Gletscher possible volcaniclastic strata occur in the middle part.

The sandstones, mostly medium grained, show colour variation along strike. Thus at Northumberland Ø and Goding Bay they have predominantly red, pink, purple and lilac hues with some pale green, white to buff beds; at Clarence Head, according to Jackson (1986), the sandstones are mainly grey and white with local red beds. At Robins Gletscher the sandstones show a colour mottling of reduction spots and irregular patterns with purple to brownish red sandstone reduced to buff colour. The shales are mostly green and red-maroon.

Sandstone and shale are thin to medium bedded (Fig. 69). Certain buff to yellow beds in the upper part are up to 1 m thick and on Northumberland Ø the section is topped by a 2–5 m thick red shale bed. Generally sandstone increases upwards relative to shale, and Jackson (1986) notes an upward change in composition at Goding Bay from subarkose to quartz arenite with red granular to pebbly sandstone in the uppermost part. Locally, both in Greenland and Canada, carbonate-cemented sandstones occur. The sandstones range from massive to laminated with common shale partings and laminae. Wavy to lenticular-bedded sandstones are common (Fig. 69). Cross-bedding, in places of herringbone type, and mudcracks are common throughout; asymmetrical ripples, minor channels and shale-flake conglomerate are seen locally.

At one section on the west side of Parish Gletscher a sequence of sandstones and shales at least 20 m thick are darker hued than normal: shales are deep purple to black, sandstones are dark grey, brown or deep purple. The rocks are variously laminated and many are characterised by disrupted laminae and bedding. Mudcracks are common. The rocks show wide textural variation from quartz arenites to varieties in which quartz grains are scattered throughout a brown, tuffaceous? cryptocrystalline matrix of clay minerals. Clasts up to 1 mm may represent volcanic rock. This analogous section is adjacent to a basic dyke that may have baked the strata to some extent and the effect is accentuated by basalt injection parallel to bedding. The section was only cursorily examined but the impression remains that certain darker strata represent volcaniclastic rocks.

Depositional environment. Wave ripples, bidirectional cross-bedding and lenticular bedding suggest that tide-dominated deposition in the intertidal to supratidal environment existed for at least the main part of the member (Frisch & Christie, 1982). Jackson (1986) suggests alternating tidal flat shale and intertidal sandstone deposition or a general estuarine environment. The appearance of granule and pebble beds in the uppermost part at Goding Bay may suggest tidal channel or fluvial influence. In Greenland the member records waning volcanism.

Fossils. None known.

Boundaries. The lower boundary of the Parish Gletscher Member is conformable, well demarcated and drawn at the top of red shales of the Cape Dunsterville Member and, in Greenland, above the massive quartz arenites of the Bamse Gletscher Member of the Barden Bugt Formation (Fig. 65). The upper contact is the formational boundary marked by the incoming of quartz arenites of the Clarence Head Formation (Fig. 49).

Barden Bugt Formation

new formation

Composition. Strata of this formation are part of the lower red sandstone of Koch (1929a) and the lower beds of the Wolstenholme Formation of Dawes (1976a).

Name. After Barden Bugt, a prominent bay in western Steensby Land (Figs 2, 70).

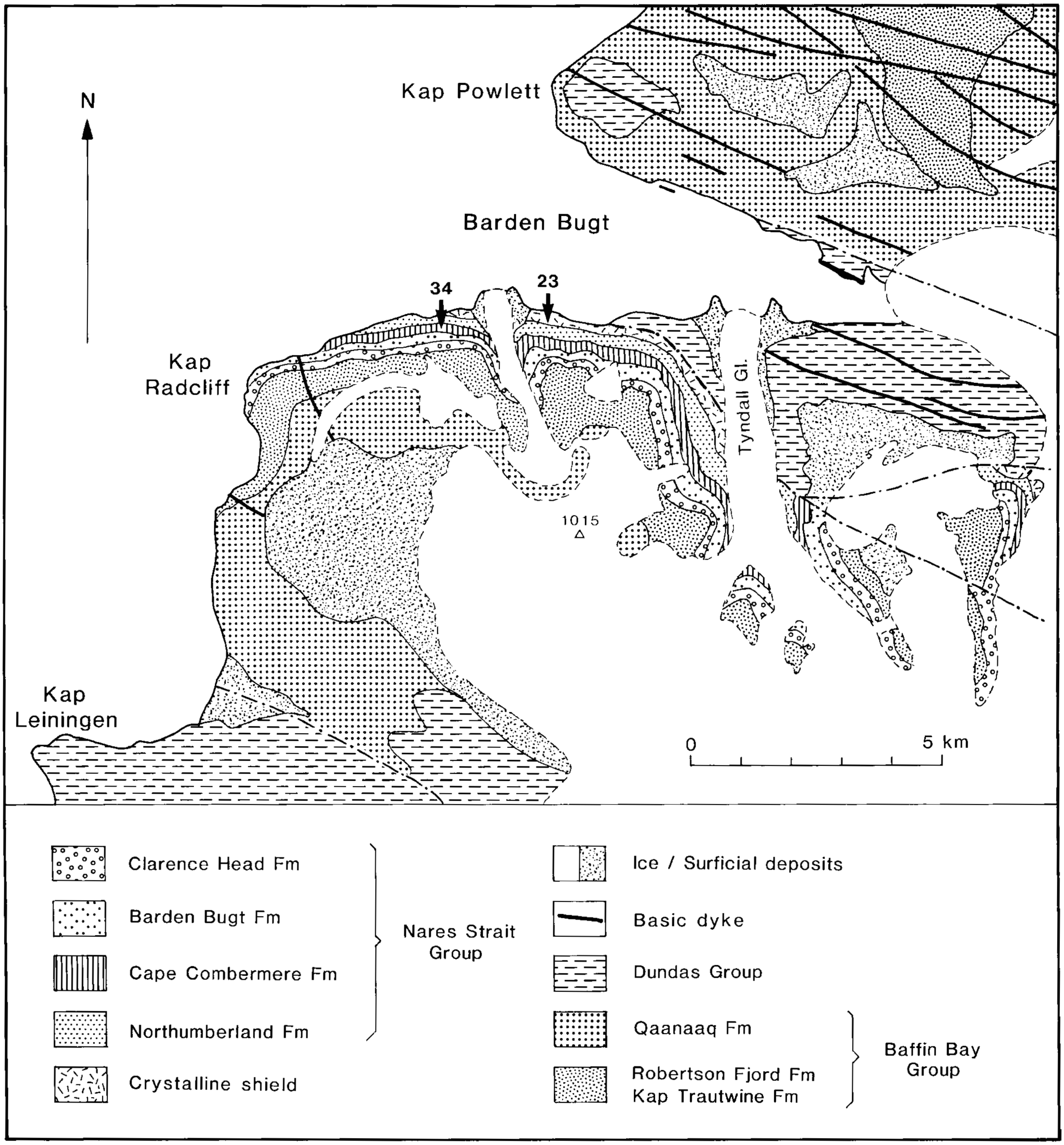


Fig. 70. Geological map of the Barden Bugt area, Steensby Land, Greenland, showing locations of sections 23 and 34. The area exposes a continuous succession from the Nares Strait Group into the Baffin Bay Group with, to the north of the bay, the passage into the more argillaceous strata marking the transition to the Dundas Group. The bay itself is etched from a down-faulted block that juxtaposes on the south the Dundas Group and the Precambrian shield, preserving the less-resistant Dundas lithologies as a WNW-trending belt across Steensby Land (Fig. 2). This faulted belt, that also forms the head of Granville Fjord (Fig. 87), is parallel to other regional faults (e.g. Fig. 109) and to a major swarm of Hadrynian basic dykes. Height of 1015 is in metres. For location, see Fig. 2.

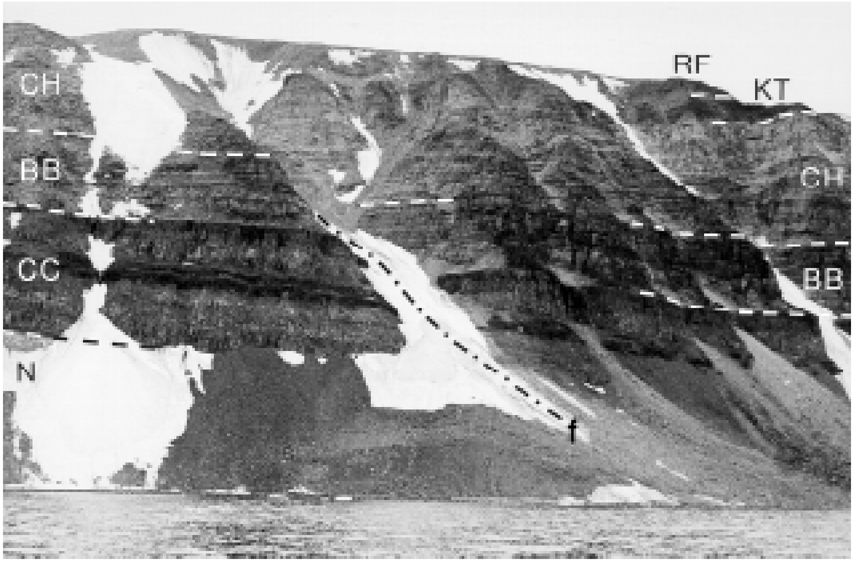


Fig. 71. Southern cliffs of Barden Bugt about 600 m high showing the Barden Bugt Formation (BB) divisible into a pale lower unit and a darker striped upper unit, flanked by the Clarence Head (CH) and Cape Combermere (CC) Formations. The tripartite division of the latter formation, viz. upper and lower basalt units separated by a bedded sedimentary unit, is well seen, as is the subdivision of the Clarence Head Formation into a lower dark, and upper, more massive, pale unit.
N = Northumberland Formation,
KT = Kap Trautwine Formation,
RF = Robertson Fjord Formation.
Sections 23 and 34 are of these cliffs but located farther east (see Fig. 70).

Distribution. Prudhoe Land between Robertson Fjord and Bowdoin Fjord, and western Steensby Land (Fig. 12).

Geomorphic expression and colour. A generally cliff-forming purple to pale red weathering unit. In western Steensby Land the lower part is pink to orange-buff weathering and moderately recessive; the upper part has a characteristic striped or banded appearance (Fig. 71).

Type and reference sections. The type section is on the south side of Barden Bugt to the west of an unnamed glacier (section 34, Figs 65, 72); a measured reference section is on the south-eastern side of Robertson Fjord at Kûgarssuaq (section 33, Figs 65, 72).

Thickness. Ranges from a maximum of about 160 m in Robertson Fjord to at least 90 m at Barden Bugt to less than 60 m in Granville Fjord (Fig. 12).

Lithology. Pink, pale purple to reddish brown quartz arenites ranging from fine to very coarse grained and from thin to thick bedded (Fig. 73). Cross-bedding and ripples are generally common but they may be locally absent. Quartz grains are generally well rounded but some rocks have subangular grains, others show secondary silica growth on rounded grains. Occasional feldspar and rounded quartzose rock fragments occur.

At Barden Bugt, basal beds are an upward coarsening and thickening sequence of pink to brown sandstone with cross-bedding prominent in thicker beds up to 1.5 m thick and absent in thinner beds down to 15 cm. At higher levels pale sandstones are interbedded with thinner red beds that show prominent ripples; this lithology produces the striped to banded appearance of the upper part of the formation in western Steensby Land (Fig. 71). The upper part is typically thin, often lenticularly bedded; sandstones show low-angle cross-bedding and mudcracks. Near the top are several deep purple, laminated beds. In addition to well-rounded quartz grains these contain an abundance of cryptocrystalline silica grains and fragments up to 2 mm long characterised by serrated borders and set in a brown matrix. These are possible volcaniclastic deposits.

A resistant unit in the middle part of the formation is composed of pale, planar cross-bedded quartz arenite (see Bamse Gletscher Member below). Pale purple sandstones, some planar bedded with small-scale channels, others with large-scale channelled cross-beds in a variety of directions, form the upper part of the formation.

Depositional environment. The Barden Bugt Formation is thought to have been deposited in an intertidal to dominantly supratidal environment. Lower coarsening-upwards beds with wave ripples may represent a regressive littoral deposit; the strata characterised by prominent cross-bedding, channelling and current ripples could be fluvial, possibly braided sandy stream deposits. Nearby volcanism is suggested.

Fossils. None known.

Boundaries and correlation. The formation overlies,

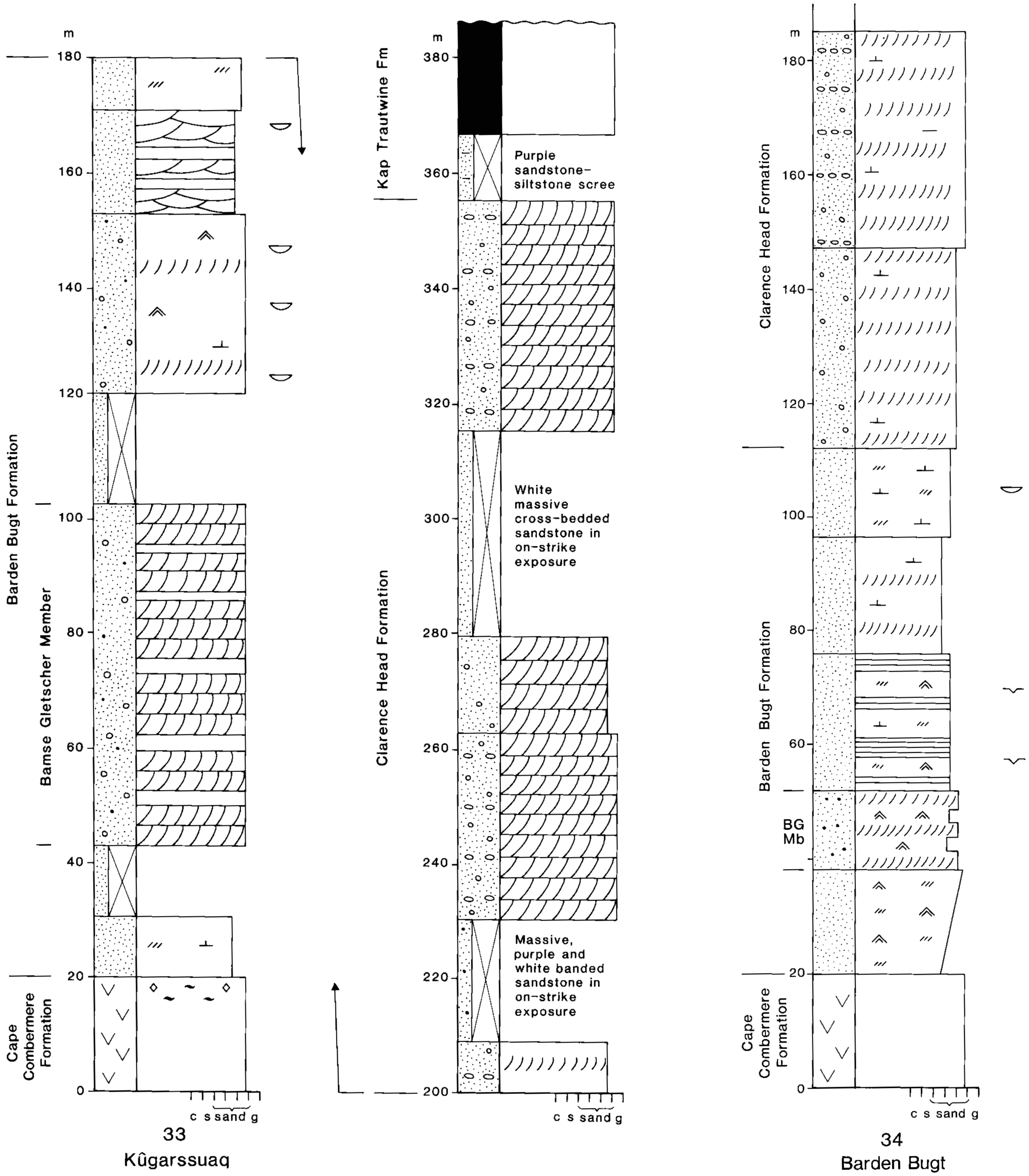


Fig. 72. Stratigraphic logs of the Barden Bugt and Clarence Head Formations from Kûgarssuaq, Robertson Fjord, and Barden Bugt, Steensby Land; the latter compiled from data in O'Connor (1980). These are the type sections of the Barden Bugt Formation (section 34) and the Bamse Gletscher Member (section 33). Map locations are given in Figs 70 and 83; the Kûgarssuaq section is shown in Fig. 74.

apparently conformably, the effusive strata of the Cape Combermere Formation; at Bowdoin Fjord its lower contact is with a basaltic (?)sill. The upper boundary is conformable to the Clarence Head Formation being drawn at the first appearance of clean quartz arenites.

The Barden Bugt Formation is a lateral equivalent of the Josephine Headland Formation with which it interfingers.

Subdivisions. The conspicuous cliff-forming, pale unit in the middle part of the formation in Prudhoe Land is defined as the Bamse Gletscher Member.

Bamse Gletscher Member

new member

Composition. This member is part of the Dolomite–Shale unit of the Wolstenholme Formation in Greenland as defined by Dawes *et al.* (1982a).

Name. After Bamse Gletscher, northern Prudhoe Land (Figs 1, 2, 27).

Distribution. Prudhoe Land between Sonntag Bugt and MacCormick Fjord, Steensby Land and Northumberland Ø.

Geomorphic expression and colour. Pale weathering, cliff-forming unit forming a prominent bench (Fig. 64).

Type and reference sections. The type section is at Kûgarssuaq on the south-eastern coast of Robertson Fjord (section 33, Figs 65, 74); reference sections are at Parish Gletscher, Northumberland Ø (section 32, Figs 65, 66) and at Bamse Gletscher (Fig. 64).

Thickness. About 20–30 m on Northumberland Ø and up to 60 m in Prudhoe Land.

Lithology. Pink, lilac and purple, medium- to thick-bedded quartz arenites that are medium to very coarse grained. Pebbly sandstone is common and granule beds up to 15 cm thick have sharp bases and display small-scale channelling. Planar cross-bedding in sets from 40 cm to 1 m is common; symmetrical ripple marks occur. Thinner bedded basal strata have purple shale partings and exhibit mudcracks.

The sandstones vary from massive and homogeneous type with sugary texture to weakly laminated finer grained varieties. Quartz is rounded to subangular; pebbles and granules are extremely well rounded and often with well-developed dusty borders. Occasional rounded rock fragments; some rocks have a sparse yellow-brown glauconitic matrix.

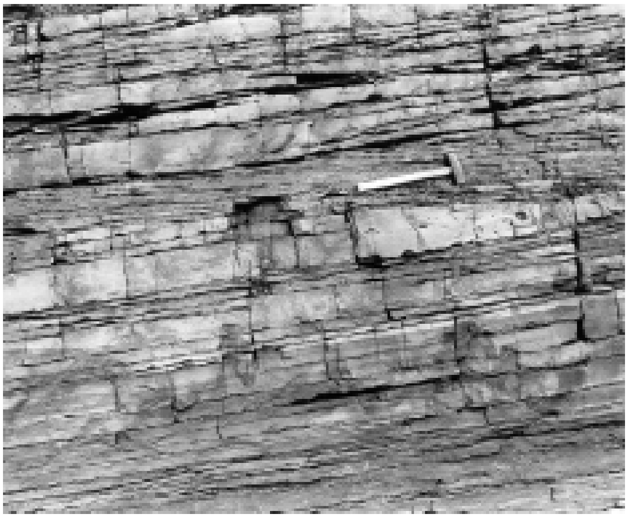


Fig. 73. Bedding characteristics of the Barden Bugt Formation: thin- to medium-bedded sandstones showing lenticularity, low-angle cross-bedding and ripple marks. West side of Bowdoin Fjord (Fig. 98).

Depositional environment. Sedimentary features provide no specific evidence on depositional environment within the intertidal to supratidal regime of the Barden Bugt Formation. One possibility is that the cross-bedded, wave-rippled sands represent an offshore bar.

Fossils. None known.

Boundaries. The Bamse Gletscher Member has conformable and well-demarcated upper and lower boundaries to unnamed strata of the Barden Bugt Formation. Where the member interfingers with strata of the Josephine Headland Formation, it has sharp contacts to both the shales of the Cape Dunsterville Member and the interbedded sandstones and shales of the Parish Gletscher Member.

Clarence Head Formation

new formation

Composition. Strata of this formation on Northumberland Ø were called member (b), subsequently unit 4, of the Wolstenholme Formation (Dawes, 1975, 1976b). At Clarence Head and Goding Bay the formation corresponds to unit IV of Frisch *et al.* (1978) and Frisch &

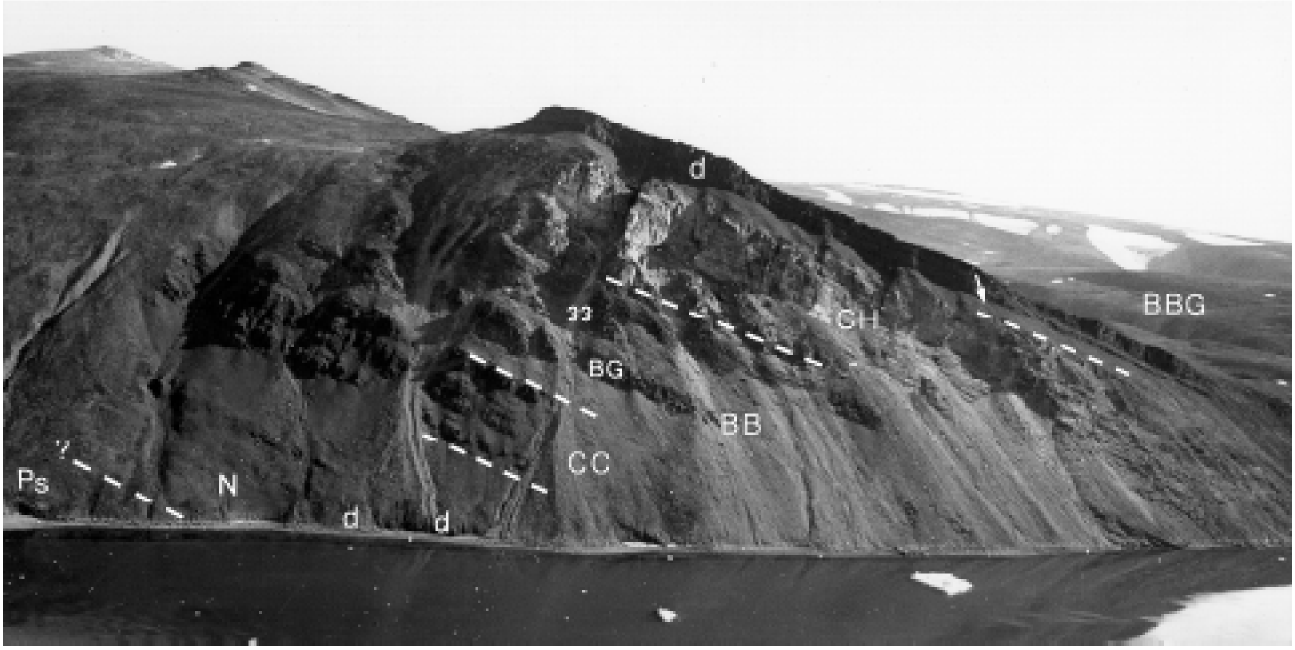


Fig. 74. Sea-cliff Kûgarssuaq, Robertson Fjord, about 400 m high, showing location of section 33 up central gully. Ps = Precambrian shield, N = Northumberland Formation with basaltic sills or ?flows (d), CC = Cape Combermere Formation, BB = Barden Bugt Formation with resistant Bamse Gletscher Member (BG), CH = Clarence Head Formation. Bipartite division of CH into lower more recessive and upper cliff-forming units is apparent. The dark recessive, unexposed strata (arrowed) under the capping basic sill (d) are the basal beds (Kap Trautwine Formation) of the Baffin Bay Group (BBG). This basic sill occurs throughout Prudhoe Land near the contact between the Nares Strait and Baffin Bay Groups. For map location, see Fig. 83.

Christie (1982) and unit 4 of Jackson, with the exception that at Goding Bay it includes 15 m of strata (units 4 and 5 of Christie, 1975) referred by Frisch & Christie (1982, p. 8) to the overlying unit V. At Cape Dunsterville units 2 and 3 of Christie (1975) are referred to this formation. In the 6-unit scheme of Dawes *et al.* (1982a) for both sides of Nares Strait the formation equates with the ‘White Sandstone unit’.

Name. After Clarence Head, a prominent coastal cliff in south-eastern Ellesmere Island (Figs 2, 75).

Distribution. In Greenland, Prudhoe Land, western Steensby Land, Northumberland Ø and Hakluyt Ø; in Canada, west of Gale Point, south of Cadogan Inlet, and at Goding Bay and Clarence Head (Fig. 12).

Geomorphic expression and colour. Monotonous in colour and appearance; a light-weathering and very resistant unit forming prominent massive bluffs and towering cliffs. The lower part, that is in many places more recessive, has a white/buff – mauve/purple, striped to banded appearance (Figs. 64, 74, 76).

Type and reference sections. Complete accessible sections are rare because of precipitous outcrops. The type section is at Clarence Head (section 35, Figs 75, 79). Accessible reference sections in Canada are at the head of Goding Bay and at Paine Bluff (sections 39 and 40, Fig. 79), and in Greenland at Kûgarssuaq in Robertson Fjord and at Barden Bugt (sections 33, 34, Figs 72, 79). Other partly accessible sections exposing both lower and upper boundaries occur on Northumberland Ø and in northern Prudhoe Land between Bamse Gletscher and Diebtisch Gletscher.

Thickness. In its maximum development at Paine Bluff in Goding Bay, the formation is at least 280 m thick; on Northumberland Ø and Hakluyt Ø it reaches 250 m, possibly more, varying to less than 100 m in parts of western Steensby Land and south-eastern Prudhoe Land (Fig. 12). At Castle Cliff, Bowdoin Fjord (Fig. 98), a tapering body provisionally referred to the formation is estimated to range in thickness from 75 to 20 m. The wedge-shaped nature of the formation is also seen at Goding Bay where it is from 165 to 280 m thick and at Clarence Head where it ranges from less than 100 to over 200 m (Frisch & Christie, 1982).

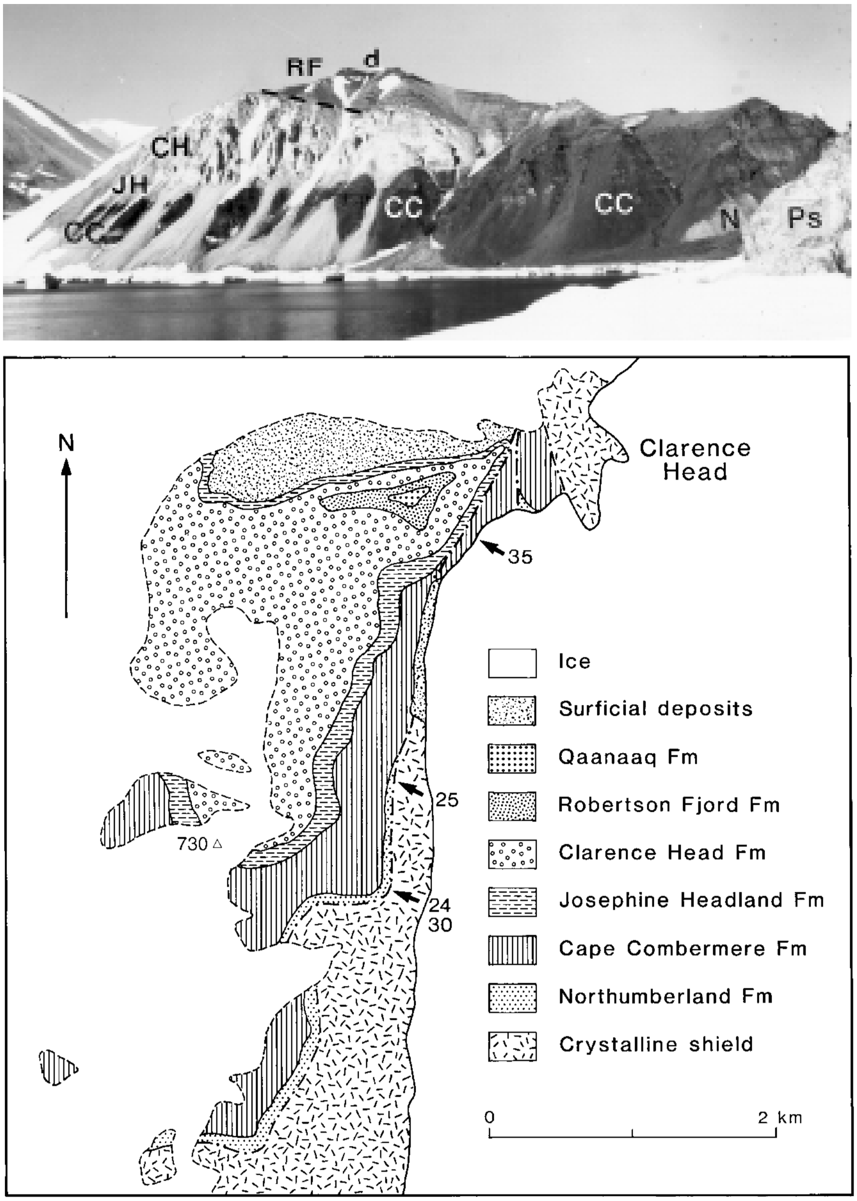


Fig. 75. Geology of the Clarence Head area, Canada. The geological map, showing the locations of sections 24, 25, 30 and 35, is compiled from aerial photographs based on interpretation of data in Frisch & Christie (1982) and Frisch (1988) and from T. Frisch (personal communication). View of the coast south of Clarence Head (section 35) shows the prominent white cliffs of the type section of the Clarence Head Formation (CH) above scree-covered Josephine Headland Formation (JH) and Cape Combermere Formation (CC), with red beds of the Robertson Fjord Formation (RF) of the Baffin Bay Group capping the section. The dark craggy summit at about 600 m a.s.l., is a basic sill (d), above which (out of sight) are pale sandstones of the Qaanaaq Formation. The contact with the Precambrian shield (Ps) is tectonised and the Northumberland Formation (N) is in places cut out. Height of *c.* 730 is in metres. Photo: T. Frisch. For location, see Fig. 2.

Dominant lithology. Pale weathering, white, buff, light grey and pink, medium- to coarse-grained, medium- to very thick-bedded sandstones, with quartz-pebble conglomerates, in which cross stratification and symmetrical ripple marks are common. The lower part is often characterised by purple to mauve, pale brown to orange and red interbedded sandstones (Fig. 76) in which colour striping and banding are caused by hematite laminae and partings, reduction, and discoloration layering. Brown to lilac liesegang rings, often developed as pseudo-bedding, occur throughout the formation. Thin, laminated red sandstones occur in the lower strata, as well as minor subarkoses. The main thickness of the formation is particularly uniform and homogeneous, so that very rare, thin red beds in the uppermost strata at Paine Bluff (see Fig. 82) and at Bowdoin Fjord (see Fig. 78) appear conspicuous.

Cross-bedding, abundant throughout the formation, occurs mostly in sets between 0.5 and 1.5 m thick. At Goding Bay cross-beds are slightly bimodal (Jackson, 1986), while at Clarence Head abrupt reversals in current direction are recorded by Frisch & Christie (1982). Grits, pebbly sandstone and quartz-pebble conglomerates are irregularly distributed; such lithologies may be local and sporadic, common elsewhere. Well-rounded quartz pebbles are generally below 3 cm long; pebbles twice that size are sporadic. The rudaceous layers, discontinuous along strike, form discrete beds but more commonly, conglomerate beds have irregular diffuse borders grading to sandstone.

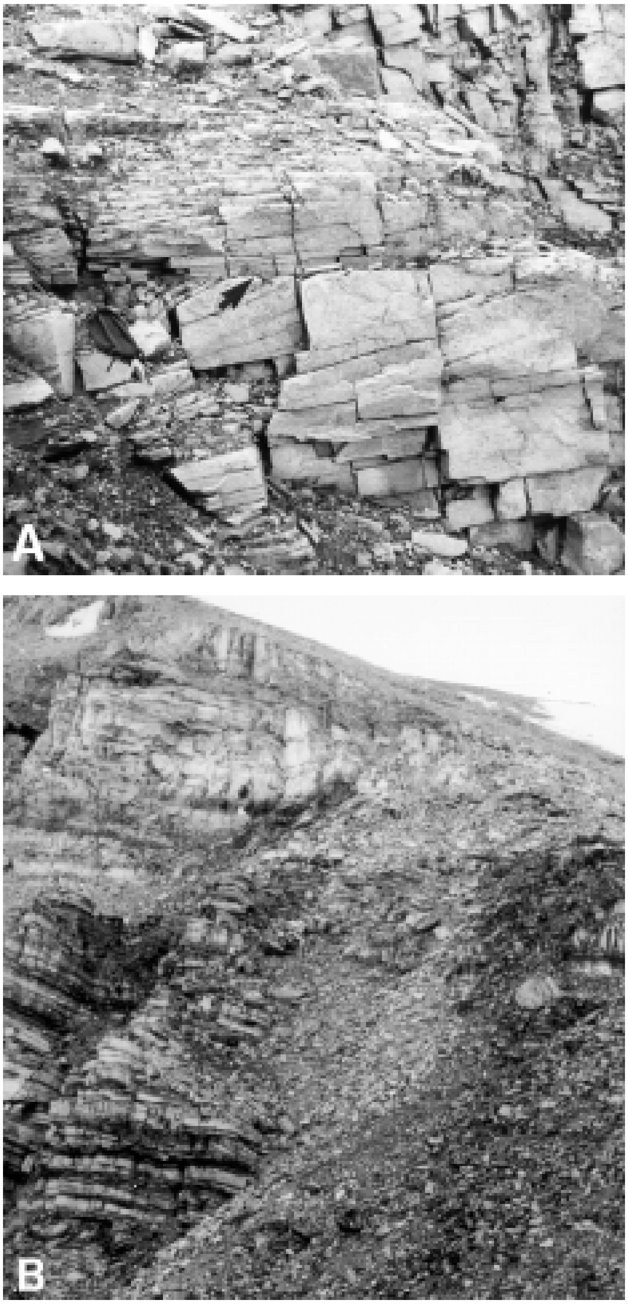


Fig. 76. Bedding characteristics of the Clarence Head Formation. **A:** large-scale planar cross-bedding, with hammer (arrowed) as scale. Upper part of the formation at Barden Bugt; **B:** banded, purple and white sandstones overlain by more homogeneous and thicker bedded white quartz arenites. Clarence Head, section 35. Photo: T. Frisch.

The majority of the sandstones are very clean quartz arenites that show a varying degree of authigenic silica overgrowth. There is a textural range from a rock having well-rounded quartz and an interstitial matrix of finer quartz, hematite-limonite dust and sericite, to a well-cemented rock in which quartz shows subrounded to subangular form due to heavy overgrowth. Some well-rounded quartzite fragments occur but feldspar grains are rare.

The two red beds at the top of the Paine Bluff section (see Figs 79, 82) have different lithologies. The lower bed, up to 2 m thick, is a cross-bedded pink to white sandstone with shaly partings; the upper, 3 m thick, is interbedded micaceous siltstone and cross-bedded sandstone with minor intraformational breccia (Christie, 1975). Red beds of similar appearance and stratigraphic position elsewhere, e.g. Bowdoin Bugt (see Fig. 78), have not been examined.

Depositional environment. The white, very clean sands, a reflection of distance from source and substantial reworking, and the thick, abundant cross-beds, in places bimodal, suggest a shallow marine depositional environment in the tidal zone. Deposition as offshore sand bars could account for the fairly abrupt thickness variations. Reversals of palaeocurrent directions are suggested to be related to longshore or tidal currents (Frisch & Christie, 1982; Jackson, 1986).

Fossils. None known.

Boundaries and correlation. The formation rests conformably on underlying strata – the Josephine Headland and Barden Bugt Formations (Figs 49, 71). If outcrop would allow, it might be shown to overlap onto crystalline basement at the basin margin in the south-east. The upper boundary is a regional marker representing the incoming of red bed sedimentation of the Baffin Bay Group (Figs 75, 77). Over the main part of the Thule Basin it is overlain with sharp contact by the Kap Trautwine Formation (in places the contact is with a basic sill); in the Goding Bay – Cape Dunsterville area it is overlain by the Goding Bay Formation.

Although stratigraphical relationships are not preserved in northernmost Prudhoe Land, the Clarence Head Formation is regarded as a lateral equivalent of the Kap Alexander Formation of the Smith Sound Group (see Fig. 120).

Subdivisions. In many sections in both Greenland and Canada, a bipartite division into lower, more recessive and banded, and upper, more massive and cliff-forming, units is apparent (Figs 49, 64, 74, 76) but no formal recognition is made here.

Fig. 77. Baffin Bay Group (Kap Trautwine Formation, KT; Robertson Fjord Formation, RF and Qaanaaq Formation, Q) overlying the Nares Strait Group (Cape Combermere Formation, CC; Josephine Headland Formation, JH; Clarence Head Formation, CH) in the cliffs of western Northumberland Ø at Vestgletscher. The cliffs of Josephine Headland on the left are about 900 m high. For map location, see Fig. 48.

Baffin Bay Group

The Baffin Bay Group represents the most widespread strata of the Thule Basin present in the central basin fill and overlapping the Precambrian shield on the south-eastern basin margin (Figs 2, 4, 120). It is subdivided into five formations, viz. the Kap Trautwine, Goding Bay, Robertson Fjord, Wolstenholme and Qaanaaq Formations, in which 6 members are formally recognised.

Baffin Bay Group

new group

Composition. This group composes strata from both the lower red and upper pale sandstone units of the Thule Formation of Koch (1926, 1929a; Dawes & Haller, 1979, plate 1). It includes the lower two sandstone units described by Chamberlain (1895) from Inglefield Bredning, all strata described by Munck (1941) from Siorapaluk, Robertson Fjord, and the lower part of the section examined by her at Uvdle, Wolstenholme Fjord, as well as all strata at the head of that fjord on Nunatarssuaq described by Goldthwait (1954) and Fernald & Horowitz (1964). In the North Star Bugt area the group equates with the Quartzite Series of Davies (1954) and the Wolstenholme Quartzite/Formation as used by Kurtz & Wales (1951), Davies (1957) and Davies *et al.* (1963). Farther north the group corresponds to the upper part of the Wolstenholme Formation, more precisely members (c) and (d) of Dawes (1975) and in Canada to unit V of Frisch *et al.* (1978) and units V and VI of Frisch & Christie (1982). In the 6-unit scheme for both sides of Nares Strait erected by Dawes *et al.* (1982a) and adopted by Jackson (1986) for the section at Goding Bay, the group spans units 5 and 6.

Name. After Baffin Bay, the waterway separating Greenland from south-eastern Ellesmere, Devon and Baffin Islands (Figs 1, 2).

Distribution. The most widespread group of the Thule Supergroup. In Greenland: Prudhoe Land, Herbert Ø, Northumberland Ø, Hakluyt Ø, Inglefield Bredning, Olrik Fjord, Steensby Land, Wolstenholme Fjord, Wolstenholme Ø, with isolated exposures as far south as 76°N at De Dødes Fjord. In Canada: south of Johan Peninsula, viz. Cadogan Inlet, Paget Point, Lyman Glacier, Cape Dunsterville, Goding Bay and Clarence Head (Fig. 2).

Type area. Prudhoe Land, south-east of Morris Jesup Gletscher, Greenland (Fig. 2).

Thickness. In many areas, for example in all outcrops in Ellesmere Island, the group is truncated by the present erosion surface. Where the true thickness is preserved the group ranges from perhaps as much as 1300 m in Prudhoe Land and in the Northumberland Ø – Herbert Ø area to less than 300 m in the inner part

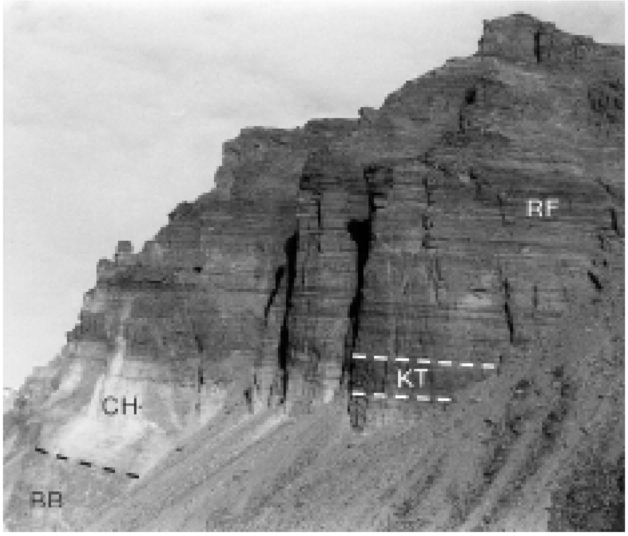


Fig. 78. Contact of Baffin Bay Group (red beds of the Kap Trautwine and Robertson Fjord Formations, KT and RF) and Nares Strait Group (Barden Bugt Formation, BB; Clarence Head Formation, CH) at Castle Cliff, Bowdoin Fjord (Fig. 98). The thin red bed at the top of the Clarence Head Formation suggests some gradation to red bed sedimentation. CH is estimated to be 25 m thick.

of Olrik Fjord (Figs 3, 12, 103). In Ellesmere Island up to about 900 m are preserved in the Goding Bay – Lyman Glacier area.

Dominant lithology. The Baffin Bay Group comprises multicoloured, shallow water siliciclastic strata: quartz arenites, quartz grits, quartz-pebble conglomerates with some subarkoses and important units of varicoloured shale and siltstone (Fig. 3). The siliciclastic rocks vary from highly ferruginous red beds to clean sands. The group shows a gross bipartite subdivision into lower red beds and upper pale weathering sandstones. Basaltic sills occur.

Depositional environment. The Baffin Bay Group is taken to represent mixed continental to marine shoreline environments, with one local interval of possibly deeper water deposition in a prodelta or an offshore basin. The group marks the incoming of red bed sedimentation in an oxidising environment with possible regolith deposits at the base. The many vertical changes in lithology and the supposed abrupt changes in sedimentary environment, may well be indicative of syndepositionary faulting. The uppermost strata indicate a gradually deepening water regime from predominantly alluvial plain deposition to a shallow-shelf tide-dominated environment. This is interpreted as part of a major regional change that continues to the subtidal and basinal deposition of the succeeding strata, the Dundas Group.

Fossils. Organic-walled microfossils (palynomorphs), both acritarchs and tubular forms.

Boundaries and correlation. In Canada and in the main exposures in Greenland, the Baffin Bay Group conformably overlies the Nares Strait Group along a conspicuous and abrupt contact that represents the change to red bed sedimentation (Figs 74, 75, 77). In places the presence of local red beds below and pale weathering sandstones above the boundary suggests some degree of gradation (Figs 78, 82). In some areas, for example at Robertson Fjord, the boundary between the two groups is followed by a basic sill (Fig. 85). In eastern and southern exposures in Greenland the group oversteps onto the crystalline basement. The upper contact in Greenland is conformable and gradational with the Dundas Group; in Canada the present erosion surface limits the group.

Due to lack of exposure the relationship of the Baffin Bay Group to the platform succession in Inglefield Land to the north is unknown, but the group must be a lateral equivalent of at least part of the Smith Sound Group (Figs 3, 4, 120).

Geological age. Neohelikian – ?Early Hadrynian. This assignment is based on radiometric dating of intrusive basaltic rock and on microfossils. The most reliable whole-rock K-Ar age is 978 ± 46 Ma on a sill from the lowest part of the group at Clarence Head (Frisch & Christie, 1982). The microfossils are from the middle and uppermost strata of the group. They are not specifically age-diagnostic, but suggest a general Late Riphean age (see under the Robertson Fjord and Qaanaaq Formations).

Subdivisions. The Baffin Bay Group is subdivided into five formations: the Kap Trautwine, Goding Bay, Robertson Fjord, Wolstenholme and Qaanaaq Formations.

Kap Trautwine Formation

new formation

Composition. This formation corresponds to the basal ferruginous strata of unit 5 and the 'Red sandstone unit', respectively, of Dawes (1976b) and Dawes *et al.* (1982a) from Northumberland Ø and Hakluyt Ø, and to the basal hematitic orthoquartzite of unit V of Frisch & Christie (1982) at Clarence Head.

Name. After Kap Trautwine, the highest part of the prominent cliffed coast on the south side of Hvalsund (Fig. 2).

Distribution. In Greenland: Prudhoe Land, western Steensby Land, Northumberland Ø, and Hakluyt Ø; in Canada: at Clarence Head (Fig. 12).

Geomorphic expression and colour. A very conspicuous dark red to deep purple-weathering unit that at a distance can be readily mistaken for a basic sill. Generally cliff forming but where argillaceous rocks predominate it can be recessive. In Prudhoe Land, and probably on Northumberland Ø, a basic sill forms precipitous benches (Fig. 74).

Type and reference sections. Accessible sections are rare because of the steep exposure. The type section is at the head of Kissel Gletscher, Northumberland Ø (section 37, Figs 48, 79); fairly accessible reference sections are at Morris Jesup Gletscher, west of Kap Trautwine and at Barden Bugt (Figs 71, 91).

Thickness. In Greenland between 15 and 40 m thick (thicker where a basic sill is present); at Clarence Head less than a metre is referred to the formation (Fig. 12).

Lithology. Interbedded, highly ferruginous sandstone, siltstone and shale, which all vary in abundance along strike. The sandstones are quartz arenites, commonly red and maroon; shale and siltstone are red, maroon and green. Conglomerates occur locally. All rock types weather in particularly dark hues.

Strata are thin to medium bedded; mudcracks are common, cross-bedding locally so. The sandstones are fine to medium grained and may be weakly laminated; the shales are recessive and variously silty, and both shales and siltstones are micaceous. Sandstones show wavy, lenticular and nodular bedding, and some shales are lensoid. Siltstones and fine-grained sandstones show loading and channelling into the shales and some beds are characterised by deep desiccation cracks. Liesegang rings and false bedding are common.

In most sections the basal sandstones are particularly ferruginous, with hematite-rich quartz arenites varying in grain size up to grit and granule beds. In places subarkoses occur. Thus at Kap Trautwine dusky red, coarse sandstone has scattered quartz granules up to 6 mm in diameter. The rock is composed of well-rounded quartz grains that have a heavy coating of hematite, occasional quartzite fragments and an isotropic interstitial matrix of hematite dust and detrital mica. At Clarence Head a similar rock type composes the entire formation (Frisch & Christie, 1982).

In Granville Fjord conglomerate beds up to half a metre thick occur near the base of the formation. Clasts, characteristically rounded, are composed of pale well-indurated orthoquartzite set in a sparse sandstone matrix. Clasts are usually pebble to cobble size; some boulders up to 40 cm exist.

Depositional environment. As basal beds of a major red bed sequence, the Kap Trautwine Formation represents the incoming of a strongly oxidising environment. The substantial amounts of hematite suggest fully aerated sedimentation, and some highly ferruginous grits and subarkoses are taken to be regolith products. Frisch & Christie (1982) suggest that rock of this type at Clarence Head represents a palaeosol. Channelling indicates stream action, and the fluvial sands and muds show common desiccation cracks, some of which are deeply penetrative suggesting repeated subaerial exposure.

Fossils. None known.

Boundaries and correlation. The lower boundary is that of the Baffin Bay Group; a distinct conformable contact accentuated by marked colour change to red beds (Figs 77, 78). In places, for example in Prudhoe Land, a basic sill, designated as part of the Kap Trautwine Formation, forms the lower boundary. The formation overlies the Clarence Head Formation and is followed conformably by the Robertson Fjord Formation (Figs 78, 85). Regionally the upper boundary is well demarcated but contact with overlying red beds can be transitional and somewhat arbitrarily placed.

The formation is deemed to be a lateral equivalent to basal beds of the Wolstenholme Formation in Greenland and to be coeval, at least in part, with the Goding Bay Formation of Canada (Figs 11, 12, 79).

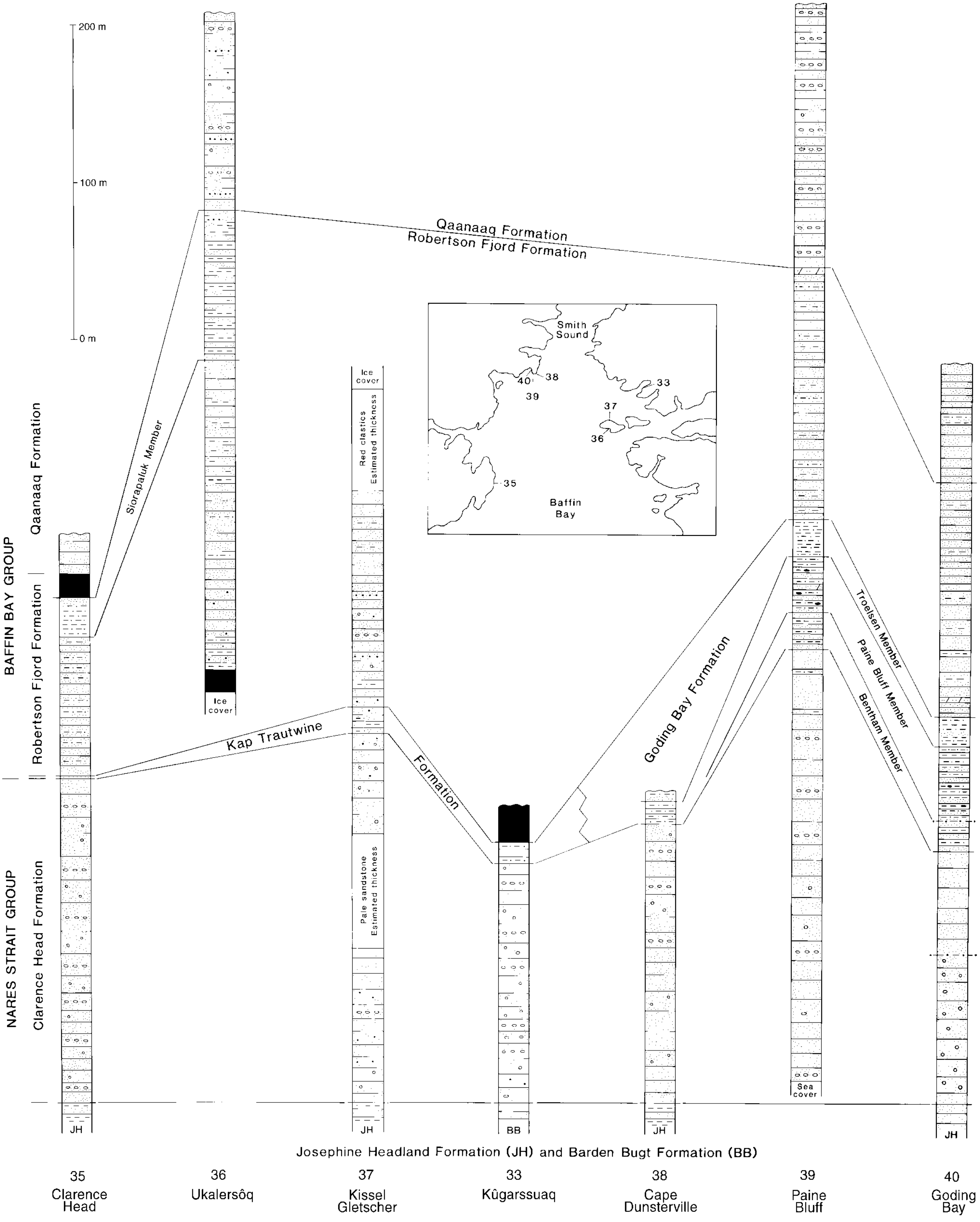


Fig. 79. Generalised sections of Clarence Head Formation of the Nares Strait Group and the Kap Trautwine, Goding Bay, Robertson Fjord and Qaanaaq Formations of the Baffin Bay Group. Canadian geology compiled from the following sources: section 35, Frisch & Christie (1982); section 38, Christie (1975); section 39, Christie (1975) and Frisch & Christie (1982); section 40, Jackson (1986). 37 is a composite section from Kissel Gletscher. Type sections: 35, Clarence Head Formation; 36, Robertson Fjord Formation; 37, Kap Trautwine; 39, Goding Bay Formation. Section locations: 33, Fig. 83; 35, Fig. 75; 36 and 37, Fig. 48; 38, 39 and 40, Fig. 80.

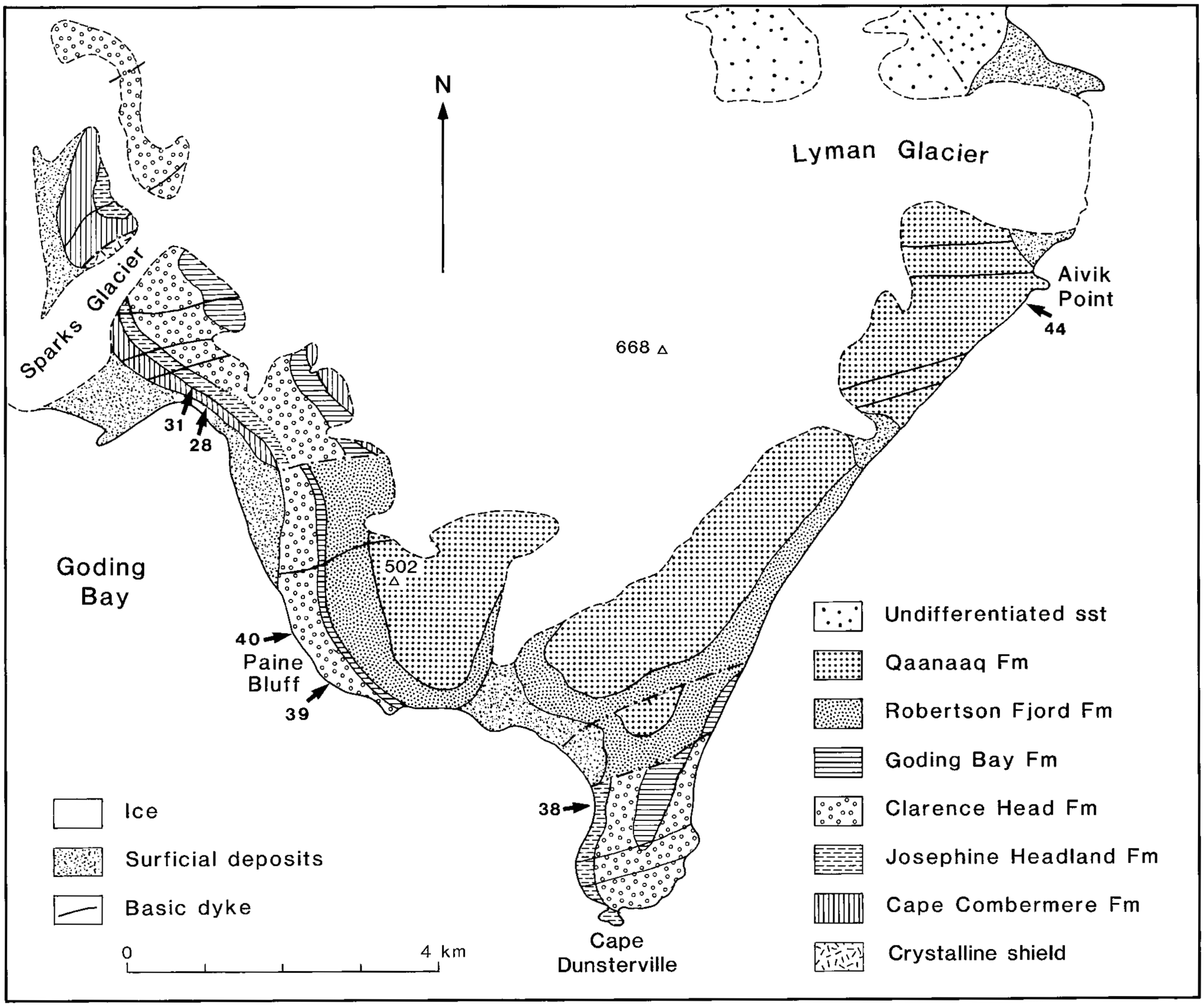


Fig. 80. Geological map of the region between Goding Bay and Lyman Glacier, Canada, showing locations of sections 28, 31, 38, 39, 40 and 44. Map and geology compiled from aerial photographs and based on interpretation of data in Christie (1975), Frisch & Christie (1982) and Frisch (1988). Heights are in metres. For location, see Fig. 2; for photographs of Goding Bay, see Figs 1, 81.

Goding Bay Formation

new formation

Composition. This formation equates with the lower part of unit V of Frisch *et al.* (1978), the 'Green Bed' and the basal part of unit 7 as logged by Christie (1975) at Paine Bluff, and units 4 and 5 of Christie (1975) at Cape Dunsterville. At Goding Bay it equates with all but the lower beds of unit V as defined by Frisch & Christie (1982, p. 8) and the entire thickness of unit 5 of Jackson (1986).

Name. After Goding Bay, the broad and prominent bay west of Cape Dunsterville (Figs 1, 2, 80).

Distribution. As yet only documented in the Goding Bay – Cape Dunsterville region but probably present northwards at least as far as Cadogan Inlet (Fig. 12).

Geomorphic expression and colour. Forms a conspicuous dark band forming steep to moderate slopes (Fig. 81). Dominantly green weathering and fairly resistant, with recessive red beds at the base and top.

Type and reference sections. On the northern slopes of Paine Bluff, eastern Goding Bay (section 39, Figs 79, 81). The sections measured by Christie (1975), Frisch (*in* Frisch & Christie, 1982) and Jackson (1986) are all in the same general area (Fig. 80); a reference section

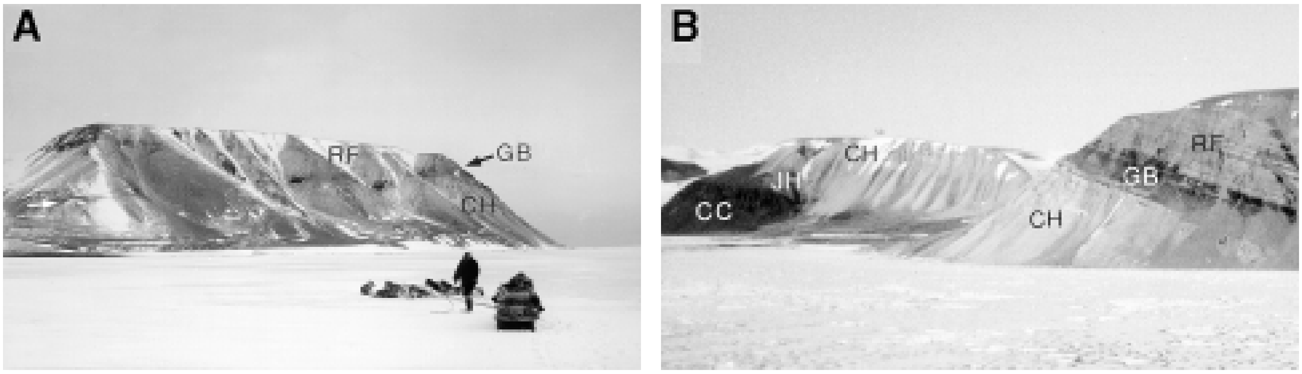


Fig. 81. East side of Goding Bay showing the Goding Bay Formation (GB) as conspicuous dark strata at the base of the Baffin Bay Group and visible even in the poorly exposed coastal slopes. CC = Cape Combermere Formation, JH = Josephine Headland Formation, CH = Clarence Head Formation, RF = Robertson Fjord Formation. **A:** view south-east, photo: R. L. Christie; **B:** view to the north with Paine Bluff in foreground, photo: G. D. Jackson. Relief about 500 m. For regional view of Goding Bay, see Fig. 1.

through the basal part of the formation is on the west side of the Cape Dunsterville peninsula (section 38, Fig. 79).

Thickness. Between 84 and 87 m thick at Paine Bluff, apparently thinning to less than 70 m to the south-east. The thickness of 87 m recorded by Jackson (1986) at Paine Bluff may be tectonically modified by faulting.

Dominant lithology. Multicoloured, interbedded sandstone, siltstone and shale, characterised by a middle unit of greenish strata flanked by red beds. The rocks are variously laminated, planar to lenticular, thin bedded, occasionally lensoid and show abundant ripple marks, cross-bedding and mudcracks, with some units characterised by channel and load structures. Minor carbonate lenses occur. A basic igneous rock (?sill) occurs north of Cape Dunsterville (R. L. Christie, personal communication, 1993).

Depositional environment. Intertidal to supratidal environments are suggested by Frisch & Christie (1982) for this sequence; Jackson (1986) suggests that middle strata are offshore deposits. The tripartite sequence of red-green-red strata is taken to indicate general changes in the oxidation-reduction potential.

Fossils. Microfossils; see under Paine Bluff Member.

Boundaries and correlation. The Goding Bay Formation overlies the Clarence Head Formation along a sharp

Fig. 82. The type section of the Goding Bay Formation (GB) (section 39, Fig. 79) at Paine Bluff showing division into Bentham (B), Paine Bluff (P) and Troelsen (T) Members. CH = Clarence Head Formation, RF = Robertson Fjord Formation. The view is east to the Cape Dunsterville peninsula; for location, see Figs 80, 81. Photo: K. W. Christie.

conformable contact that marks the incoming of a major period of red bed sedimentation. It is overlain, also along a fairly abrupt conformable contact, by the Robertson Fjord Formation (Fig. 81; see under Troelsen Member).

Correlation with the Kap Trautwine Formation is suggested. Both formations are characterised by iron-rich lithologies marking the abrupt onset of red bed sedimentation, and they share the same stratal position separating the Clarence Head and Robertson Fjord Formations (Fig. 79).

Subdivisions. The formation displays a tripartite subdivision well seen in the sea-cliffs of Paine Bluff (Fig. 82). The three units are formally defined from base upwards as the Bentham, Paine Bluff and Troelsen Members.

Bentham Member

new member

Composition. The basal sub-unit of unit IV of Frisch & Christie (1982) and sub-unit 5A of Jackson (1982) from Goding Bay constitute this member.

Name. Named for Robert Bentham (1913–1968), British geologist who, wintering in both Ellesmere Island and Greenland in the 1930’s, astutely correlated Thule beds between the two lands (see p. 18).

Distribution. Same as the formation.

Geomorphic expression and colour. Recessive, dark grey to maroon unit that is generally poorly exposed.

Type section. As for the formation.

Thickness. At Paine Bluff the member is between 20 and 24 m thick. Strata that might be referable to this member cannot be recognised in the poorly exposed section logged by Christie (1975) at Cape Dunsterville. It is possible that the member may thin or pinch out to the south-east.

Lithology. The Bentham Member is composed of red to maroon, thin- to medium-bedded, micaceous sandstone, siltstone and lensoid shale. Frisch & Christie (1982) mention shaly siltstone with buff to purplish partings, and Jackson (1986) minor buff to white sandstone in the lower part. Cross-bedding is present in the sandstone. The member shows a change along strike in the sandstone/shale-siltstone ratio.

Depositional environment. The red beds of this member are taken to indicate the regional regression or progradation of the shoreline following the shallow shelf sedimentation of the Clarence Head Formation. Jackson (1986) mentions fluvial deposition as streams readvanced into the basin.

Fossils. None known.

Boundaries. The lower boundary of the Bentham Member is that of the Goding Bay Formation; the upper is drawn at the first incoming of green strata, either siltstone or shale, that characterise the overlying Paine Bluff Member. This boundary is well demarcated and conformable (Fig. 82). Jackson (1986) indicates that in places the sharp contact is a fault.

Paine Bluff Member

new member

Composition. This member corresponds to the middle sub-unit of unit V of Frisch & Christie (1982) and sub-unit 5B of Jackson (1986) from Goding Bay, and unit 4 of Christie (1975) from Cape Dunsterville.

Name. After Paine Bluff, a prominent ice-capped coastal cliff on the east side of Goding Bay (Figs 1, 2, 80).

Distribution. Same as the formation.

Geomorphic expression and colour. A conspicuously dark green-weathering, resistant unit, generally forming steep slopes, but often scree covered. The strata break down into tabular debris.

Type section. As for the formation.

Thickness. Maximum thickness of 48 m thinning to the south-east to 36 m. At Cape Dunsterville the member is estimated at no more than 20 m.

Lithology. Thinly interbedded, green siltstone-shale and paler green to buff to brown fine-grained sandstone, for the most part arranged in fining-upward cycles (Christie, 1975; Jackson, 1986). The rocks are green on fresh and weathered surfaces; lenticular bedding is common in the sandstones, less so in shale beds. The sandstones are predominantly quartz arenites occurring in beds up to 20 cm thick; Frisch & Christie (1982) mention local dolomitic subarkose beds. According to Jackson (1986) sandstone decreases upward through the sequence; in the basal part it forms about 15% occurring in beds more than 1 m apart. The sandstones are massive to variously laminated, characterised by cross-bedding and ripple drift and climbing ripple laminae. They also show a variety of bottom structures in sharp contact with shale: load casts, flutes and channels. Some thin quartz conglomeratic lenses occur, as well as dark green weathering, coarse-grained carbonate lenses and concretions up to 25 cm thick (Jackson, 1986, fig. 65.4).

The siltstones are variously shaly, micaceous and show ripple marks and desiccation cracks. Marcasite nodules up to 2 cm in diameter and malachite staining characterise some beds.

About 3 km north of Cape Dunsterville at the outer coast, a conspicuous dark grey-green unit at least 7 m thick, composed of fractured to highly shattered rock is, on regional considerations, referred to the member. It is taken to be a basaltic or andesitic rock, possibly a sill (R. L. Christie, personal communication, 1993).

Depositional environment. The green colour of the Paine Bluff Member is taken to represent general anaerobic conditions. The quartz arenite beds may have been deposited by turbidity currents (Jackson, 1986); these beds and the marcasite nodules suggest that the member may represent an offshore basin or prodelta deposit.

Fossils. Organic-walled microfossils, including acritarchs and filamentous forms (G. D. Jackson, personal communication, 1993).

Boundaries. The lower boundary, as described earlier, is an abrupt contact with the Bentham Member. The upper contact to the Troelsen Member is equally distinct (Fig. 82), drawn on top of the last green shale bed. North of Cape Dunsterville, an igneous rock occurs at the contact.

Troelsen Member

new member

Composition. This member corresponds to the upper sub-unit of unit V of Frisch & Christie (1982), sub-unit 5C of Jackson (1986) and the basal beds of unit 7 of Christie (1975) from Paine Bluff, and unit 5 of Christie (1975) from Cape Dunsterville.

Name. After Johannes C. Troelsen (1913–1992), Danish geologist who instigated the use of common stratigraphic names to describe the Thule beds and younger strata on both sides of Nares Strait (see p. 18).

Distribution. Same as the formation.

Geomorphic expression and colour. Dark reddish-weathering, very recessive unit.

Type section. As for the formation.

Thickness. At Paine Bluff varies between 19 and 24 m. According to Frisch & Christie (1982) the unit shows an apparent six-fold thickening within a kilometre south-east of the type section – see discussion below under *Boundaries and correlation*. On Cape Dunsterville the present erosion surface caps the section with only about 7 m preserved.

Lithology. A complex sequence of interbedded shale, siltstone and very fine-grained sandstone, which are thinly laminated to very thin bedded. Rocks are red to greyish red on weathered surfaces, brown to mauve when fresh. Some shales are green; hematite-rich beds are deeper red in colour. Beds are generally less than 15 cm thick but some siltstone beds up to 35 cm thick occur near the base. Shales are generally fissile in beds less than 10 cm thick but in the upper strata Jackson (1986) notes green shale and siltstone beds and lenses up to 30 cm thick. Christie (1975) notes ropy and nodular bedding.

Other structures, noted by Frisch & Christie (1982), are ripple marks, cross-bedding and desiccation cracks; Jackson (1986) mentions common load structures, channel fillings and interference ripples, and likens brown siltstone and green shale with channels to rocks of the underlying unit, i.e. Paine Bluff Member.

Depositional environment. The return to red bed sedimentation, shown by the hematite-rich layers, indicates higher oxidation conditions. Mudcracks indicate periodic exposure; other sedimentary structures suggest current action. According to Jackson (1986) the strata may represent an overall delta plain or beach environment.

Fossils. None known.

Boundaries and correlation. As described earlier the lower boundary is a conformable contact to the Paine Bluff Member; the upper boundary corresponds to that of the Goding Bay Formation. This boundary at Paine Bluff is a well demarcated, planar contact seen as an abrupt colour change from dark red strata to the lighter red and purple, more banded rocks of the Robertson Fjord Formation (Fig. 82). This contact is a persistent feature along strike and can be picked out north and south of Paine Bluff even though the coastal section has scree cover (Fig. 81A).

This stratigraphy is difficult to reconcile with the suggestion by Frisch & Christie (1982) that 24 m of strata (Troelsen Member of this paper) thickens within a kilometre in the Paine Bluff area to a 120 m thick sandstone-shale sequence that represents unit 7 as logged by Christie (1975). This proposed thickening is not substantiated by my interpretation of the regional geology, and all but the lower 24 m of Christie's 120 m unit is here referred to the overlying Robertson Fjord Formation.

Robertson Fjord Formation

new formation

Composition. This formation encompasses the bulk of the strata previously referred to as member (c), and subsequently unit 5, of the Wolstenholme Formation as described by Dawes (1975, 1976b) from Northumberland Ø and to the middle part of unit V of Frisch *et al.* (1978) from Ellesmere Island. North of Siorapaluk,

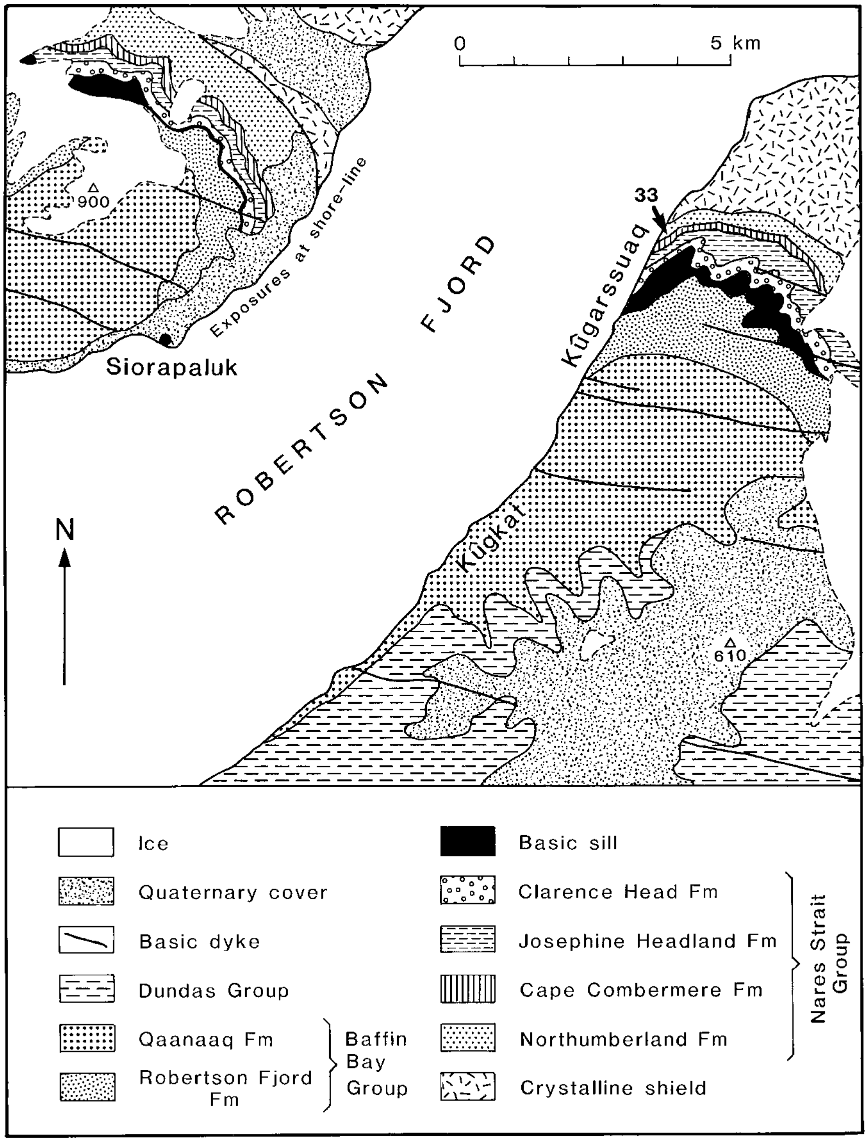


Fig. 83. Geological map of the central part of Robertson Fjord area, Prudhoe Land, Greenland, showing location of section 33 and the settlement of Siorapaluk. The massif Kûgarssuaq is shown in Fig. 74; that north of Siorapaluk in Fig. 85. The Kap Trautwine Formation is not shown but included with the basic sill that occurs at the boundary of the Nares Strait and Baffin Bay Groups. Heights are in metres. For location, see Fig. 2.

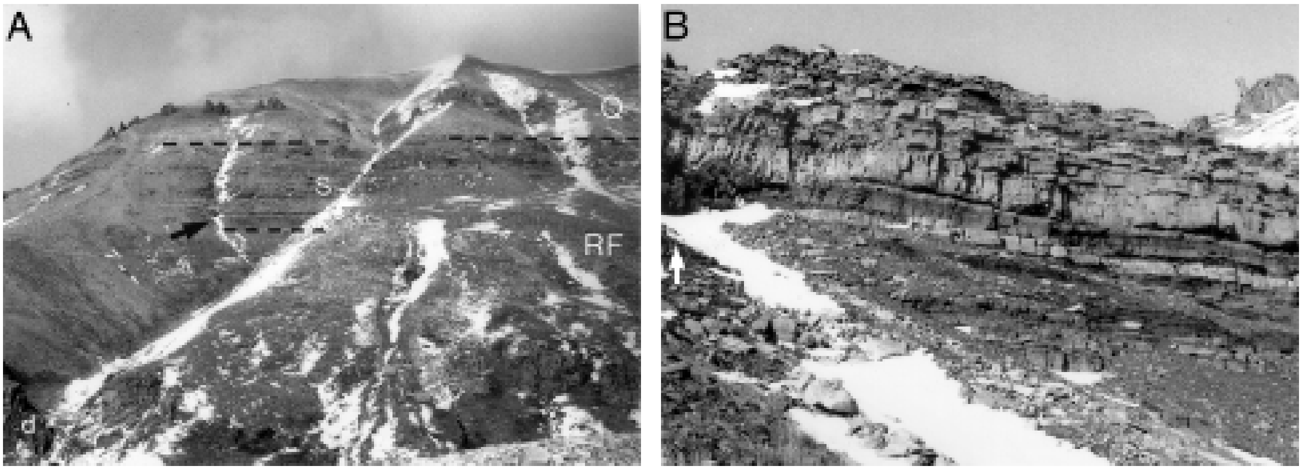


Fig. 84. The type section of the Robertson Fjord Formation (RF), south side of Ukalersôq, Northumberland Ø, overlain by the Qaanaaq Formation (Q) (section 36, Fig. 79). **A:** general view with dolerite (d) at base; **B:** detail of upper part (arrows mark common snow bank) showing interbedded sandstone-shale lithology of the Siorapaluk Member (S).

Robertson Fjord, it includes the lower part of the section examined by Munck (1941); at Goding Bay it corresponds to all but the basal 24 m of unit 7 of Christie (1975), the lower half (161 m) of unit VI of Frisch & Christie (1982) and the lower 151 m of unit 6 of Jackson (1986). At Clarence Head all strata of unit V of Frisch & Christie (1982), except the basal ferruginous bed, are referred to the Robertson Fjord Formation. In the 6-unit scheme pertaining to both sides of Nares Strait (Dawes *et al.*, 1982a), the formation broadly corresponds to the 'Red Sandstone unit' but with the basal beds of that unit being referred to the Kap Trautwine and Goding Bay Formations.

Name. After Robertson Fjord, a major inlet in Prudhoe Land (Figs 2, 83).

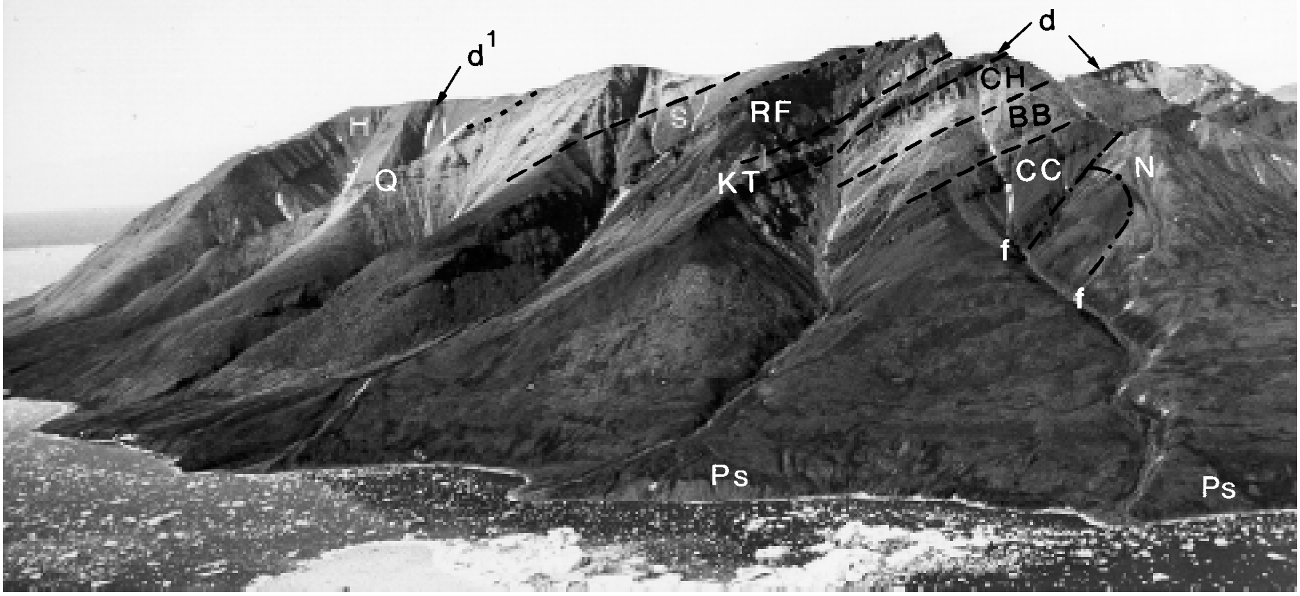


Fig. 85. The massif behind Siorapaluk (settlement just out of view left; located in Fig. 83) showing the Nares Strait and Baffin Bay Groups with a basic sill (d) at the group contact. Northumberland Formation (N), Cape Combermere Formation (CC), Barden Bugt Formation (BB), Clarence Head Formation (CH), Kap Trautwine Formation (KT), Robertson Fjord Formation (RF) composed of cliff-forming and more recessive intervals and with the Siorapaluk Member (S) at the top. Section is completed by the Qaanaaq Formation (Q) with the darker, thinner-bedded Herbert Member (H) forming the youngest strata. The unconformity with the Precambrian shield (Ps) is covered; d^1 = late Hadrynian basic dyke. Relief about 900 m.

Distribution. In Greenland: Prudhoe Land, western Steensby Land, Northumberland Ø and Hakluyt Ø; in Canada: present in main outcrop areas south of Johan Peninsula, viz. between Cadogan Inlet and Goding Bay and at Clarence Head (Fig. 12).

Geomorphic expression and colour. Overall reddish weathering, often banded and generally resistant forming cliffs to steep slopes. Recessive intervals occur and these form medium slopes and may be poorly exposed. One such unit forms the uppermost strata of the formation, viz. the Siorapaluk Member.

Type and reference sections. The section on the south side of Ukalersôq through the upper part of the formation is designated type section (section 36, Figs 79, 84); a better exposed section through the basal part is on the prominent buttress at the head of Kissel Gletscher (section 37, Fig. 79). Main reference sections are on the south side of Morris Jesup Gletscher (section 41, Fig. 89), at Clarence Head and Goding Bay (sections 35, 39, 40, Fig. 79).

Thickness. Ranges from 200 to 400 m in Greenland to between 150 and 160 m at Goding Bay; a little less than 120 m at Clarence Head (Fig. 12).

Lithology. A thick red bed sequence of varicoloured sandstones, siltstones and shales; overall, sandstones dominate but in many areas siltstones and shales predominate in the uppermost part. The sandstones are variously laminated and coloured, mainly red, purple, lilac and pink, with smaller intervals of orange, brown, buff and green rocks; siltstones and shales are mainly dark red, purple, grey and green. On an outcrop scale sandstone and siltstone-shale may be interbedded and this, together with the alternation of red and lighter coloured sandstones, produces a banded appearance typical of many parts of the formation. On a regional scale the formation is composed of units that are variously dominated by sandstone and siltstone-shale and this produces cliff-forming and more recessive intervals, as at Siorapaluk (Fig. 85).

The formation is dominated by thin- to medium-bedded, less commonly thick-bedded, fine- to coarse-grained sandstones that are commonly cross-bedded and ripple marked. Colour banding, striping and mottling are common and some intervals are characterised by liesegang rings. Planar to wavy lamination with ripple-drift lamination characterises some intervals (Fig. 86A). Bedding is usually planar, but it may be irregular with some channelling. Channels up to 2 m deep were noted in a section at Robertson Fjord. Cross-beds are mainly of the planar type with some herringbone stratification (Fig. 86B); ripples are commonly symmetrical with asymmetrical and interference types.

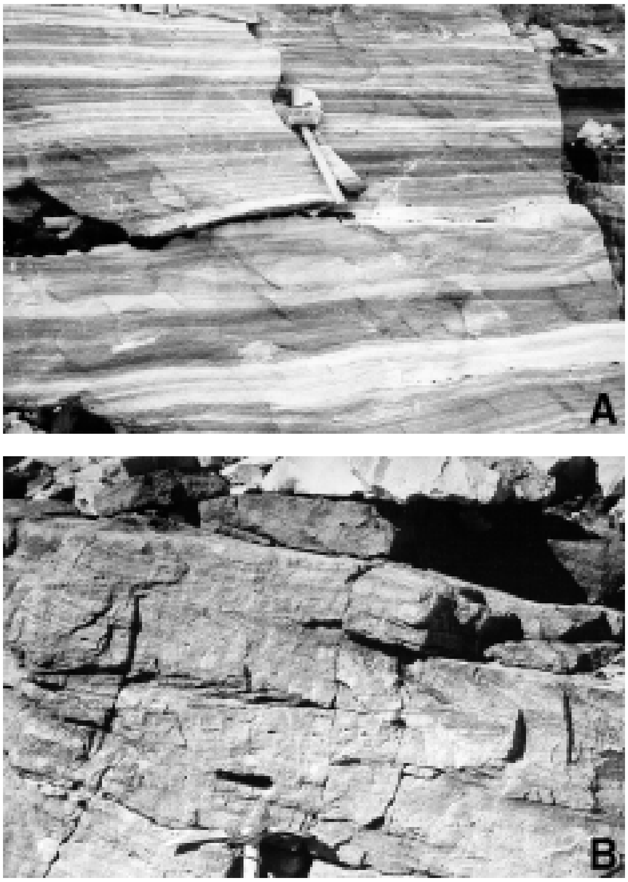


Fig. 86. Bedding characteristics of the Robertson Fjord Formation. **A:** planar- to wavy-bedded, banded sandstones showing beds with ripple-drift lamination. Kissel Gletscher, section 37. **B:** herringbone cross-beds. Paine Bluff, section 39. Ice-axe as scale; photo: R. L. Christie.

A typical feature in south-eastern outcrops is the presence of grits and conglomeratic intervals, either as discrete rudaceous beds or quartz granules and pebbles irregularly scattered and variously concentrated through the sandstone. Quartz pebbles are also concentrated as lag deposits on the truncated surfaces of cross-beds. Red and green shale lamellae and partings characterise some sandstone intervals; others show brecciation of partings and thin beds and some sandstones contain rip-up clasts. Jackson (1986) notes that green shale chips are disseminated throughout the formation at Goding Bay. Mudcracks are common on mud partings.

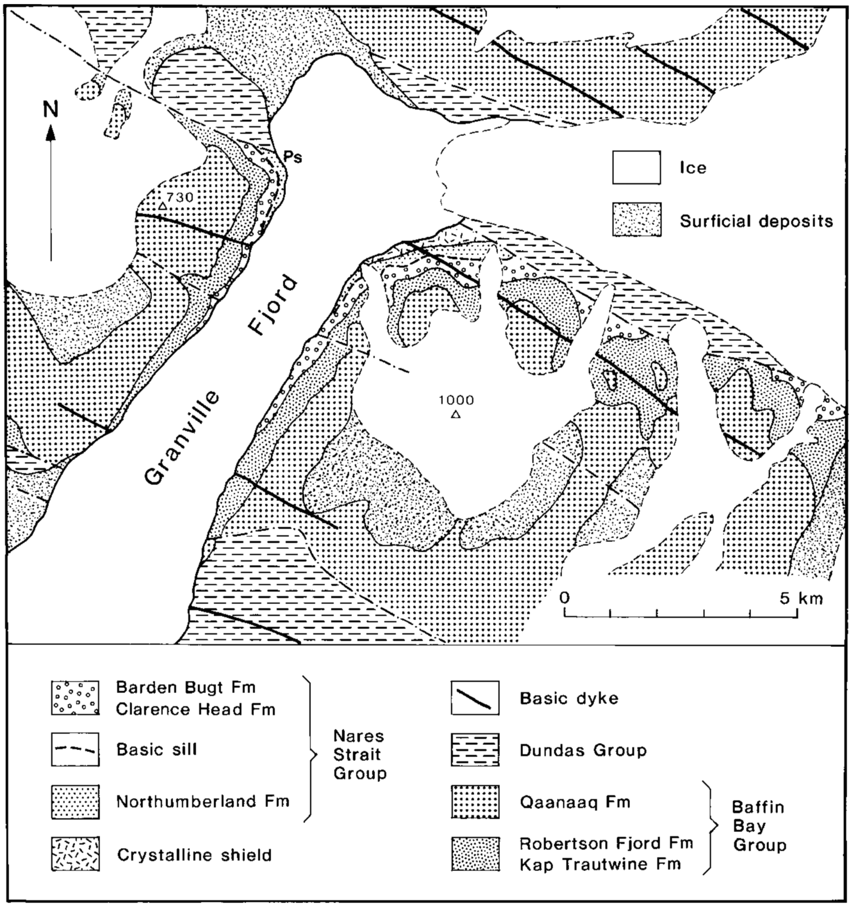


Fig. 87. Geological map of the region around the head of Granville Fjord, Steensby Land, Greenland. Ps = coastal outcrop of Precambrian shield. The Cape Combermere Formation is represented by a basic sheet (?sill). The Dundas Group at the head of the fjord is preserved in a down-faulted block (cf. Fig. 70). The position of the glacier front in Granville Fjord is from 1985. Heights are in metres. For location, see Fig. 2.

The sandstones are quartz arenites, variously ferruginous, with characteristically well-rounded quartz grains that show various amounts of authigenic overgrowth: some beds have typically subangular quartz. Iron oxide coating of quartz grains is common; the iron-rich types have in addition appreciable interstitial oxide (hematite ± limonite) that in places forms a ferruginous cement. Such rocks are typically dusky red to bluish purple and are commonly banded on a millimetre scale. Some rocks contain up to 3 per cent quartzite fragments, mostly rounded. Rock matrix varies from such monomineralic composition to material in which fine hematite is thoroughly disseminated occurring along with detrital sericite. Frisch & Christie (1982) note that the abundance of hematite increases upwards in the formation at Clarence Head where iron oxide is also present as veneers on bedding surfaces and along fractures. The fining-upward beds may grade from pink, medium-grained to dusky red fine-grained sandstone which is thinly coated with mammillary hematite or specularite.

Shale and siltstone occur as thin beds and partings but predominate in the upper part (see Siorapaluk Member). In a section described by Christie (1975) at Goding Bay, red shale is apparently common, occurring interbedded with sandstone throughout a 100 m thick section. From the same area, Jackson (1986) notes a unit of laminated to very thinly bedded shale and siltstone, some 3 m thick, about 40 m above the base.

Calcareous components are restricted to occasional carbonate laminae while carbonate rarely is seen in thin section. A recessive 3 m thick bed of laminated dolomitic subarkose is mentioned by Frisch & Christie (1982).

Depositional environment. The Robertson Fjord Formation is interpreted to represent deposition in terrestrial to shallow intertidal shelf environments. The highly ferruginous nature of some sandstones characterised by dense iron cement, suggests subaerial diagenesis, and aeolian deposition of some sandstones is probable. For the Clarence Head section Frisch & Christie (1982) suggest a gradually deepening littoral environment. In general terms this is applicable to the formation as a whole, with the fine-grained lithologies in the uppermost part (Siorapaluk Member), as well as detrital carbonates, representing supratidal to intertidal deposition. Abundance of cross-bedding, some of which is of herringbone type, suggests tide-dominated environments (Jackson, 1986); however, pebbly sandstone and rudaceous intervals with channels and some fining-upward units common in Greenland sections, particularly towards the south-east, is taken to indicate fluvial deposition.

Fossils. Organic-walled microfossils (acritarchs) – see under Siorapaluk Member.

Boundaries and correlation. The Robertson Fjord Formation rests conformably on the Kap Trautwine and Goding Bay Formations (Figs 77, 82, 85). Contact with the former is usually well demarcated and indicated by a distinct colour change; however, in some places the boundary is gradational and drawn somewhat arbitrarily where dark ferruginous beds give way to lighter-coloured, cross-bedded sandstones. The boundary with the Goding Bay Formation is discussed under the Troelsen Member.

The Robertson Fjord Formation is conformably overlain by the Qaanaaq Formation (e.g. Figs 84, 85). This is usually along a fairly sharp contact which is drawn at the incoming of the buff-weathering quartz arenites which are usually quite distinct from the red beds, particularly from the interbedded sandstone-siltstone-shale lithology (Siorapaluk Member) that in many areas characterises the upper part of the Robertson Fjord Formation. Where that member is missing, the boundary may be gradational and more arbitrarily placed after the last major red sandstone. In sections where there is a gradual colour change from red-purple beds through interbedded purple and lilac sandstone to pink and buff sandstones involving tens of metres of strata, e.g. the high sea-cliffs of western Northumberland Ø, the boundary is arbitrarily defined on regional considerations. At Paine Bluff in Goding Bay, the boundary is placed above a 3 m thick bed of dolomitic subarkose described by Frisch & Christie (1982; section 39, Fig. 79).

Both the lower and upper boundaries of the Robertson Fjord Formation may be followed by a basaltic sill, for example at Kûgarssuaq in Robertson Fjord, Prudhoe Land (lower, Fig. 74) and at Clarence Head, Canada (upper, Figs 75, 79).

In south-eastern exposures the Robertson Fjord Formation interdigitates with the Wolstenholme Formation and the boundary between the two formations can only be defined arbitrarily. Lack of exposure in northern Prudhoe Land prohibits precise knowledge of relations to the Smith Sound Group, but the formation is regarded to be, at least in part, the lateral equivalent of the Rensselaer Bay Formation (Figs 11, 120).

Subdivisions. In Greenland in particular, the Robertson Fjord Formation can be subdivided into a number of readily recognisable units. However, the lithostratigraphy of these has not been studied in detail, and formal definition here is restricted to two members: Granville Fjord and Siorapaluk Members.

Granville Fjord Member

new member

Composition. Shale-siltstone interval of the lower red member of the Wolstenholme Formation at Granville Fjord of Dawes (1976a).

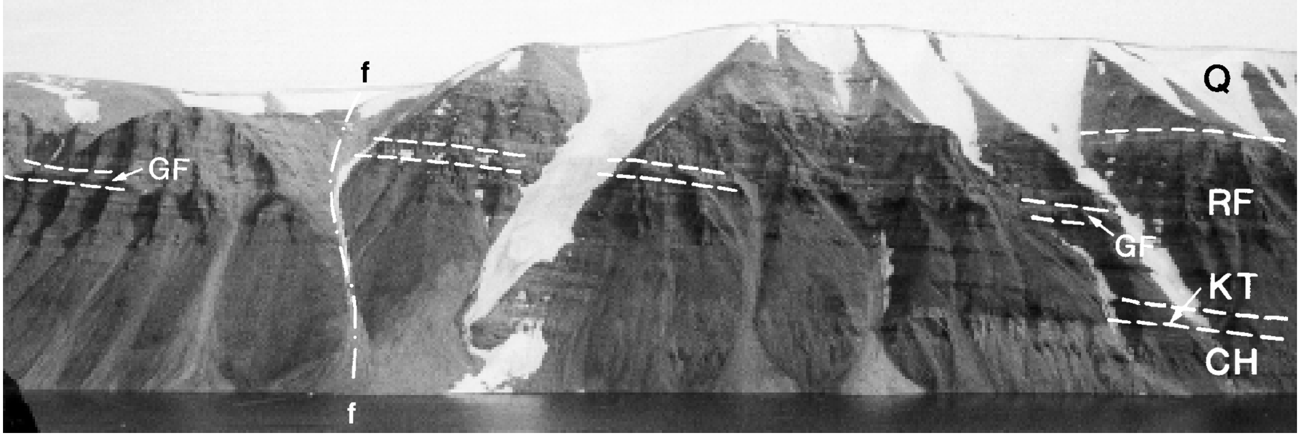


Fig. 88. The Granville Fjord Member (GF) as a dark marker in the middle of the Robertson Fjord Formation (RF) on the eastern side of Granville Fjord, Steensby Land. Down-faulting to the north, see Fig. 87. CH = Clarence Head Formation, KT = Kap Trautwine Formation, Q = Qaanaaq Formation. Cliffs are about 700 m high.

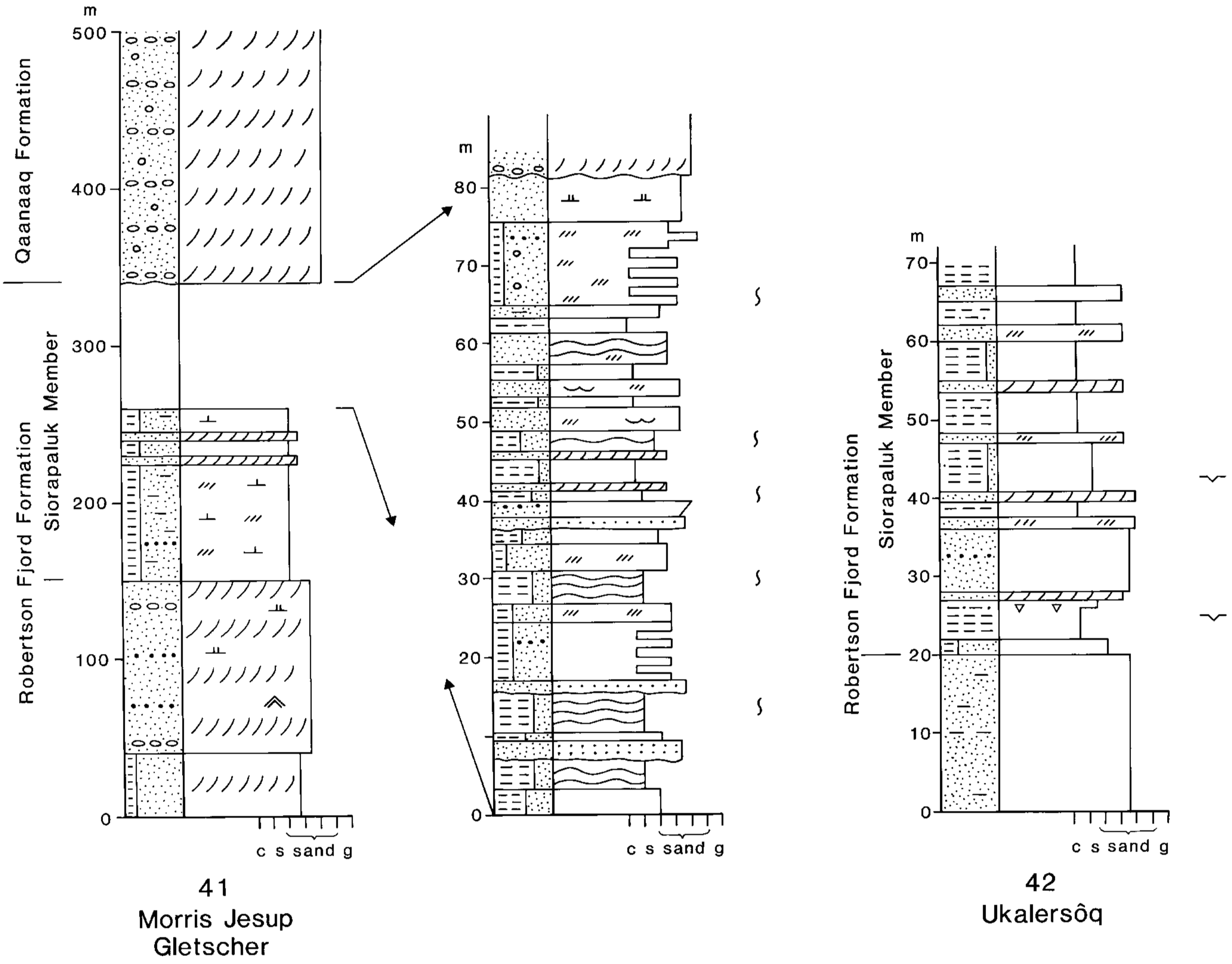


Fig. 89. Stratigraphic logs of the upper part of the Robertson Fjord Formation and basal strata of the Qaanaaq Formation. Section 41 is the type section of the Siorapaluk Member located in Fig. 90; section 42, located in Fig 48, refers to part of the generalised section 36 that is given in Fig. 79.

Name. After Granville Fjord, the main fjord of southern Steensby Land (Figs 2, 87).

Distribution. Steensby Land and south-eastern Prudhoe Land.

Geomorphic expression and colour. A dark purple-weathering, resistant unit that forms a conspicuous regional marker.

Type area and reference section. The type area is the sea-cliffs of Granville Fjord (Fig. 88). The single section examined is on the west side of the fjord at the pronounced break in the cliffs.

Thickness. About 15 m.

Lithology. Thin-bedded, purple, ferruginous sandstone with shale and siltstone interbeds. The sandstones are predominantly fine to medium grained but with some variation to coarse sandstone with quartz grains reaching 1 mm or more in size. The sandstones and siltstones are variously laminated; some have shale partings, others show a well-developed dense planar to wavy lamination. Fining-up cycles occur with the sandstones having sharp contacts to bounding shale-siltstone. Sandstones display cross-bedding and ripple marks, and argillaceous surfaces show mudcracks.

The top of the member is composed of a dark purplish grey to almost black, fine-grained sandstone 10–15 cm thick. The bed has a massive appearance so that at a distance it can easily be mistaken for a basic sill, but where examined the rock contains discontinuous thin micaceous laminae.

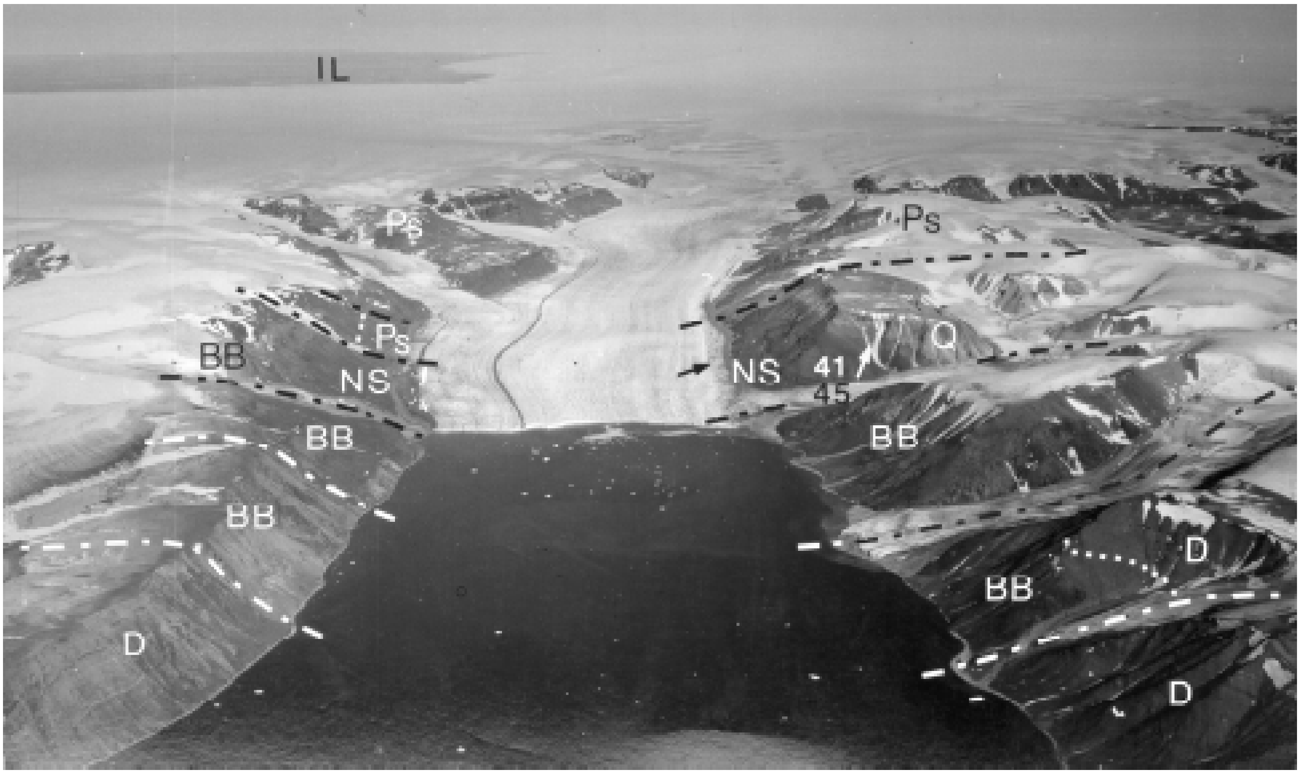


Fig. 90. View north-west up Morris Jesup Gletscher, Prudhoe Land, Greenland, showing fault blocks, and location of sections 41 and 45 that are given in Figs 89 and 99. Arrow on glacier locates view seen in Fig. 91A. Inglefield Land (IL) in the background. Ps = Precambrian shield, NS = Nares Strait Group, BB = Baffin Bay Group, Q = Qaanaaq Formation, D = Dundas Group. Coastal cliffs are about 600 m high. Photo: 543 B-NØ 2738, July 1950; Kort- og Matrikelstyrelsen, Denmark.

Thin sections show a range in quartz mode. Fine-grained arenites and siltstones are characterised by moderately well-sorted subangular to rounded quartz with limited size variation and with interstitial iron oxide, silica cement and mica; coarse types have a pronounced size bimodality with exceptionally well-rounded oxide-coated quartz grains which are set in a fine matrix. Such coarse rocks may be grain or matrix supported, the texture varying within the same rock.

Depositional environment. The member is taken to represent an interval of fluvial deposition in a general oxidising environment. Mudcracks indicate repeated subaerial exposure.

Fossils. None known.

Boundaries. The Granville Fjord Member has conformable lower and upper contacts with unnamed sandstones of the Robertson Fjord Formation. The lower boundary is well demarcated by a colour change to deep purple, but lithologically it is fairly gradational, drawn at the main incoming of shale or siltstone beds. The upper boundary is sharply defined at the top of the thin, dark purplish grey, massive sandstone described above.

Siorapaluk Member

new member

Composition. The member includes the uppermost strata of unit 5 of Dawes (1976b) from Greenland and the uppermost sub-unit of unit V of Frisch & Christie (1982) from Clarence Head.

Name. After Siorapaluk, Robertson Fjord, the northernmost native settlement in Greenland (Figs 2, 83).

Distribution. In Greenland, Prudhoe Land south-east of Diebitsch Gletscher, Northumberland Ø and possibly western Steensby Land; in Canada, at Clarence Head and possibly in the Lyman Gletscher area.

Geomorphic expression and colour. Dark red to deep purple weathering, generally recessive and rather

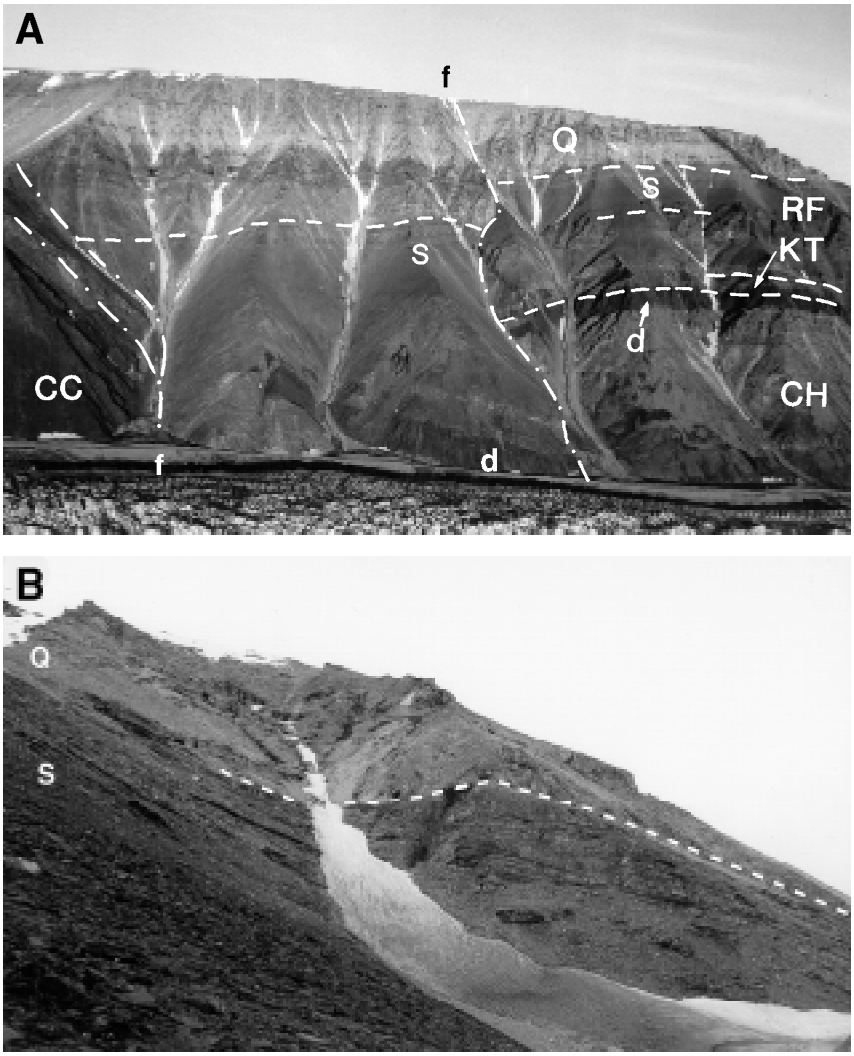


Fig. 91. The Siorapaluk Member (S) of the Robertson Fjord Formation (RF) at Morris Jesup Gletscher, Prudhoe Land. **A:** faulted exposures showing the member as a conspicuous recessive unit overlain by pale sandstones of the Qaanaaq Formation (Q). The division into a lower dark unit and a thinner paler unit is visible. CC = Cape Combermere Formation, CH = Clarence Head Formation, KT = Kap Trautwine Formation, d = dolerite sill. Height of cliff above glacier about 750 m; **B:** the type section; section 41, Fig. 89. Locations are shown in Fig. 90.

poorly exposed. Where the member contains prominent sandstones, medium to steep slopes occur.

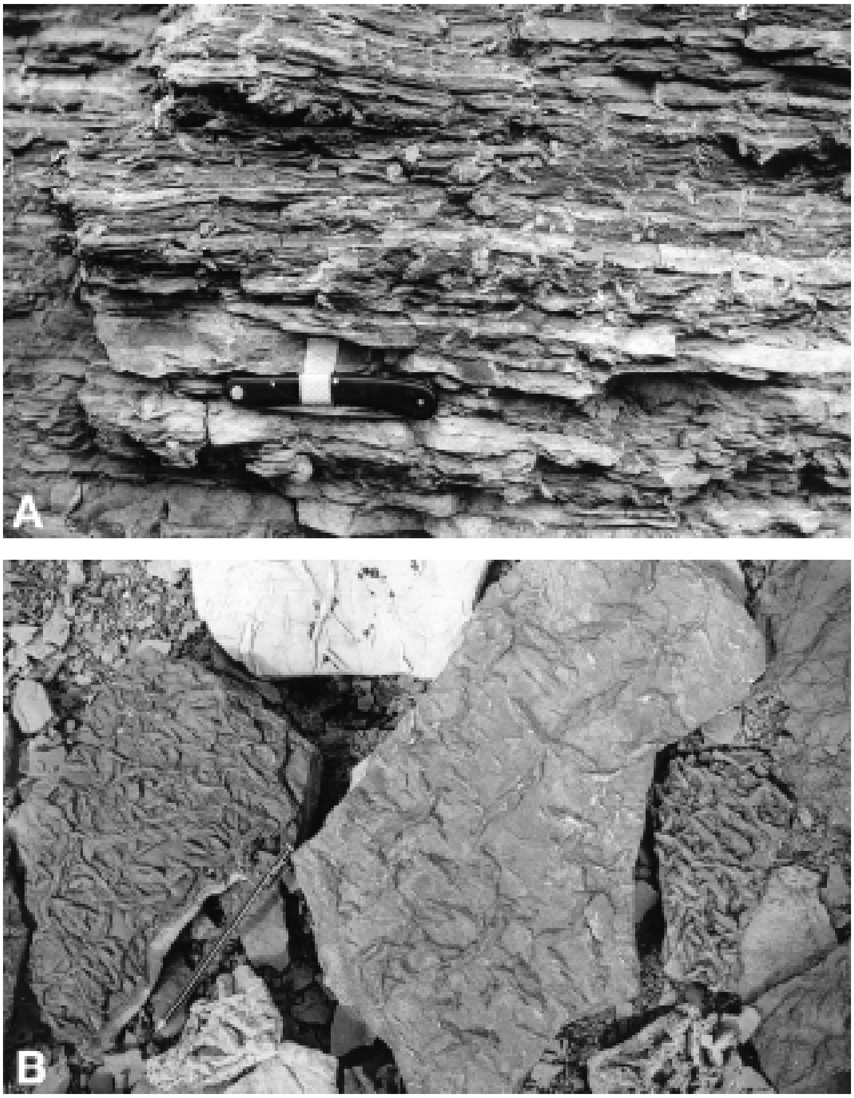
Type and reference sections. The type section is on the south-eastern side of Morris Jesup Gletscher, Prudhoe Land (section 41, Figs 89, 90, 91B). Reference sections occur at Ukalersôq, Northumberland Ø (section 36, Fig. 79; section 42, Fig. 89) and at Clarence Head (section 35, Fig. 79).

Thickness. The member reaches a maximum thickness of about 190 m in Prudhoe Land; the thinnest section is at Clarence Head, where the member is 26 m thick.

Lithology. Dark red-purple weathering, thinly to very thinly interbedded sandstone, siltstone and shale. The rocks are varicoloured: sandstones are mainly purple with brown to buff, grey to pale green and greenish white varieties; siltstones and shales are mainly deep purple and green. The ratio of sandstone to siltstone-shale varies both vertically and laterally; in general terms the sandstones coarsen upwards. The type section is divisible into a lower unit of deep purple, fine-grained sandstone, siltstone and shale, and an upper unit in which paler, generally coarser sandstone is intercalated with lower unit lithologies (Fig. 91). Medium-bedded, pale green sandstone forms the uppermost 5 m of the member. At Clarence Head dark laminated hematitic sandstones characterise the top of the member; the bulk of the unit is dark red, shaly siltstone flecked with muscovite (Frisch & Christie, 1982).

The strata are planar to lenticularly bedded. In the type section wavy to irregular bedding surfaces characterise several levels, and thin sandstone beds less than a centimetre thick may be completely disrupted and enveloped by shale. Some of the bedding irregu-

Fig. 92. Thin-bedded sandstone-shale lithology of the Siorapaluk Member of the Robertson Fjord Formation showing prominent mudcracks.
A: irregular sandstone infillings disrupting shale; penknife is 7 cm long;
B: diastasis cracks on bedding planes seen as sinuous to curvilinear structures, pencil as scale. Morris Jesup Gletscher, section 41.



larities seem due to loading or channelling of sandstone into shale, but others are due to diastasis cracks (Fig. 92).

The sandstones are generally fine grained and with the siltstones may be variously laminated. Most sandstones have silty or shaly partings but some thin pale structureless beds also occur; these are of medium to coarse grain size grading into grits with scattered quartz granules up to 2 mm across. Some sandstones show small-scale cross-bedding, ripple marks and in places flaser bedding. Mudcracks occur locally. Dusky red hematite-rich sandstone is present sporadically in beds 10–30 cm thick.

The sandstones are quartz arenites in which quartz varies from rounded to subangular. Fine-grained rocks are generally well sorted with original grain boundaries indistinct; coarser types are mainly grain supported with rounded quartz in an interstitial matrix of hematite and sericite. Some sandstones show bimodal quartz with well-rounded grains set in a much finer-grained subrounded to subangular matrix. Some rocks show appreciable secondary enlargement of well-rounded quartz grains. Glauconite is present in some sandstones, and samples from Northumberland Ø have matrix carbonate. Shales can be fissile, and both shales and siltstones are micaceous.

Depositional environment. The fine interlayering of the sandstones and shales, small-scale cross-beds with flaser and lenticular bedding indicate overall deposition in a low-energy shallow-water environment, such as an intertidal sand flat or a tidal delta plain. White, coarser-grained sand sheets with irregular bases are possibly tidal or subtidal channel sands.

Fossils. Acritarchs from shales on Northumberland Ø and at Morris Jesup Gletscher contain an assemblage of eight species (Vidal & Dawes, 1980). The most age diagnostic taxa are *Leiosphaerida asperata, Chuaria circularis* and *Kildinella chagrinata*, all typical Late Riphean forms.

Boundaries and correlation. The Siorapaluk Member has a well-defined and commonly sharp boundary to the underlying cliff-forming sandstones drawn at the base of the first shale-siltstone bed (Fig. 91A). It is often marked by a clear break in slope. The upper limit is the formational boundary, viz. a conformable contact with the buff sandstones of the Qaanaaq Formation (Fig. 91B).

The relationship to the Smith Sound Group in the north is not exposed but there is lithological similarity to the Hatherton Bugt Member of the Rensselaer Bay Formation, which is a possible lateral equivalent.

Wolstenholme Formation

redefined

Composition. Redefinition entails drastic reduction of stratigraphic range and geographical distribution. The redefined Wolstenholme Formation corresponds to the lower red sandstone of Chamberlin (1895) from Inglefield Bredning (Figs 6, 95). It is grossly equivalent to the lower reddish part of the Wolstenholme Quartzite/ Formation of Kurtz & Wales (1951), Davies (1957), Davies *et al.* (1963) and Fernald & Horowitz (1964) as described from the North Star Bugt area and environs, as well as the lower red bed member of the formation as illustrated by Dawes (1976a) from south-eastern outcrops of the Thule Basin, viz. Bylot Sund, Steensby Land and south-easternmost Prudhoe Land. It has to be stressed that, as redefined, the formation does not include any strata from Northumberland Ø, Prudhoe Land and Ellesmere Island previously referred to the Wolstenholme Formation by Dawes (1976b, 1979a), Frisch *et al.* (1978), Frisch & Christie (1982), Dawes *et al.* (1982a) and Jackson (1986).

Name. After Wolstenholme Ø, the island forming the western entrance to Bylot Sund (Figs 2, 93).

Distribution. Forms the south-eastern outcrops of the Thule Basin, viz. Wolstenholme Ø and on the opposing mainland at Magnetitbugt, De Dødes Fjord, lands bordering Wolstenholme Fjord, Olrik Fjord and Inglefield Bredning, Nunatarssuaq, with isolated outcrops

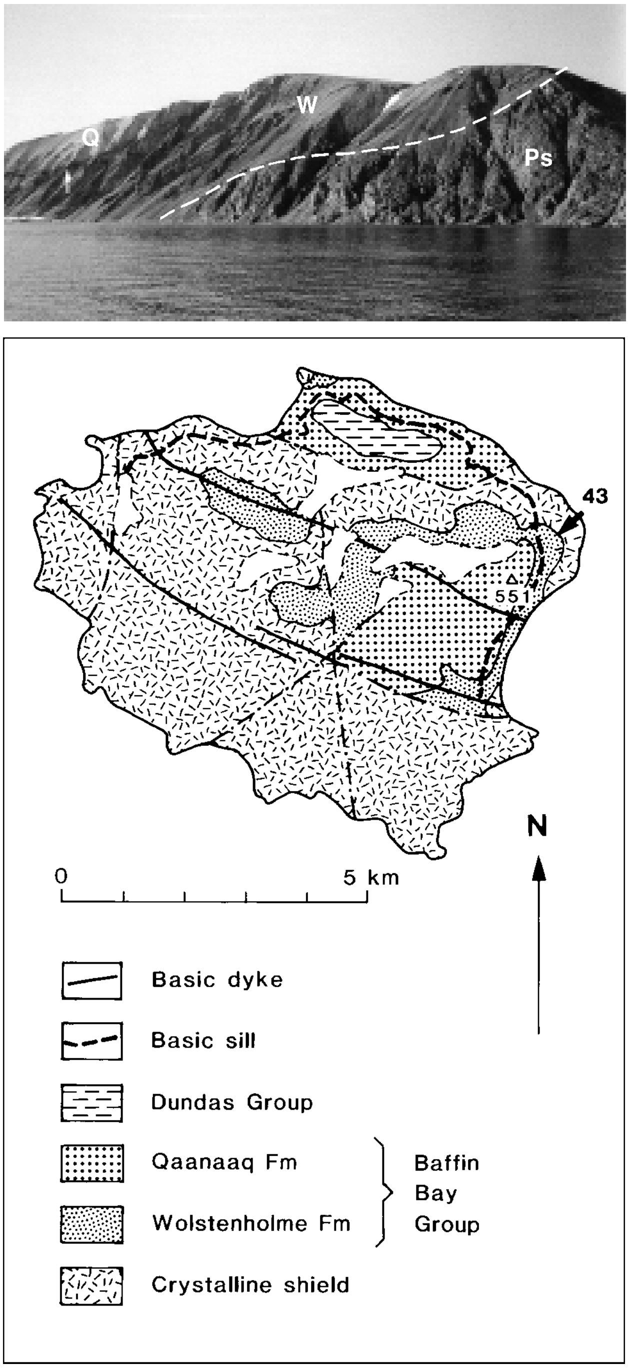


Fig. 93. Geology of Wolstenholme Ø, Greenland, showing the location of section 43. The photographic view is of the north-eastern sea-cliffs (section 43) showing the Wolstenholme Formation (W) overlying the Precambrian shield (Ps). The contact with the Qaanaaq Formation (Q) is partly followed by a basalt sheet (arrowed). Height of 551 is in metres. For location, see Fig. 2.

at Freuchen Nunatak, Dryasbjerg, Rampen and east and west of Academy Bugt (Figs 2, 12).

Geomorphic expression and colour. A dark red to purple weathering resistant unit, commonly banded and generally forming cliff sections and steep coasts. The thin, isolated inland outliers are poorly exposed.

Type and reference sections. The type section is that described by Davies *et al.* (1963) from Wolstenholme Ø (section 43, Figs 93, 94). A well-exposed and accessible reference section, examined but not measured, is at Tikeraussaq on the south side of Inglefield Bredning (Fig. 95); sections in Olrik Fjord are generally poorly exposed (see Fig. 103).

Thickness. The formation has an estimated maximum thickness of about 250 m in the Inglefield Bredning area, thinning to less than 100 m in Wolstenholme Fjord. This regional thinning is thought to continue farther east and south but the isolated outliers forming marginal strata of the Thule Basin, for example at Academy Bugt at the head of Inglefield Bredning, are truncated by the present erosion surface (Fig. 12). If the relationship with pale sandstones of the overlying Qaanaaq Formation at Freuchen Nunatak (Fig. 2) is stratigraphic (rather than tectonic), thinning down to perhaps some tens of metres is demonstrable.

Lithology. A red bed sequence dominated by sandstones with grits, pebbly sandstones and conglomerates (Fig. 96), and minor amounts of siltstone and shale. Where fresh, the sandstones – variously ferruginous quartz arenites – are red-pink to purple-maroon-lilac in colour, weathering in darker hues, but orange, brown and buff varieties also occur. Generally, the rocks are medium to coarse grained with common gradation to granule and conglomeratic beds; a characteristic feature is the very common lateral and vertical variations in grain size.

The sandstones vary from thin- to very thick-bedded, commonly with trough and tabular planar cross-bedding, and ripple marks. Erosive undulose bases to sandstone and conglomerate beds are common locally as are scour-and-fill structures. Oligomict quartz-pebble conglomerates were noted at levels throughout the formation, but in some sections rudaceous rocks are rare or absent. Conglomerates vary in bed size and in density of pebbles. Many conglomerate incursions have diffuse contacts with pebbly sandstone and sandstone; discrete sheets are lenticular to wedge-shaped and up to 2 m thick. Some fining-upward beds from conglomerate to sandstone occur. Typical conglomerates are matrix-supported with pebbles several centimetres long composing up to 70% of the rock (Fig. 96). Sporadic quartz clasts are of cobble dimension and boulders of quartz up to 30 cm were noted by Kurtz & Wales (1951) composing a 5 m thick conglomerate near the base of the formation on Wolstenholme Ø.

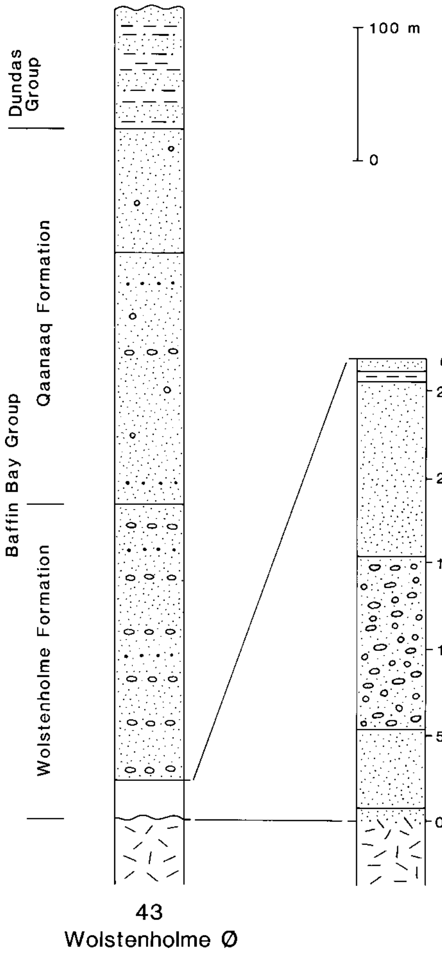


Fig. 94. Generalised sections of the Wolstenholme and Qaanaaq Formations (Baffin Bay Group) on Wolstenholme Ø. Compiled from data in Davies *et al.* (1963). This is the type section of the Wolstenholme Formation; for location, see Fig. 93.

True basal conglomerate is inconspicuous. Where the unconformity between the Wolstenholme Formation and crystalline rocks has been examined by this author, for example on the north side of Wolstenholme Fjord (Fig. 97), the basal beds are brownish orange, regularly bedded, medium-grained, ripple-marked sandstones, in places with a basal 0–10 cm thick conglomerate mainly composed of quartz pebbles but with small angular to subrounded fragments of granite. Some

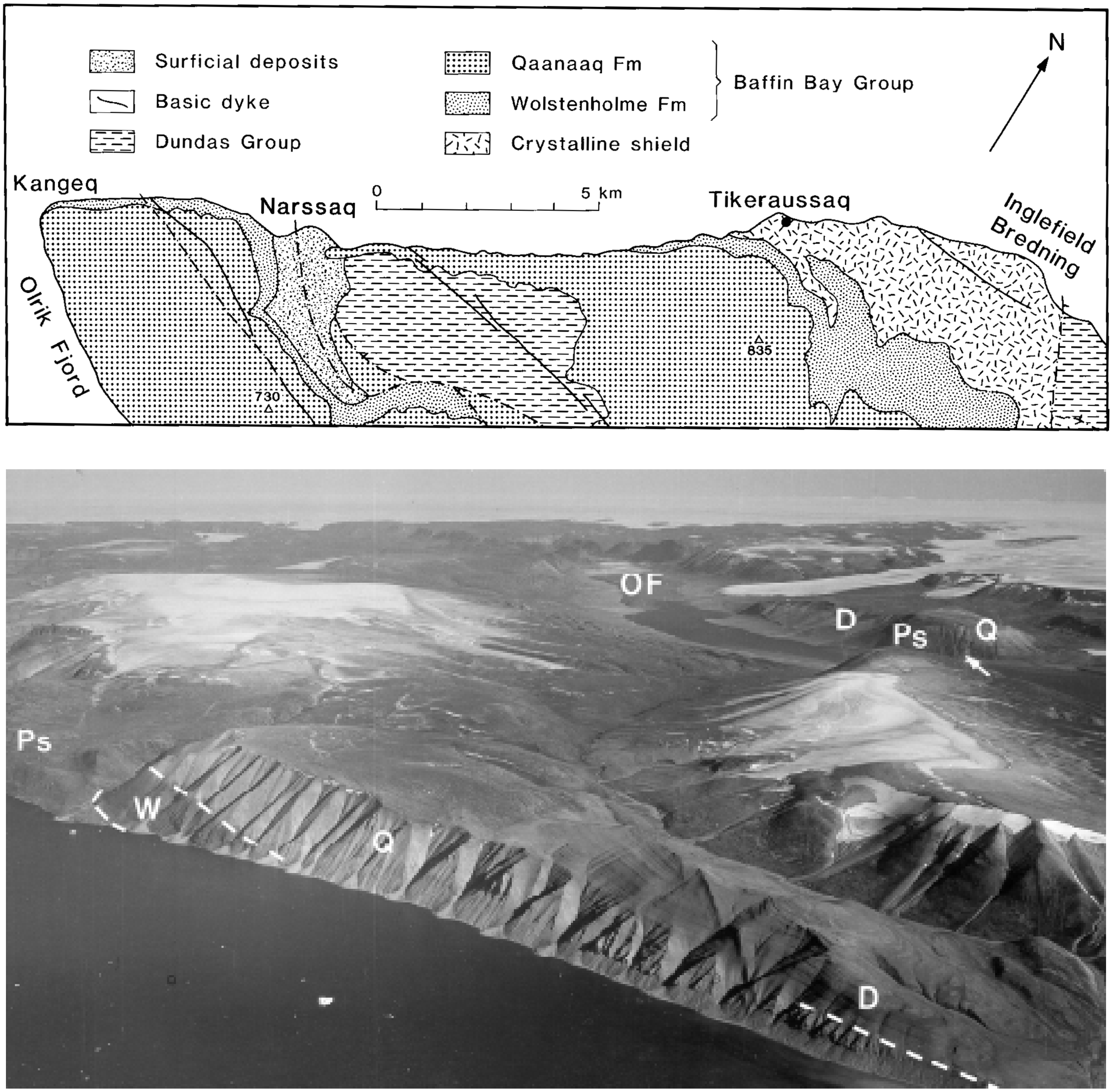


Fig. 95. Geology of the Tikeraussaq area, on the south side of Inglefield Bredning, Greenland, illustrating the westernmost outcrops of the Wolstenholme Formation (W). The photographic view is east to Olrik Fjord (OF) with the Inland Ice in the distance. The Precambrian shield (Ps) forms a basement high (Tikeraussaq High, see Fig. 119) over which the Baffin Bay Group is draped. The nearest exposures to the north around Bowdoin Fjord (Fig. 98) and to the south in Steensby Land (Fig. 87) preserve strata of the Nares Strait Group that farther east are cut out and define the south-eastern margin of the central part of the Thule Basin. The fault block (arrowed), preserving Wolstenholme and Qaanaaq (Q) Formations, is flanked on the east by the Dundas Formation (D). The tripartite division seen at the coast (W, Q and D) corresponds to the three stratigraphic units recognised initially by Chamberlin (1895) and adopted by Koch (1926, 1929a) for the entire Thule district. Heights are in metres. Photo: 543 K1-Ø 2803, July, 1950; Kort- og Matrikelstyrelsen, Denmark. For location, see Fig. 2.

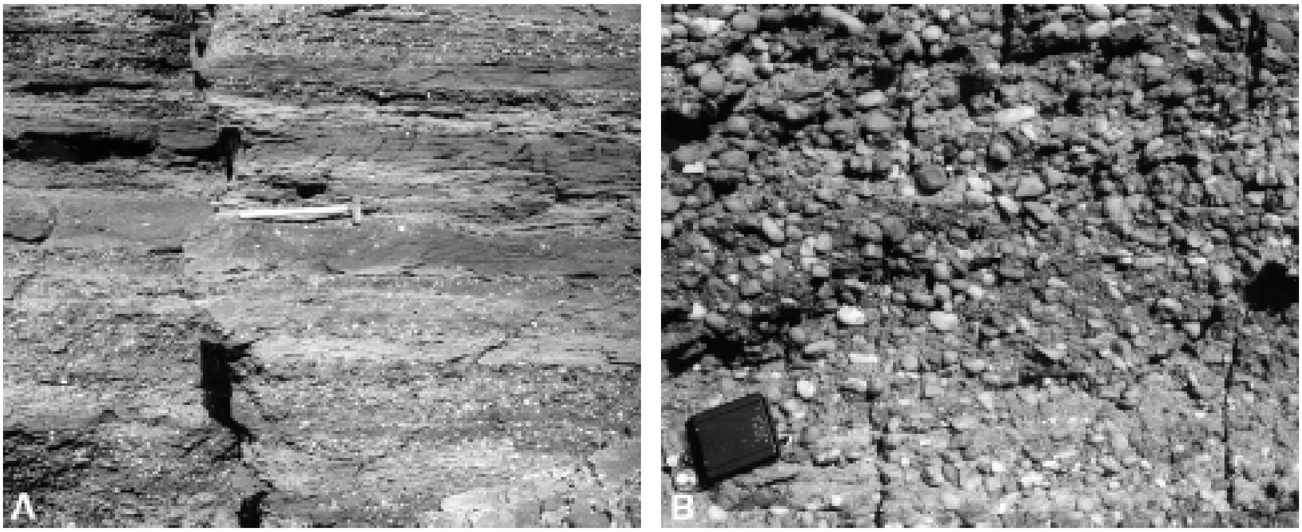


Fig. 96. Bedding characteristics of the Wolstenholme Formation at Kangeq, Inglefield Bredning (Fig. 95). **A:** red sandstone with shallow cross-bedding, pebbly sandstones and quartz-pebble conglomerates; **B:** matrix-supported quartz-pebble conglomerate on bedding plane; the compass is 10 cm long.

beds about 3 m above the contact contain intraformational conglomerate. Sandstone dykes 1 to 3 cm thick occur as joint infillings in the underlying gneiss. The gneiss is lilac to reddish in colour, well jointed and containing extraneous hematite and quartz. A similar contact has been described from Wolstenholme Ø by Kurtz & Wales (1951), who interpreted the basal siltstones as reworked residual soils with scattered pebbles of crystalline rock.

Minor dark purple siltstone and shale occur interbedded with fine-grained sandstones. Shale laminae and partings occur, and some sandstone beds contain rip-up shale chips. Desiccation cracks can be common on the upper surfaces of shale beds and on shale-siltstone partings. On Wolstenholme Ø, Davies *et al.* (1963) report a yellow shale unit 60 cm thick. Argillaceous beds give rise to some of the banding that typifies the formation but other lithological variations causing distinct banding are beds of dark purple to dark bluish grey hematite-rich sandstone. These beds range from a few centimetres thick up to about a metre.

Ferruginous banding occurs on all scales from regular, fine lamination parallel or subparallel to bedding, to liesegang rings and coarser discordant bands. Such banding is often more conspicuous than bedding and can be easily mistaken as such. Three generations of liesegang rings, determined by cross-cutting relationships, have been recorded on one rock slab.

Fig. 97. The unconformity between the Wolstenholme Formation (left) and the Precambrian shield. The basal beds are ripple-marked, cross-bedded sandstone with some grits and conglomerate. Basal sandstone bed (in centre) is *c.* 20 cm thick. North side of Wolstenholme Fjord; location is given in Fig. 107.

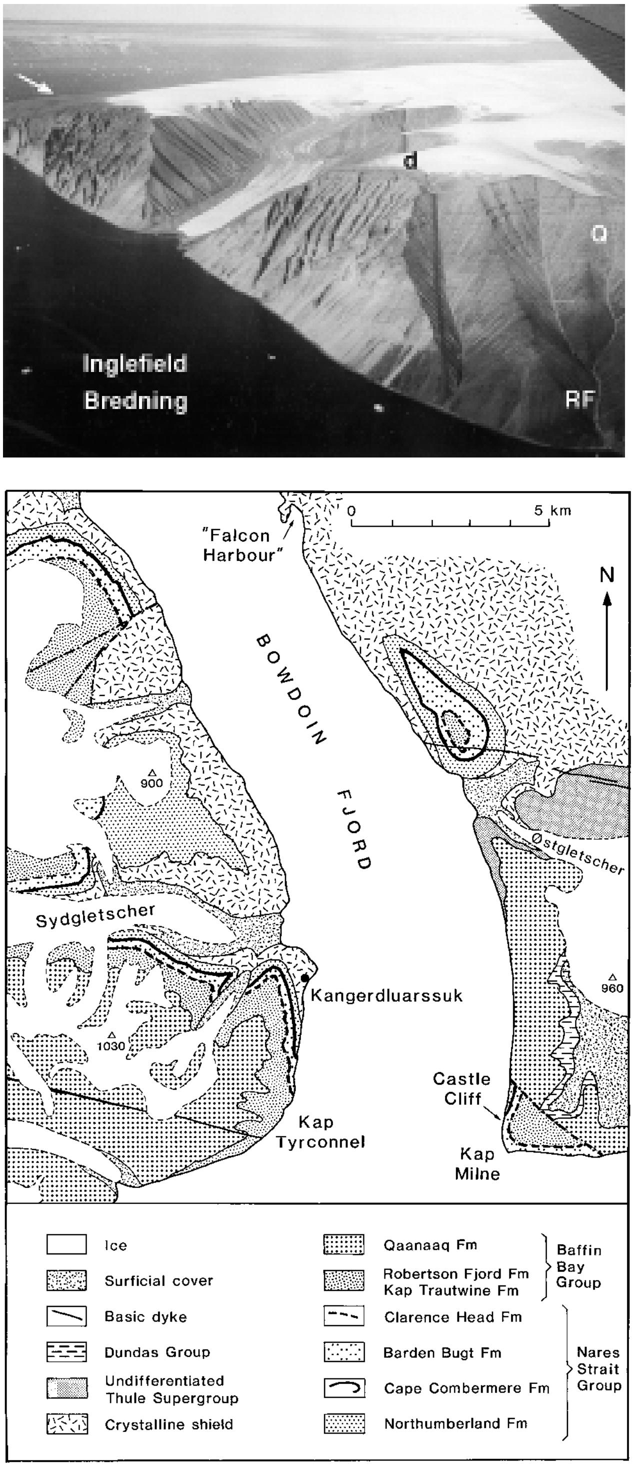


Fig. 98. Geology of the Bowdoin Fjord – Qaanaaq area, southern Prudhoe Land, Greenland. The view of the sea-cliffs, over 800 m high, is to the west over Kap Tyrconnel showing the type area of the Qaanaaq Formation (Q). The basic dyke (d) is shown on the map reaching the coast at Kap Tyrconnel. Qaanaaq town is arrowed and Herbert Ø is visible in the distance. The horst at Castle Cliff exposes the easternmost outcrops of the Nares Strait Group. RF = Robertson Fjord Formation. Heights are in metres. For location, see Fig. 2.

The quartz arenites show limited gradation towards subarkoses, particularly in basal strata, but feldspar content only reaches a few per cent. Main rock types are well sorted with well-rounded quartz grains showing various degrees of authigenic silica outgrowths. Some rocks are hard quartzites with appreciable grain intergrowth and tight silica cementation. Iron compounds, mainly hematite, vary both in abundance and in setting: thin to thick coatings around quartz grains, fine dissemination in the matrix, substantial interstitial concentration, or a ferruginous cement.

Depositional environment. The Wolstenholme Formation is interpreted as an alluvial deposit laid down in an overall oxidising environment. The scarcity of argillaceous material suggests fairly immature reaches of the fluvial system, and the main part of the succession is taken to represent deposition in a braided river system. The lithologies with finer clastic sequences could represent meandering stream channel deposition.

Fossils. None known.

Boundaries and correlation. The Wolstenholme Formation directly overlies the crystalline shield. The upper boundary is a conformable contact to the Qaanaaq Formation and represents a regional marker (Figs 93, 95). The contact is generally well demarcated, with the red beds of the Wolstenholme Formation giving way fairly abruptly to overlying pale sandstones.

In Steensby Land and eastern Inglefield Bredning, the Wolstenholme Formation grades laterally into the Robertson Fjord Formation and probably also into the underlying Kap Trautwine Formation (see Fig. 120). The boundary to the thicker, more basinal Robertson Fjord Formation is somewhat arbitrarily placed but drawn to coincide with the marginal faults that limit the extension of the Nares Strait Group to the south and east. Hence the Wolstenholme Formation directly overlies crystalline basement, while the thicker and more lithologically diverse red bed strata represented by the Kap Trautwine and Robertson Fjord Formations overlie the Nares Strait Group. In some outcrops, for example on Wolstenholme Ø and in eastern Steensby Land, pale sandstones at the base of the Wolstenholme Formation may well be coeval to strata of the Nares Strait Group.

Qaanaaq Formation

new formation

Composition. The Qaanaaq Formation corresponds to the pinkish grey sandstone unit of Chamberlin (1895) from Inglefield Bredning (Figs 6, 95). It is grossly equivalent to the upper light-coloured part of the Wolstenholme Quartzite/Formation as defined in the North Star Bugt area by Kurtz & Wales (1951), Davies (1957) and Davies *et al.* (1963), and member (d), subsequently unit 6, of that formation as described from Northumberland Ø and Herbert Ø by Dawes (1975, 1976b). It includes the upper 100 m of the section at Siorapaluk and about 200 m of strata at Uvdle, Wolstenholme Fjord, examined by Munck (1941). In Canada the formation includes the entire section described by Christie (1975) from south of Lyman Glacier, the upper sub-unit of unit V of Frisch *et al.* (1978), unit VI of Frisch & Christie (1982) as exposed at Clarence Head, and the upper part of unit VI and unit 6 of Frisch & Christie (1982) and Jackson (1986) as defined at Goding Bay. In the scheme erected by Dawes *et al.* (1982a) for both sides of Nares Strait, the Qaanaaq Formation corresponds to the 'Buff Sandstone unit'.

Name. After Qaanaaq, the Greenlandic name for the largest native settlement in North-West Greenland and capital of Avanersuup municipality (bears also the Danish name Thule) (Figs 2, 98).

Distribution. The most widely distributed formation of the Thule Basin. In Greenland it is present from Prudhoe Land in the north to inner Olrik Fjord in the east and to Wolstenholme Ø in the south, and also in the De Dødes Fjord outlier; in Canada the formation is represented in main outcrops south of Cadogan Inlet, from Paget Point to Goding Bay and at Clarence Head (Fig. 12).

Geomorphic expression and colour. A pale-weathering, predominantly buff to light brown, erosion-resistant unit, monotonous to indistinctly banded in general appearance, forming steep slopes and in places precipitous and spectacularly etched cliffed coasts (Fig. 98). Where the upper part contains fine-grained lithologies, medium slopes result and these can be poorly exposed inland.

Type area and reference sections. The type area is the coastal cliffs between Qaanaaq and Bowdoin Fjord (Fig. 98). No type section is designated but good reference sections are on the south side of Morris Jesup Gletscher in Prudhoe Land, at Aivik Point, south of Lyman Glacier (sections 44, 45, Fig. 99) and at Goding Bay (sections 39, 40, Fig. 79).

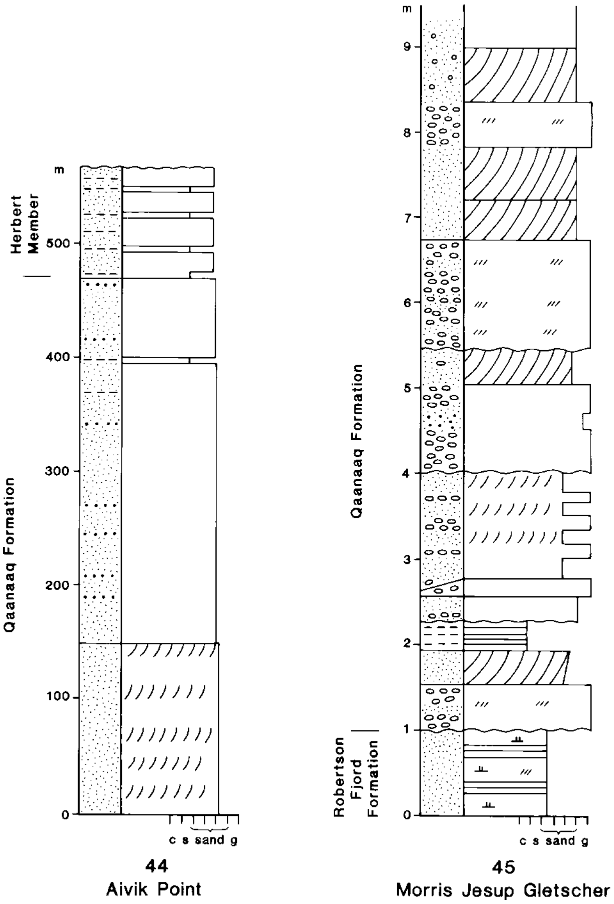


Fig. 99. Reference sections of the Qaanaaq Formation. The generalised section from Aivik Point showing the Herbert Member is compiled from data in Christie (1975) and located in Fig. 80. Stratigraphic log of the basal strata at Morris Jesup Gletscher is located in Fig. 90: it refers to part of the generalised section 41 shown in Fig. 89.

Thickness. The formation ranges from less than 200 m in eastern outcrops to an estimated 900 m, perhaps as much as 1000 m, in Prudhoe Land (Fig. 12). In Canada where the formation is truncated by the present erosion surface, minimum thicknesses vary from 25 m at Clarence Head to 550 m at Aivik Point (Figs 79, 99).

Dominant lithology. Pale weathering, rather monotonous, thin- to thick-bedded quartz arenites with in some sections intervals of grit and quartz-pebble conglomerate with minor argillites (Figs 100, 101). The strata are varicoloured but predominantly light grey, buff,

Fig. 100. Medium to thick, planar cross-bedded sandstones of the Qaanaaq Formation. Morris Jesup Gletscher, section 41. One-metre measuring staff (lower centre) as scale.

pale brown, mauve and pink, with occasional darker red beds in the lower part. In the upper part, shale and siltstone beds break up the homogeneity of the sandstone lithology. These more argillaceous strata, which are recognised regionally, are described separately as the Herbert Member (see below).

In general terms the Qaanaaq Formation represents a gross fining-upwards succession. There is also marked lateral lithological variation both on a regional and a local scale. Hence such features as cross-bedding, fining-upwards units and quartz-pebble conglomerates can each characterise intervals of a succession, being elsewhere scarce or absent.

The sandstones are variously ferruginous with iron compounds being in the form of rusty brown spots, bedding surface films, or sandy concretions. Liesegang staining also occurs. In general, beds of darker hues occur in the lower part of the formation, and in places, for example on Herbert Ø and in western Steensby Land, lilac and red beds are interbedded with buff, giving the strata a banded appearance.

The sandstones are mainly medium grained, but there is a wide range in grain size, from fine to coarse with, in some sections, a fairly common gradation to granule and conglomerate beds. Cross-bedding and ripple marks have been seen at most levels but generally these structures appear to be more commonplace in the lower strata. Cross-beds, both of planar and trough types, are commonly in 15–50 cm sets but may be over 1 m.

Conglomeratic rocks are typified by rounded quartz pebbles that generally range between 0.5 and 3 cm; exceptionally attaining 8 cm. Blue quartz grains up to 5 mm across characterise some beds. The lithology varies from pebbly sandstone to matrix-supported or, less commonly, orthoquartzitic conglomerates (Fig. 101). The conglomerates are almost invariably quartz oligomictic, with occasional pebbles of other compositions. For example, Munck (1941) records frequent ‘rolled fragments’ of crystalline rocks, particularly a reddish gneiss, in a 10–15 m thick bed at Siorapaluk.

Conglomeratic layers commonly have gradational contacts to sandstone but sharply defined beds characterise some intervals. In these, upward-fining sequences may occur with a sharp conglomeratic erosive base passing into pebbly sandstone and sandstone. Conglomerate beds occur throughout except in the uppermost part (Herbert Member), but they show varying persistence laterally.

Sandstones range from homogeneous to weakly laminated. Some well-laminated rocks have brown to green-grey argillaceous partings that may be closely spaced or irregular. Shale, commonly brownish green in colour, may form discrete beds, particularly in the lower part and in the transition to the Herbert Member, but many of these are discontinuous. For example at Goding Bay, Jackson (1986) noted a 7 m thick interval of thinly laminated shale-siltstone-sandstone about 40 m from section base. This unit was not registered in the nearby well-exposed sections examined by T. Frisch and R. L. Christie (personal communications, 1990).

The sandstones are quartz arenites showing very limited variation towards subarkose. Feldspar content occasionally reaches 5 per cent, and rare beds, particularly in the upper part, have carbonate as a matrix mineral; some have well-rounded quartzite grains. In the main the sandstones are durable rocks showing authigenic overgrowth of well-rounded quartz grains. There is variation to less durable types that are often coarser grained or conglomeratic, and to hard durable quartzites that are characterised by appreciable secondary silica, grain intergrowth and thorough cementation. The sandstones are mainly well sorted and many are bimodal with rounded overgrown quartz grains, within a matrix or with interstitial, subrounded to subangular grains. Where fine hematite is disseminated in the matrix the rock takes on a variable pinkish hue; at one locality in Olrik Fjord fresh sandstone is speckled green by disseminated copper oxide.

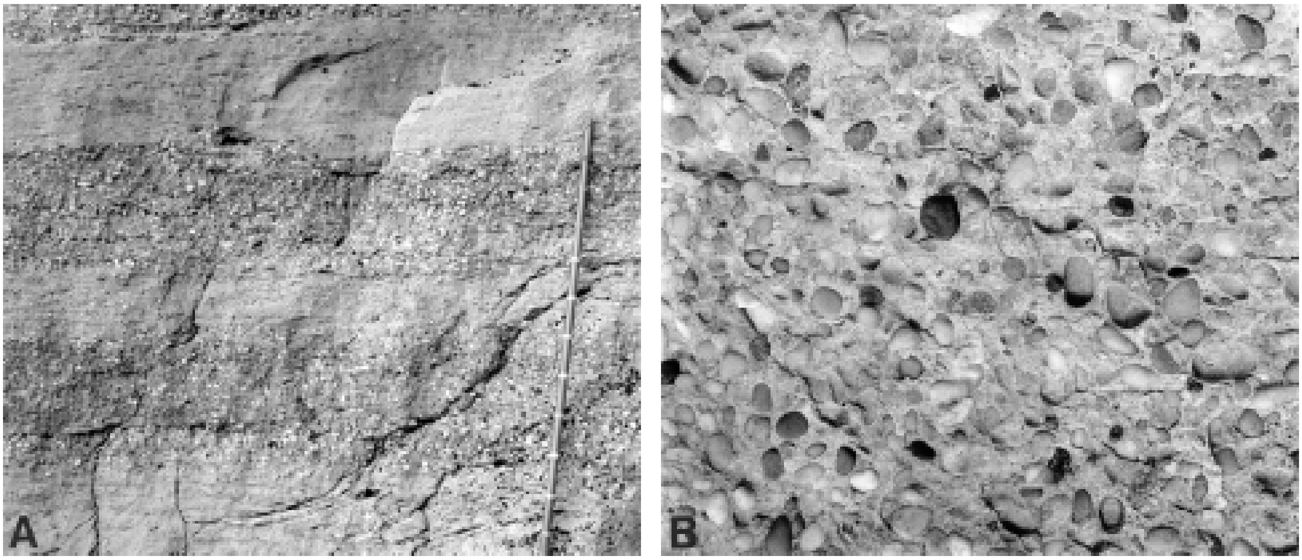


Fig. 101. Conglomerates and sandstones of the Qaanaaq Formation. **A:** fluvial sandstone and conglomerate, Morris Jesup Gletscher, section 41; **B:** bedding plane of quartz-pebble conglomerate with dark pebble in centre about 3 cm across, north side of Olrik Fjord.

Depositional environment. The Qaanaaq Formation is taken to represent varying depositional environments from alluvial plain to marine shoreline (Frisch & Christie, 1982; Jackson, 1986). Much of the succession in Greenland is interpreted as a braidplain deposit while some sections, with bimodal and herringbone cross-beds (Jackson, 1986), show tidal influence. The gross fining-upwards nature with incoming of argillites at the top is seen as a regional regression of the shoreline with a passage to coastal flood plain deposition and, subsequently, as exemplified by the succeeding formations of the Dundas Group, to perhaps an overall deltaic environment.

The presence of conglomerates, abundant in some sections, with trough-bedded sands, and the general absence of fine-grained overbank deposits, suggest overall deposition in a braided river system. The local fining-upward units are taken to be channel bar sands. The thick sections composed almost entirely of sands could represent sheet sand deposits due to the long-lasting migration of channels. Western outcrops may represent marine coastal deposition. For example, the conglomeratic, ripple-marked sands at Goding Bay are regarded by Frisch & Christie (1982) as possible offshore bars, while Jackson (1986), noting the paucity of cross-beds in the succession (compared to the tide-dominated sandstones below – herein referred to the Robertson Fjord Formation), suggests that in periods storm-dominated deposition may have prevailed.

Fossils. Organic-walled microfossils (acritarchs) – see under Herbert Member.

Boundaries and correlation. In Greenland, in eastern and southern outcrops, the Qaanaaq Formation conformably overlies the Wolstenholme Formation along a fairly well-demarcated boundary (Figs 93, 95); elsewhere the underlying strata are those of the Robertson Fjord Formation. This boundary is also distinct, generally marked by the abrupt change from the siltstone-shale dominated, red bed lithology of the Siorapaluk Member to pale sandstones (Figs 85, 88, 91). Where the lowest strata contain red beds, as for example at Bastion Pynt, the eastern point of Herbert Ø (Fig. 109), a somewhat gradational boundary exists and here the contact is placed at the top of the uniformly coloured red bed succession. At Morris Jesup Gletscher, Prudhoe Land, the boundary is drawn below a conglomerate having an erosional base (Fig. 99); at Paine Bluff in Goding Bay it is drawn above a 3 m thick dolomitic subarkose bed (Fig. 79).

The upper boundary of the Qaanaaq Formation represents the upper limit of the Baffin Bay Group in conformable contact with the Dundas Group (Fig. 102). The contact is transitional produced by the gradual increase upwards of darker fine-grained sandstone, siltstone and shale, within the paler sandstone lithology. The width of this transition zone varies. It may involve just several metres of strata in which case the boundary is fairly distinct and can be drawn at the top

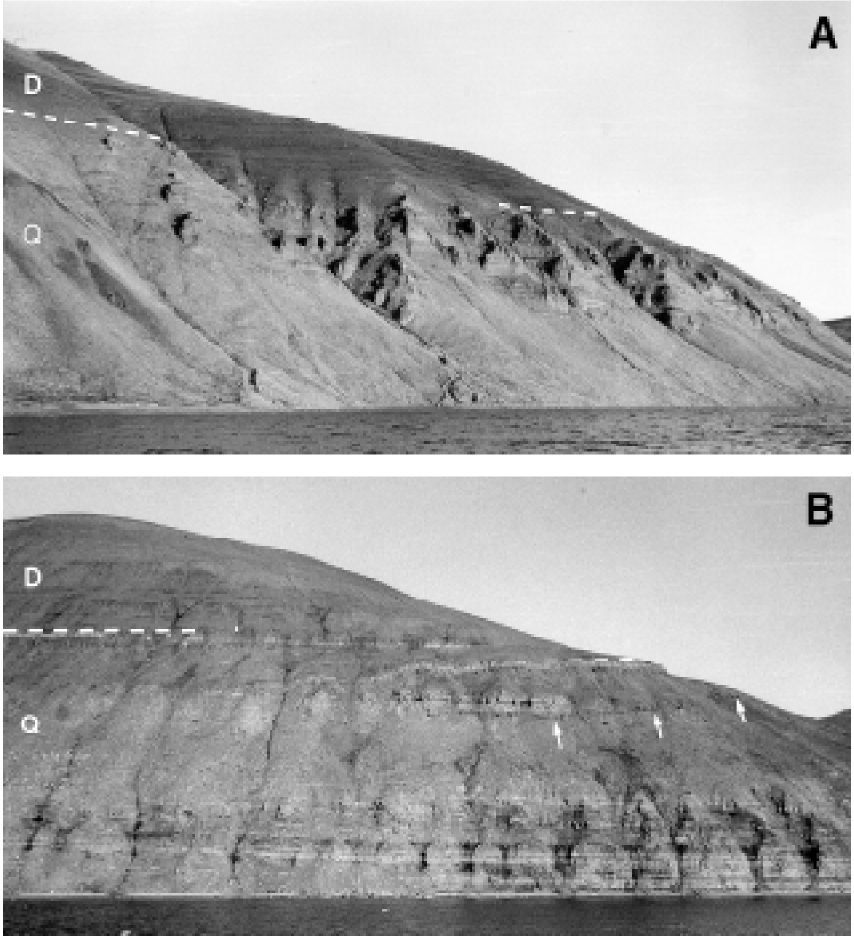


Fig. 102. The boundary of the Baffin Bay Group (Q, Qaanaaq Formation) and Dundas Group (D).
A: Conformable, fairly abrupt contact between pale sandstone-dominated lithology and darker siltstones and shales at Narssaq, Inglefield Bredning, with cliffs about 450 m high.
B: Transitional boundary with disruption of pale sandstone beds, suggesting penecontemporaneous faulting. Thin basic sills occur in the Qaanaaq Formation (Herbert Member) and one sheet (arrowed) strikes parallel to the displaced slab. Western end of Herbert Ø with the summit of the hill at about 350 m.

of the last buff-weathering sandstone (Fig. 102A); elsewhere the gradation is through tens of metres of strata, and the boundary definition is more arbitrary (Fig. 102B), often being determined by regional considerations. In several sections the upper boundary is drawn at the top of a ferruginous sandstone bed (see below under Herbert Member).

There is some evidence of penecontemporaneous faulting at the upper boundary of the Qaanaaq Formation (Fig. 102B) and in Prudhoe Land, for example west of Siorapaluk, the Dundas Group appears to overlap the structurally higher Qaanaaq Formation.

Lack of exposure prevents precise knowledge of the relationship of the Qaanaaq Formation to the Smith Sound Group, but the formation is deemed to thin northwards and to be, at least in part, a lateral equivalent of the Sonntag Bugt Formation (Figs 11, 120).

Subdivisions. The bulk of the Qaanaaq Formation is not formally subdivided but an uppermost, more argillaceous unit, recognised regionally, and in both Canada and Greenland, is defined as the Herbert Member.

Herbert Member

new member

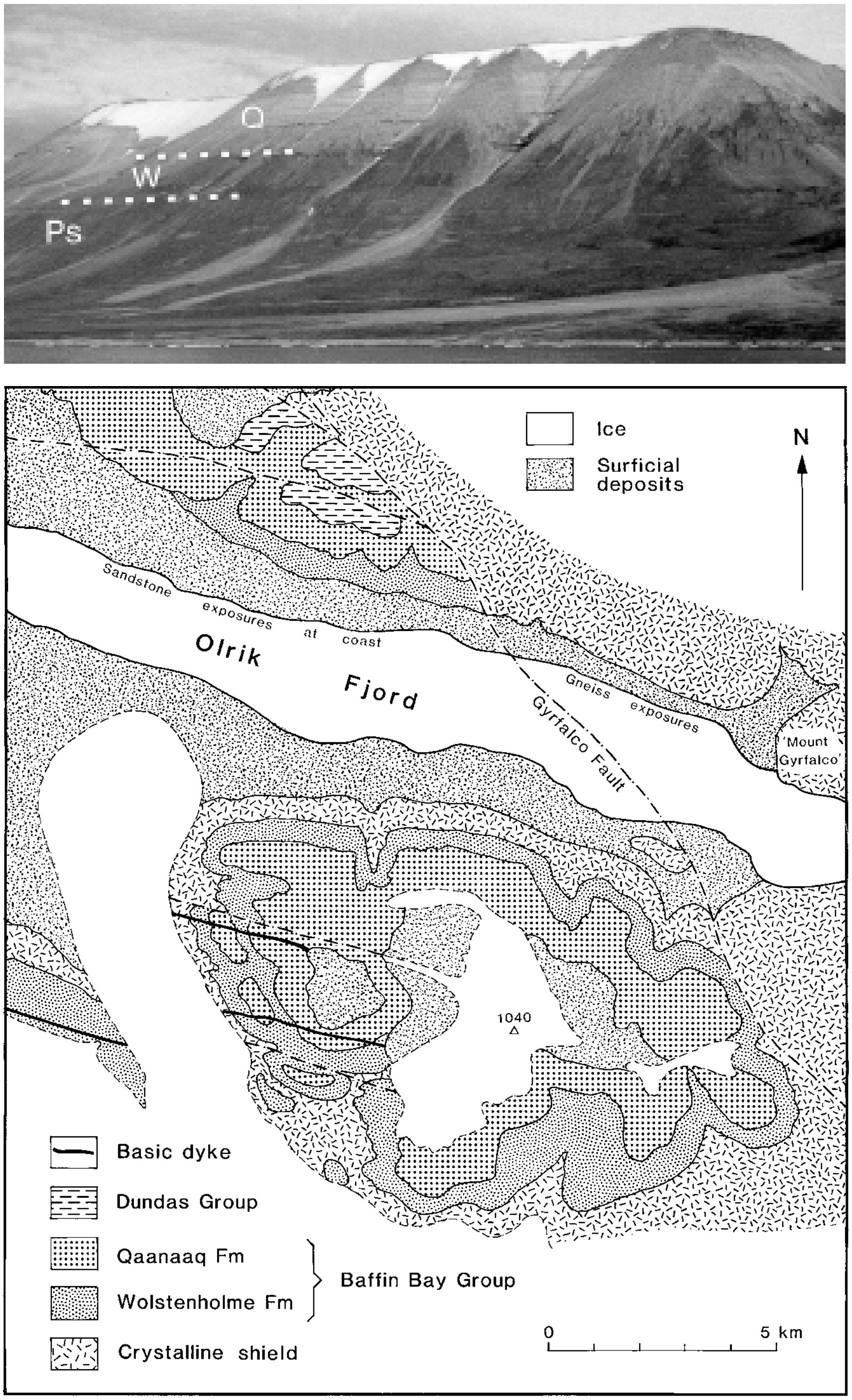
Composition. This member corresponds to the ‘upper beds’ of Christie (1975) from Aivik Point, and the upper darker part of unit 6 of Dawes (1976b) from Northumberland Ø and Herbert Ø. It can be recognised as a 35–40 m thick interval in the section examined by Munck (1941) at Uvdle, Wolstenholme Fjord.

Name. After Herbert Ø, the eastern of three islands separating Murchison Sund and Hvalsund (Figs 2, 109).

Distribution. In Greenland: Prudhoe Land, Olrik Fjord, western Steensby Land, Northumberland Ø, Herbert Ø, Wolstenholme Fjord and Wolstenholme Ø; in Ellesmere Island, at Aivik Point and probably elsewhere in the Lyman Glacier area.

Geomorphic expression and colour. A light brown- to tan-weathering unit, rather monotonous in appearance, forming generally poorly exposed moderate slopes.

Fig. 103. Geological map and view of inner Olrik Fjord, Greenland, showing the eastern outcrops of the Thule Supergroup. The photographic view is of the south side of the fjord with the Baffin Bay Group overlying the Precambrian shield (Ps).
W = Wolstenholme Formation,
Q = Qaanaaq Formation, with the conspicuous darker Herbert Member forming the upper strata. Height of 1040 is in metres; sea-cliffs are about 700 m high. For location, see Fig. 2.



Type area and reference sections. The type area is the sea-cliffs of western Herbert Ø (Fig. 102); main reference sections are at Aivik Point (section 44, Fig. 99) and Uvdle, Wolstenholme Fjord (see Fig. 105). Other accessible sections, examined but not measured, are on eastern Northumberland Ø (Fig. 48), the interior of Olrik Fjord (Fig. 103) and in western Steensby Land at Kap Powlett and north-east of Kap Leiningen (Fig. 70).

Thickness. Ranges from about 30 m to at least 120 m.

Lithology. The main rock types are sandstone and shale grading to siltstone (Fig. 104). Overall, sandstone predominates. Upwards there is a marked increase in siltstone and shale, and sandstones become finer grained.

Sandstones are mainly buff, grey and brownish, very fine- to medium-grained, variously laminated quartz

Fig. 104. Interbedded sandstone and darker shales of the Herbert Member of the Qaanaaq Formation. Western end of Herbert Ø, south of Kap Lee. Height of the section is about 15 m.

arenites. Some are mildly calcareous and carbonate can form the predominant component of the cement matrix. Many sandstones are ferruginous, characterised by rusty flecks that reach several millimetres in size. Iron compounds are common on bedding surfaces, and rocks can take on a tan colour. The sandstones are mainly thin to medium bedded and planar to lenticular; beds more than 30 cm thick are rare. Thick beds are laterally continuous but in shale-dominated units thin sandstones show lensing.

The shales and siltstones are grey and greenish grey, and commonly weather buff to light brown. They are variously laminated and micaceous, and are ripple marked and mudcracked.

In several areas, the uppermost strata are richer in iron compounds. Dark beds of medium- to very coarse-grained ferruginous sandstone occur at Uvdle, Wolstenholme Fjord (see Fig. 105) and at Narssaq, Inglefield Bredning (Fig. 95). These beds, 75 cm and 1 m thick respectively, are characterised by well-rounded quartz and occasional quartzite grains, with dusty borders, set in a matrix of carbonate and hematite, with or without fine-grained quartz. At Narssaq, the bed is conglomeratic, containing rip-up clasts of ferruginous calcareous sandstone.

Depositional environment. A speculative interpretation of the Herbert Member is that it was deposited by meandering rivers in a coastal plain environment. Lowermost strata may represent point bar sands broken by intermittent overbank silts and clays, while the uppermost finer-grained beds could be a floodplain deposit. This interpretation is supported by abundant mudcracks indicating subaerial exposure, some carbonate precipitation and richly ferruginous beds.

Fossils. Curvilinear to curlicue bedding plane features regarded as trace fossils by Dawes & Bromley (1975) are reinterpreted as diastasis cracks (Cowan & James, 1992). An acritarch assemblage composed of thirteen species is derived from shales from Prudhoe Land (Dawes & Vidal, 1985). The stratigraphically most important taxa are *Kildinosphaera verrucata, K. lophostriata, K. chaginata, Leiosphaerida asperate, Tasmanites rifejicus* and *Satka colonialica*, an assemblage that indicates a Late Riphean age.

Boundaries. The member is bounded by conformable and gradational contacts with unnamed buff sandstones below and with the Dundas Group above (Figs 102, 103). The lower boundary is arbitrarily drawn within a zone of gradation marked by the incoming of thin shale-siltstone beds that increase upwards and pass into the interbedded sandstone and shale lithology of the Herbert Member. This boundary cannot be located regionally with precision but is drawn where shale-siltstone constitutes more than a single isolated bed. The boundary may mark a very gradual incoming of argillaceous material, such as at Aivik Point (Fig. 99), or a more abrupt change as in Olrik Fjord (Fig. 103). The boundary is commonly recognised as a marked colour change from pale brown-buff to the darker hues of the overlying Herbert Member.

In the type area the upper contact of the Herbert Member is drawn on a dark 10–15 cm thick ferruginous sandstone, although elsewhere in the vicinity and on eastern Northumberland Ø a basic sill occupies the contact. At two other sections, viz. at Narssaq, Inglefield Bredning (Fig. 95) and at Uvdle, Wolstenholme Fjord (Fig. 105), similar hematite-rich clastic beds have been conveniently chosen as the boundary.

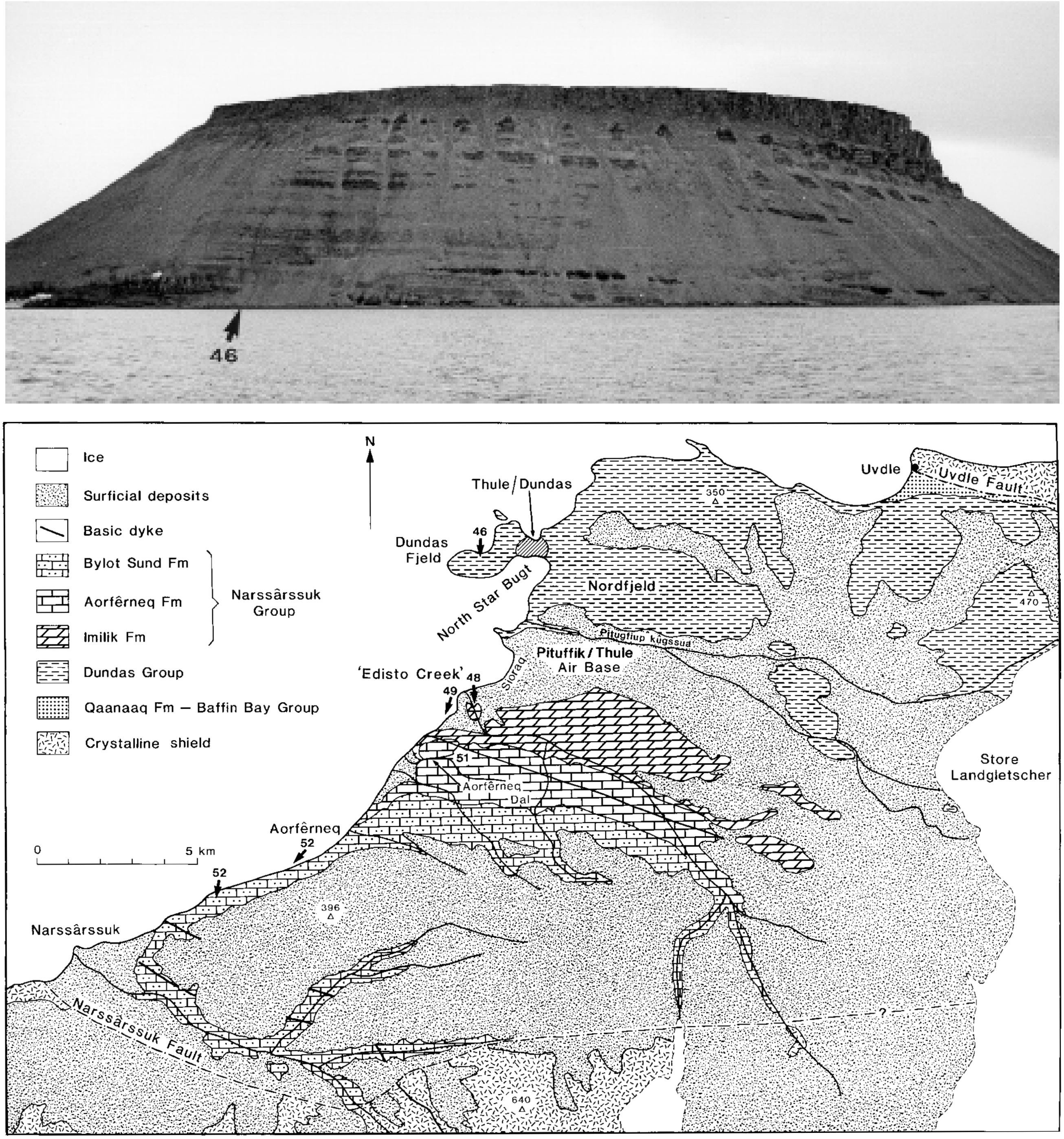


Fig. 105. The mesa-like landmark of the Thule district, Dundas Fjeld (Ummannaq), viewed from the north, and a geological map of the North Star Bugt – Narssârssuk area showing locations of sections 46, 48, 49, 51 and 52. This mountain and adjoining peninsula including Nordfjeld, and the coast between Sioraq and Narssârssuk, are respectively the type areas of the Dundas and Narssârssuk Groups. Section 46, given in Fig. 108, is composed of dark sandstones and shales of the Dundas Group (Steensby Land Formation) capped by a Hadrynian basic sill; summit is at about 225 m. Frequent basic sills in the Dundas Group are not shown on the map (cf. outcrop pattern in Fig. 107) but dykes of the late Hadrynian ESE-trending swarm are shown cutting the Narssârssuk Group. The boundary between the Dundas and Narssârssuk Groups is hidden by the surficial deposits of the wide valley supporting Pituffik. It is assumed to be a tectonic contact with the Narssârssuk Group preserved in a graben structure. The Narssârssuk Fault, limiting the Narsârsssuk Group to the south and juxtaposing it against the Precambrian shield, represents a substantial throw, in the order of kilometres. Heights are in metres. The cross-hatched area marked Thule/Dundas represents the abandoned sites of the Eskimo village and trading station Thule, and that of the Danish settlement, Dundas. For location, see Fig. 2.

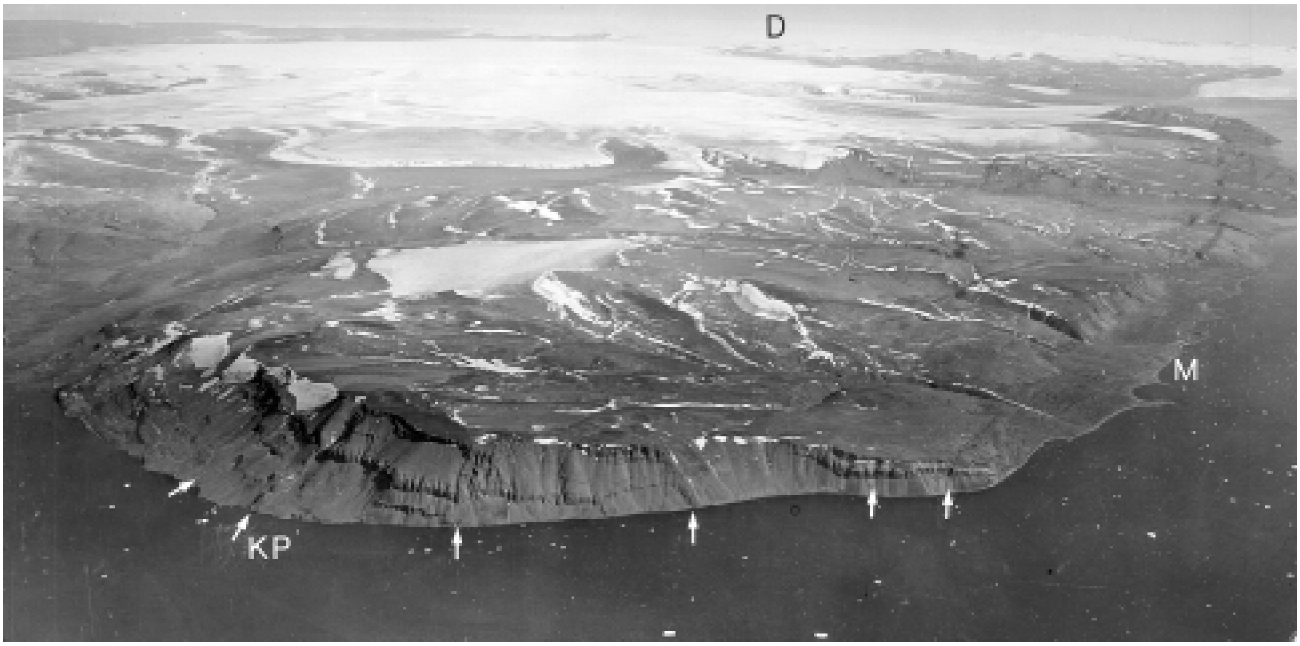


Fig. 106. Typical exposures of the Dundas Group (Steensby Land Formation) punctuated by resistant basic sills and later dykes. The Steensby Land sill complex, composed of a dozen or so Hadrynian sills, is cut by WNW-trending late Hadrynian dykes (arrowed) that represent the latest event of the Franklin magmatic episode. View is east over Granville Fjord and Moriussaq settlement (M) with Dryasbjerg (D) in the background. Kap Peary (KP) is about 650 m high. Photo: 543 I-Ø 4585, July 1950; Kort- og Matrikelstyrelsen, Denmark.

Dundas Group

The Dundas Group representing thick basinal strata is widespread in Greenland (Figs 2, 4, 120). Three units have been mapped as formations: the Steensby Land, Kap Powell and Olrik Fjord Formations. However, formal nomenclatorial definition at formational level is not made in this bulletin.

Dundas Group

new group

Composition. The group corresponds broadly to the ‘dark shales and sandstones’ of Chamberlin (1895) that were recognised subsequently by all workers to constitute a major rock series (Figs 6, 95). However, the group does not include the dolomites of Koch (1926, 1929a) thought to underlie the dark clastic rocks and mapped together with them (see Koch, 1926; Dawes & Haller, 1979, plate 1). All strata of the Danish Village formation of Kurtz & Wales (1951), as well as the lowermost beds of their Narssarssuk formation, outcropping north of Sioraq, are included in the group. The Dundas Group represents an elevation in status of the Dundas Formation of Davies *et al.* (1963) as defined in the North Star Bugt area, and as used regionally by Dawes (1976a) and Dawes *et al.* (1982a).

Name. After Dundas Fjeld, North Star Bugt, the characteristic mesa-like landmark of the Thule district (Fig. 105).

Distribution. Wide distribution in Greenland from Sonntag Bugt in the north to central Olrik Fjord in the east to Wolstenholme Ø in the south (Fig. 2).

Geomorphic expression and colour. Dark grey to brownish-weathering sediments punctuated in many areas, e.g. Steensby Land, by darker, more resistant basic sills that dominate the landscape (Figs 106, 107). Variable resistance of the well-bedded arenaceous and argillaceous beds produces stepped to terraced geomorphic expression. In southern exposures, sediments are generally poorly exposed except where protected by igneous rock; in northern Prudhoe Land the group forms some steep coastal sections with good exposures (Figs 5B, 112), but moderate slopes are prone to scree cover.

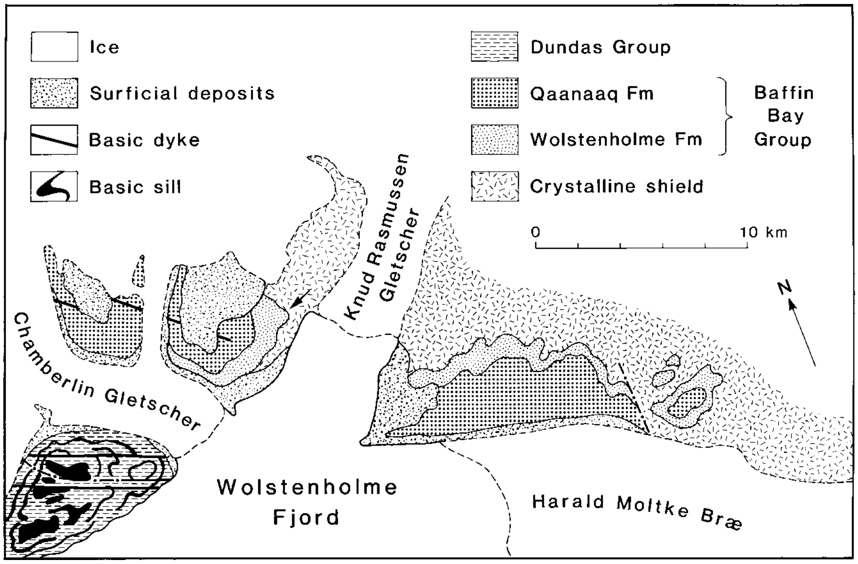


Fig. 107. Geological map of the head of Wolstenholme Fjord, Greenland. The Baffin Bay Group is composed of relatively thin outliers on the crystalline shield; the down-faulted Dundas Group is characterised by prominent basic sills and dykes. The arrow locates the view of the unconformity seen in Fig. 97. For location, see Fig. 2.

Type area. North Star Bugt area including Dundas Fjeld, Dundas peninsula and inland area. Thus defined the type area includes the 'type locality' of the forerunner to the group (Dundas Formation) referred to by Davies *et al.* (1963) as two sections, namely on Nordfjeld and Dundas Fjeld (Fig. 105). A stratigraphic log of Dundas Fjeld is given in Fig. 108.

Thickness. An unknown but very substantial thickness. The Dundas Group is estimated to be at least 2 km, possibly 3 km, thick. In view of the grossly monotonous lithology without regional markers and the separation of sections by block faulting (Figs 5B, 109), regional correlation is not obvious. True sedimentary thickness is frequently obscured by basic sills and the thickest intrusion-free sedimentary section is in northern Prudhoe Land, at least 700 m thick. The upper limit of the group is unknown since all sections are cut by the present erosion surface.

Dominant lithology. Regularly interbedded, dominantly thin- to medium-bedded, variously laminated quartz arenites, siltstones and shales, with lesser amounts of dolomite and dolomitic limestone, chert and evaporitic rocks (Figs 108, 110). Interlayering of fine-grained sandstones, siltstone and shale occurs on all scales from interlamination to thin beds. Regionally the Dundas Group shows wide lateral variation in the ratio of sandstone to siltstone-shale. In southern exposures (Northumberland Ø, Herbert Ø, southern Steensby Land, Wolstenholme Fjord and North Star Bugt) the strata are intruded by numerous basaltic sills (Figs 106, 107). In association with these, the sediments may be baked, slaty and often rusty weathered with pyrite increasing towards the intrusion.

In the type area (Steensby Land Formation; section 46, Figs 105, 108) quartz arenites are very fine grained to medium grained with gradation to siltstone, and thin laminated to medium bedded. As well as fine interbedding of shale and siltstone, coarsening-upwards cycles from shales to fine sands occur (Fig. 110A, B). Sedimentary structures include current ripples and ripple-drift bedding with transition to flaser lamination; mudcracks are common in some units, and small-scale cross lamination and bedding and small channels were noted occasionally. Shales are black to dark grey, variously laminated, fissile and micaceous with some calcareous types and in places with pyrite (Fig. 110D). Typical black paper shales are common. In the upper part siltstones may be siliceous, some thin green cherts occur and evaporite appears as bedding plane coatings, occasional nodules and as secondary veins (Fig. 110). Some laminated shale beds are dissected by a network of subconcordant veins of fibrous gypsum (Fig. 110B, C). Dolomite, in places stromatolitic (Fig. 110H), occurs as occasional thin beds showing gradations to calcareous sandstone and siltstone in which pyritic concentrations occur parallel to bedding. The carbonate rocks increase in abundance upwards.

In southern Steensby Land grey to bluish grey dolomite and dolomitic limestone form units up to several metres thick varying from massive thick-bedded rock to thin-bedded, platy dolomites (Fig. 110G). Some of these rocks are rusty weathering indicative of concentrations of iron sulphides in thin veins and small lodes. At Barden Bugt discrete beds of dolomitic limestone

Fig. 108. Stratigraphic logs of the Dundas Group from Dundas Fjeld, North Star Bugt and Kap Powell, Prudhoe Land. The sections are compiled from the following sources: section 46, own data; section 47, mainly from O'Connor (1980). Sections are located in Fig. 105, and Figs 111, 112, respectively.

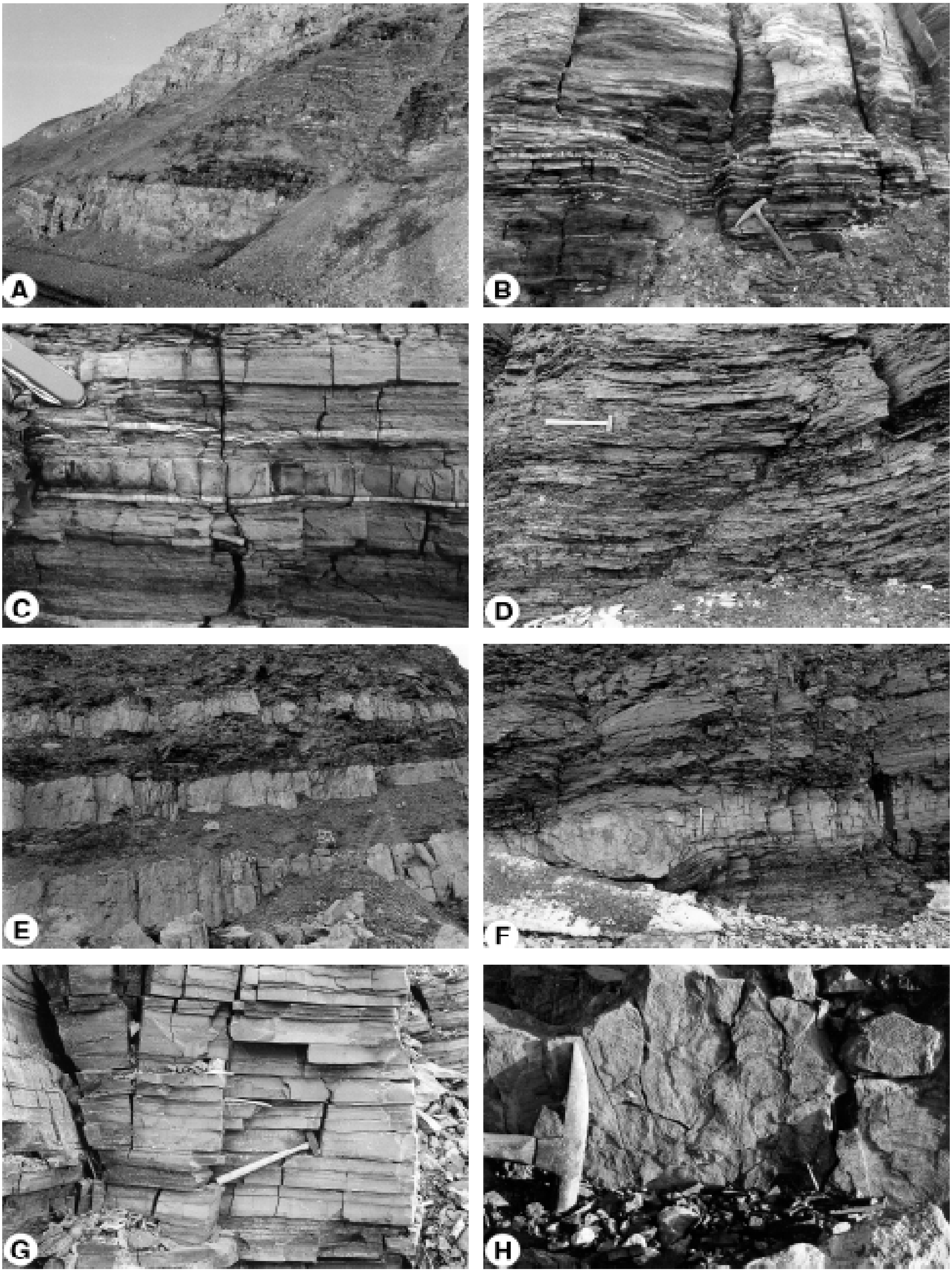
Fig. 109. The Olrik Fjord graben juxtaposing Dundas Group (D, Olrik Fjord Formation) against Precambrian shield (Ps). NS = Nares Strait Group, BB = Baffin Bay Group (Qaanaaq Formation). The view is to the west; the islands are Herbert Ø (H) and Northumberland Ø (N) with Ellesmere Island in the distance. The Barden Bugt Fault (f) is also shown (see Fig. 70). Photo: 543 L-V 1349, July 1949; Kort- og Matrikelstyrelsen, Denmark.

in black shales show small reef build-ups, commonly stromatolitic with columnar and cone-in-cone structures that may be variously brecciated (Fig. 110E, F).

Several parts of the group are dominated by thick shale sequences. One such sequence is in the Olrik Fjord graben (Olrik Fjord Formation, Fig. 109) where multicoloured shales dominate a 400 m succession. Black, grey, maroon, green, buff and brown weathering shales are variably intercalated with laminated silts and fine arenaceous beds, some of which can be calcareous. Fine-grained sandstones forming distinct geomorphic ribs occur in lower and upper parts of the succession.

In northern exposures in Prudhoe Land (Kap Powell Formation; section 47, Figs 108, 111), the succession contains more sandstone than in the type area. Quartz arenites may be coarse grained and cross-bedding is much more common; both planar and festoon types occur. Ripple marks and channels are common. The succession is characterised by prominent cliff-forming units of sandstone separated by intervals of darker sandstone-siltstone-shale (Fig. 112). The cliffed sandstones are either the tops of coarsening and thickening upwards cycles, or discrete planar sand bodies that are commonly cross-bedded and may have erosive bases. A typical cycle is: at the base, black shales with millimetre-thick sandstone beds passing upwards into laminated thinly-bedded fine-grained sandstone and siltstone containing millimetre-thick shale layers with, at the top, thin to medium bedded, medium- to coarse-grained sandstone. A few fining-upwards cycles also occur. Some shale units have a distinct green colour and sandstone-siltstones may weather olive green. Towards the top, sandstones are calcareous and yellow-weathering dolostone and arenaceous dolostone may display rip-up clasts.

Depositional environment. The Dundas Group marks a change from the continental and littoral sedimentation of the Baffin Bay Group to more basinal deposition. The general setting is suggested to be intertidal to subtidal; the many upward-coarsening units may be indicative of an overall deltaic environment. The thick coarsening-up cycles in the north (Kap Powell Formation), characterised by channels and thicker bedded, cross-bedded tops, might represent progradation delta front sequences; the thinner, lower energy cycles of the type area with some pyrite development (Steensby Land Formation) may indicate delta plain deposition. The thick shale packages are interpreted as prodelta muds. Some non-cyclic sand bodies may represent tidal channel sands and Jackson (1986) suggests that some quartz arenites in the North Star Bugt area may have been deposited by turbidity currents during storms or periods of flood. The incoming of calcareous rocks in the uppermost part of the group, both as carbonates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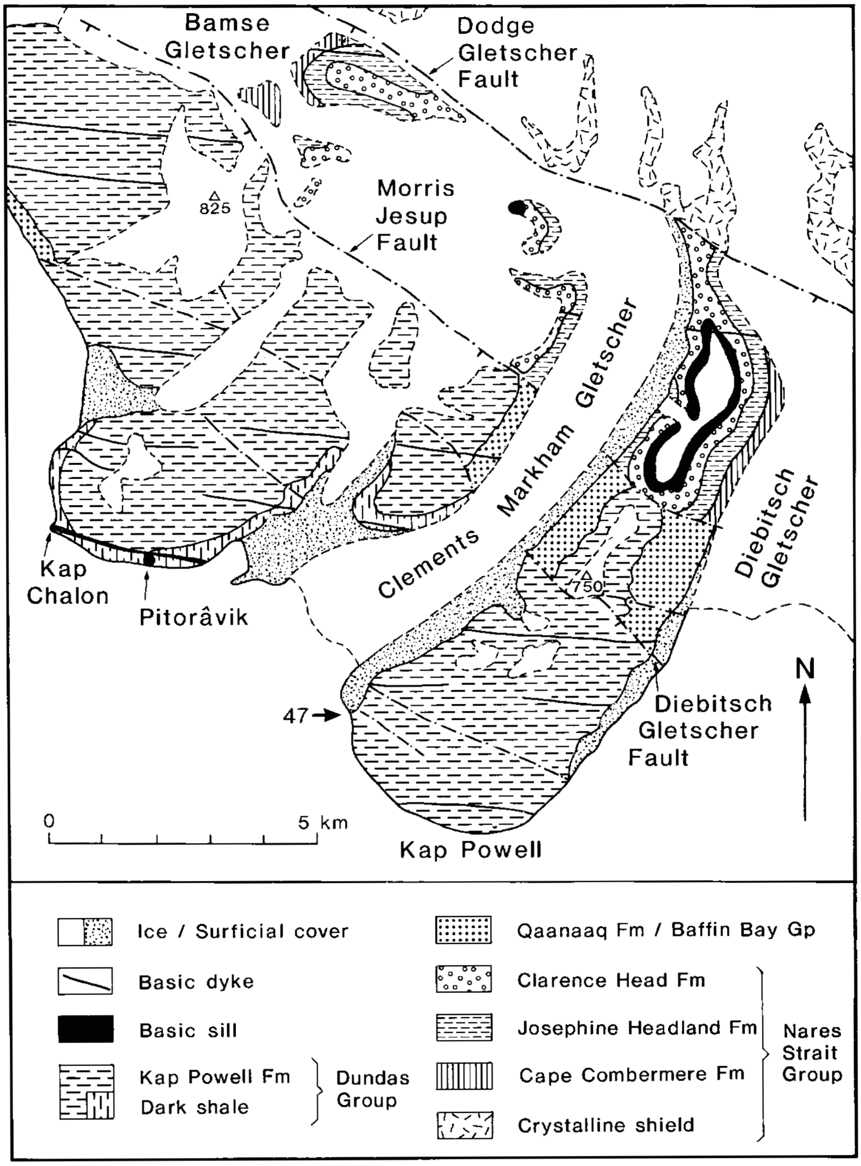


Fig. 111. Geological map of northernmost Prudhoe Land, Greenland, showing main faults with downthrow to the south-west and the location of section 47 (cf. Fig. 5B). Heights are in metres. For location, see Fig. 2.

and sulphates, together with reefs and stromatolites, are interpreted as marking a change to intertidal and supratidal environments and, as has been suggested earlier (Dawes, 1979a), progradation of the coastline and the passage to the restricted peritidal environment of the Narssârssuk Group. However, the occurrence of carbonates and evaporites with black shales invites comparison with an evaporite-euxinic shale association; the possibility that some calcareous rocks are basinal rather than littoral deposits cannot be excluded.

Fossils. Stromatolites: columns; low relief, laterally-linked domes; conical forms of *Conophyton*-type (Grey, 1995), and organic-walled microfossils (acritarchs and filamentous forms). The acritarch assemblage includes typical Late Riphean taxa known from elsewhere in

Fig. 110. Characteristic lithologies of the Dundas Group. **A:** buff-weathering shales and siltstones (5–6 m thick above beach) overlain by black shales that pass upwards into pale sandstones. White evaporite veins are conspicuous, **B:** part of coarsening-upwards unit with black shales and siltstones (ribbed by evaporite veins) passing upwards into paler fine-grained sandstones; **C:** detail of B showing fine-grained sandstone beds in shales with fibrous gypsum veins and stringers. **D:** Black shales and laminated siltstones showing lenticular bedding. **E:** Discrete pale limestone beds within black shales; **F:** small reef about 80 cm thick showing internal brecciated structure within calcareous siltstone bed; **G:** grey, thin-bedded laminated limestones with wavy bedding surfaces; **H:** stromatolites of *Collenia* type in grey arenaceous dolomite. Locations: **A**, east side of North Star Bugt; **B**,**C**, Dundas Fjeld, section 46; **D**,**E**,**F**, south coast of Barden Bugt; **G**, Nûgdlît, Steensby Land; **H**, south of Uvdle, Wolstenholme Fjord.

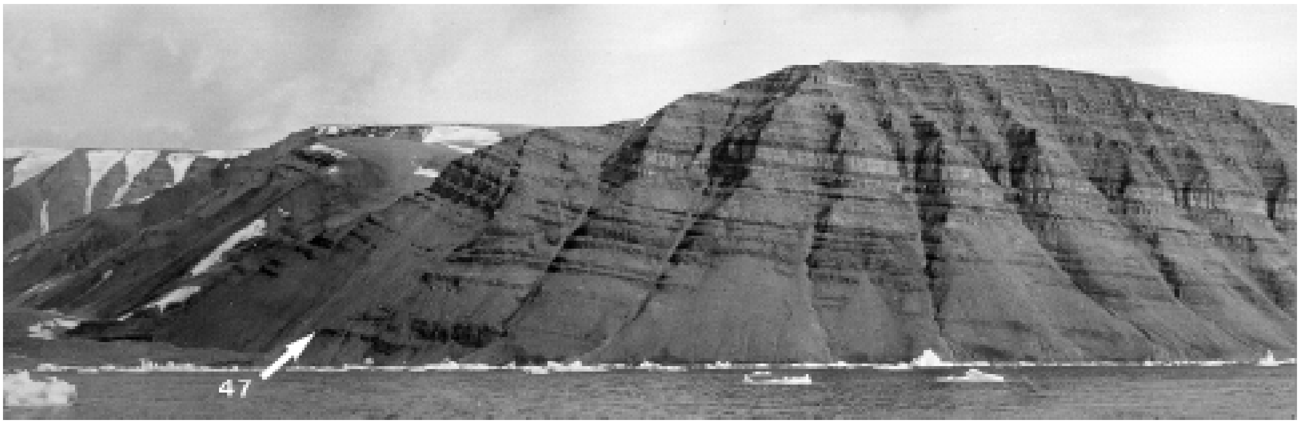


Fig. 112. Kap Powell Formation of the Dundas Group at Kap Powell, Prudhoe Land, showing the location of section 47 that is given in Fig. 108. The summit of the cape is around 500 m. Faults affect the succession on the left (see geological map, Fig. 111).

the North Atlantic (Vidal & Dawes, 1980; Dawes & Vidal, 1985), the stratigraphically most important taxa being: *Kildinosphaera*, *Lophostriata*, *K. chaginata*, *Tasmanites rifejicus* and *Vandalosphaeridium varangeri* (see under *Geological age* below).

Boundaries and correlation. The Dundas Group conformably overlies the Baffin Bay Group along a gradational contact that has been described earlier (Fig. 102); the only strata demonstrably overlying the group are Quaternary deposits. Local, apparently non-conformable relationships between the Dundas Group and the Baffin Bay Group (Qaanaaq Formation) are seen as local overlapping of the Dundas strata onto fault blocks.

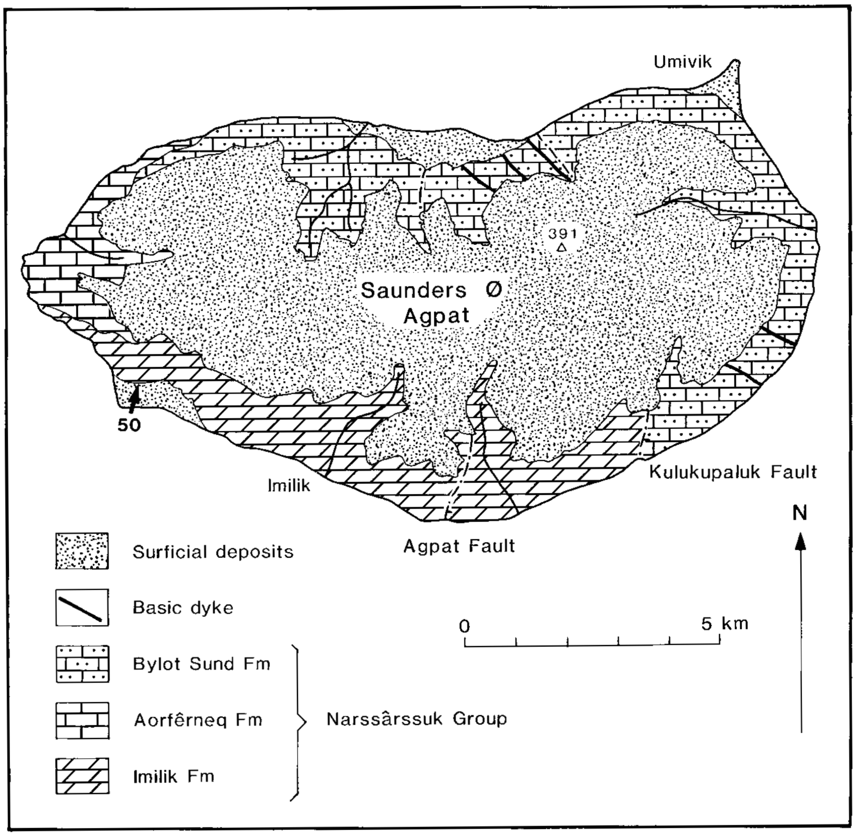
The group is in near contact with the Narssârssuk Group, the boundary being situated under the wide Quaternary-filled valley supporting the air base Pituffik. This valley is parallel to regional faults and is likely to be tectonically controlled. The Narssârssuk Group is preserved in a graben or half-graben (see later under that group). Dundas strata on the north side of Sioraq, and the isolated outcrops protruding through the surficial cover of the valley floor, form the south-eastern extension of a 20 km wide belt of southerly-dipping rocks that form southern Steensby Land (Figs 2, 105). If no major structural complications exist, the Dundas Group can be projected to underlie the Narssârssuk Group.

One can only speculate as to the nature of the lower boundary of the Narssârssuk Group. It may be conformable with the Dundas Group, a disconformity of varying significance, or the groups may, in part, have an intertonguing relationship. Inconclusive evidence suggests that the two groups are lithologically linked. The uppermost part of the Dundas Group shows some variation to Narssârssuk lithologies, i.e. the incoming of carbonate with stromatolites, chert and evaporitic rocks. This fits a model of inherent transition between the two groups rather than a major hiatus.

Geological age. Neohelikian–Hadrynian, possibly reaching late Hadrynian (Sturtian–Vendian); an age range based on microfossils and radiometric dating of intrusive rocks. The most recent and reliable whole-rock K-Ar ages on dolerite from the Steensby Land sill complex, including sills from Dundas Fjeld that cut the uppermost strata of the group, are in the range from 705 to 660 Ma (Dawes & Rex, 1986). Acritarch assemblages indicate a Late Riphean (Karatauian and Kudashian) age for the main part of the Dundas Group (Vidal & Dawes, 1980; Dawes & Vidal, 1985). However, the presence of *Vandalosphaeridium varangeri* in downfaulted strata in Olrik Fjord (Olrik Fjord Formation, Fig. 109) suggests that the group might pass into the Vendian. This typical Scandinavian species is inferred to have a stratigraphical range restricted to the Kudashian – Lower Vendian (G. Vidal, personal communication, 1991) and it is also present in the Narssârssuk Group.

Subdivisions. The Dundas Group is not formally subdivided in this bulletin, but three units have been mapped as formations: the Steensby Land, Olrik Fjord and Kap Powell Formations. These are essentially geographically defined formations based on lithological lateral facies of the group, but the Olrik Fjord Formation may represent the youngest stratigraphic package. On the most recent map (Dawes, 1991a), the Olrik Fjord Formation is named; the other two formations constitute the 'undivided' strata.

Fig. 113. Geological map of Saunders Ø, Greenland, showing the location of section 50. The tripartite division of the Narssârssuk Group has been established in the type area on the mainland (see Fig. 105); assignment of formational names on Saunders Ø is provisional. The height of 391 is in metres. For location, see Fig. 2.



Narssârssuk Group

The occurrence of the Narssârssuk Group is restricted to a graben structure on the south-eastern margin of the Thule Basin (Figs 2, 4, 120). Three formations are provisionally recognised: the Imilik, Aorfêrneq and Bylot Sund Formations, but these are not formally defined in this bulletin.

Narssârssuk Group

new group

Composition. Strata assigned to this group are part of four different units of the Thule Formation of Koch (1929a; see Dawes & Haller, 1979, plate 1). The strata were first recognised as a distinct rock division by

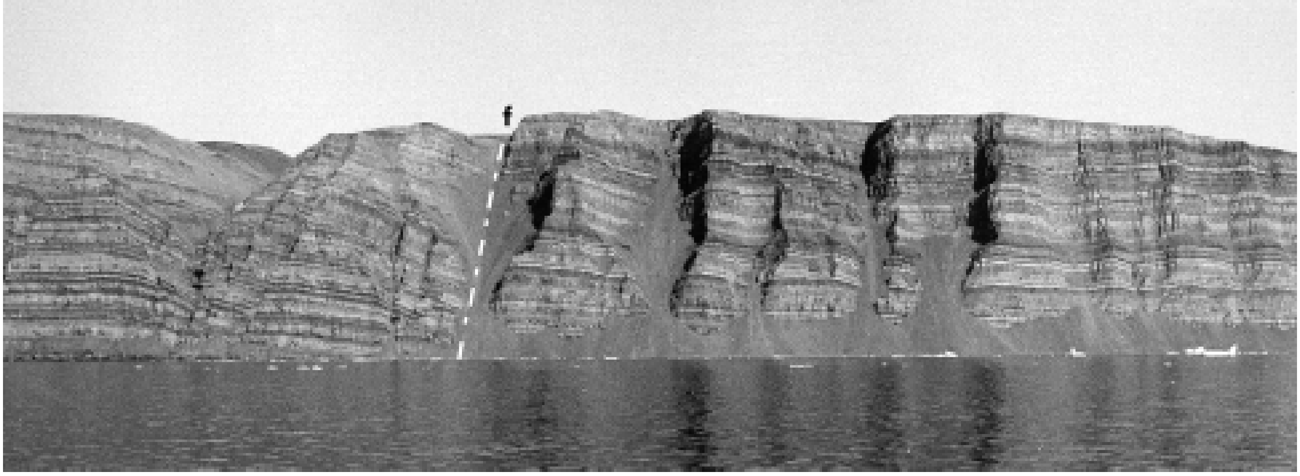
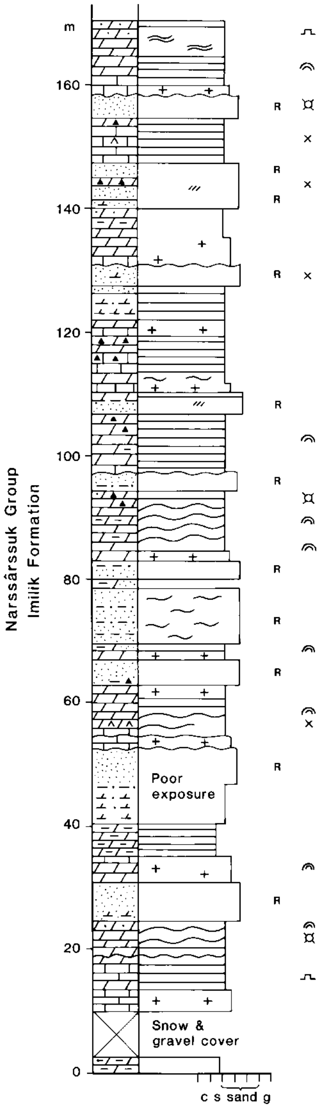
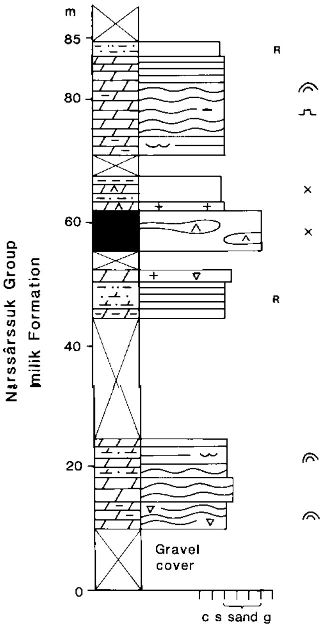


Fig 114. The Narssârssuk Group in the sea-cliffs of southern Saunders Ø, showing characteristic banding formed essentially by cyclic arrangement of siliciclastic (mainly red) and paler carbonate units. Displacement on the Agpat Fault (see Fig. 113) is greater than the cliff height, which exceeds 300 m.

Fig. 115. See facing page



49
Pituffik



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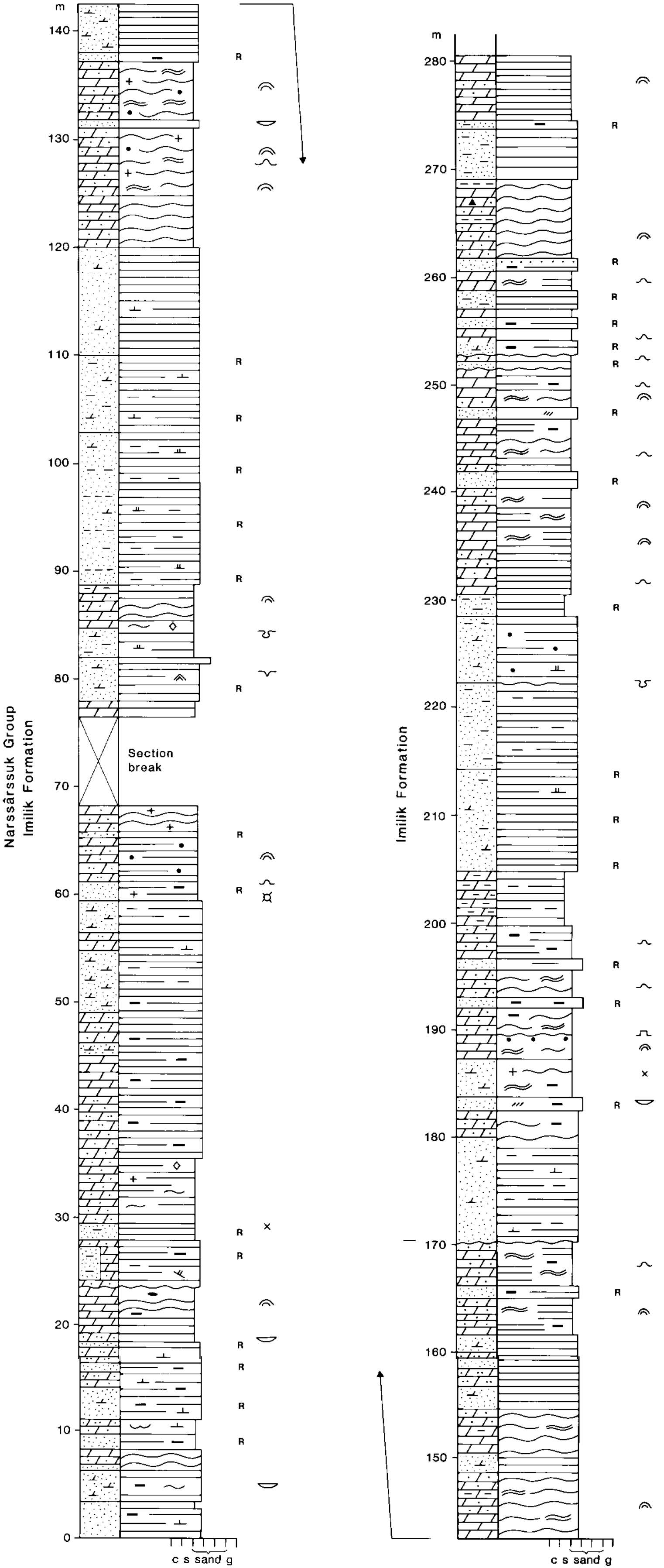
'Edisto Creek'



50
Saunders Ø

Fig. 115. See facing page

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Fig. 115. Stratigraphic logs of the Narssârssuk Group through lower, middle and upper parts of the succession (Imilik, Aorfêrneq and Bylot Sund Formations). The sections are compiled from the following sources: sections 48, 49 and 51, own data; section 50 logged by the author and B. O'Connor; section 52 mainly from O'Connor (1980). R = red beds. Map locations: sections 48, 49, 51 and 52, Fig. 105; section 50, Fig. 113.

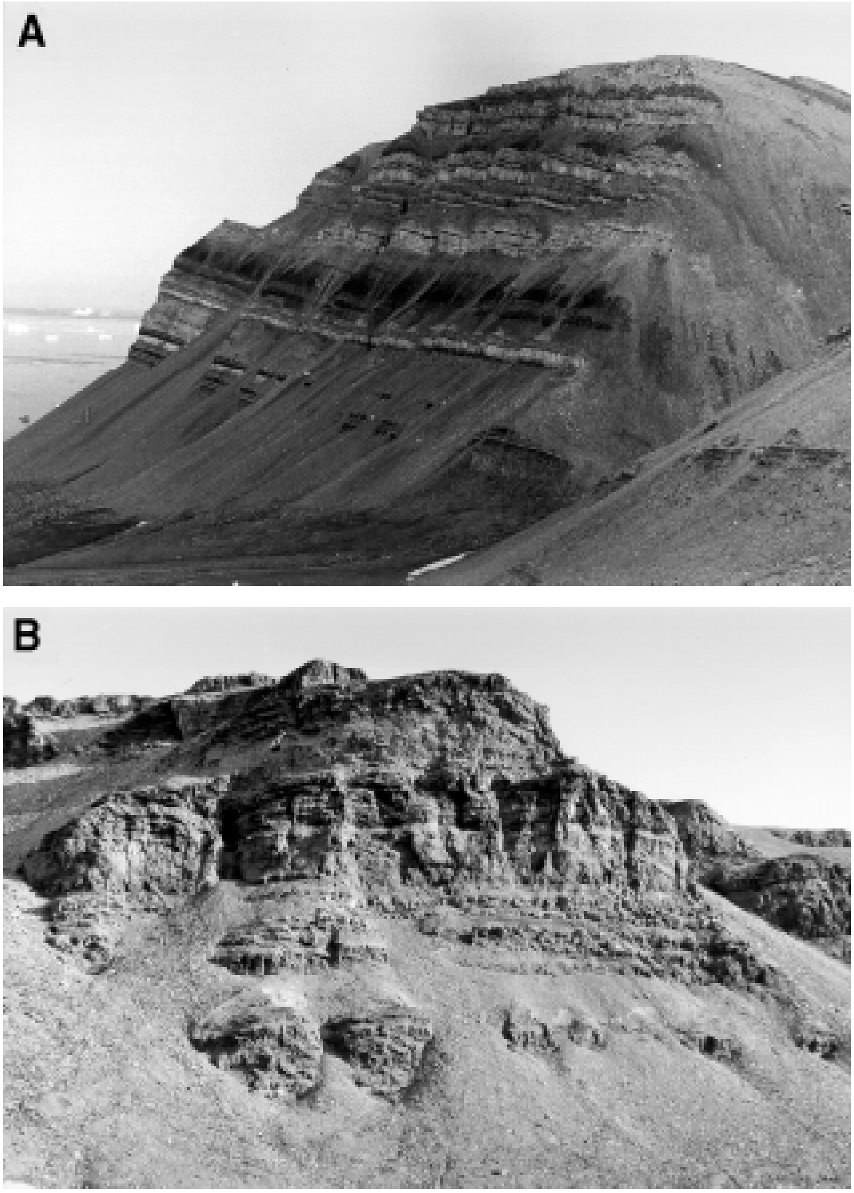


Fig. 116. Views of sections 50 and 51 in the Narssârssuk Group; stratigraphic logs are given in Fig. 115.
A: section 50, south-western Saunders Ø, with conspicuous dark siliciclastic units and pale dolomites; the dark unit in the middle of the section is 33 m thick;
B: section 51, south side of Aorfêrneq Dal, is dominated by grey dolomites of which about 135 m are exposed in foreground hill.

Munch (1941); her ‘Sandstone-dolomite series’ (Fig. 6). The group correlates essentially with the Narssarssuk formation of Kurtz & Wales (1951), although it excludes the uppermost beds of that formation north of Sioraq; it constitutes a direct raise in status of the Narssârssuk Formation of Davies *et al.* (1963; fig. 7) and Dawes (1976a, fig. 232).

Name. After Narssârssuk, the valley and traditional Eskimo dwelling place on the east side of Bylot Sund (settlement now abandoned) (Figs 2, 105).

Distribution. The most restricted of the five groups of the Thule Supergroup, occurring only in the Bylot Sund area as a south-east trending belt from Saunders Ø across the mainland to the Inland Ice (Figs 2, 105, 113).

Geomorphic expression and colour. A picturesque multicoloured group, very conspicuously banded in reddish, greenish and grey colours. It forms spectacular, in places precipitous, coastal sections as on Saunders Ø (Fig. 114); inland sections are heavily drift covered.

Type area. Coast between Sioraq and Narssârssuk (Fig. 105). Stratigraphic logs through parts of the lower, middle and upper strata in the type area (sections 48, 49, 51, 52), and one section from the lower part of the group from Saunders Ø (section 50), are given in Fig.

115; views of sections are in Figs 116 (sections 50, 51) and 117A (section 49).

Thickness. The group has an estimated thickness of between 1.5 and 2.5 km. In the type area four sections with a composite thickness of 670 m through parts of the lower, middle and upper reaches of the group have been logged. Extrapolations between these sections suggest a thickness on the mainland exceeding 1 km. On south-western Saunders Ø a 600 m section through the lower part of the group has been logged. Strata outcropping to the north and south-east, stratigraphically above and below the log, are estimated to be as much as 1.5 km thick.

Saunders Ø is cut by major faults, several of which have throws of several hundred metres (Fig. 114). The consistent interbedded nature of the group with some lateral facies changes are not conducive to regional correlation between fault blocks or between the type area and Saunders Ø. Carbonates in the middle part of the group appear to thicken westwards, and there may well be strata in eastern Saunders Ø that are stratigraphically higher than the top of the section on the mainland.

Dominant lithology. A well-layered, dominantly fine-grained carbonate-siliciclastic sequence, with evaporites and red beds, which is characterised by lithological cyclicity (Figs 114, 115). Lithologies are gradational both vertically and laterally.

Carbonates are grey, buff and pink dolomite and dolomitic limestone with some pure limestone; siliciclastic strata are red, grey, green and buff sandstone and siltstone with lesser amounts of shale. Thin- to medium-bedded strata dominate but both carbonates and sandstones show variation from thick beds down to very thin laminae. Generally, dolostones and limestones are fine to very fine grained but coarser, blocky recrystallised rocks occur, as well as porous and vuggy types. Sandstones are fine-grained quartz arenites with some subarkoses and arkoses. Some thin beds reach medium grain size; coarser grained pockets are rare. There is widespread compositional gradation between carbonates and siliciclastic rocks. Thus, dolostones are variously arenaceous and sandstones commonly have matrix carbonate; argillaceous dolomites and calcsiltites are common. Many rocks are laminated, often finely planar to wavy lamination, with locally well-developed wave-ripple lamination and wavy algal laminites (Figs 117B, F; 118A, B, H). Carbonates and siliciclastic rocks are variously interlayered from bed down to lamina scale; vertical passage between arenaceous dolomites and sandstones is often seen as a colour interlamination (Fig. 117D, E).

Disturbance of bedding and lamination is common in some intervals. This ranges from flaser bedding and irregular laminations, to flakes and flat clasts occurring in discrete pockets, to rip-up breccia beds (Fig. 118C). Other sedimentary structures are desiccation and diastasis cracks, small-scale channels, symmetrical and asymmetrical ripple marks, ripple-drift bedding and cross-bedding, the latter particularly in red siliciclastics. Cracks take on a variety of forms from mudcracks to dewatering structures and small tepees (Figs 117E, 118G). Cracks can be deeply penetrative and are often filled by detritus, in places forming thin dykes that are conspicuous in the axial regions of tepees and also occur in the troughs between algal mounds. Carbonates show stylolites (Fig. 118E), and a variety of diagenetic compaction structures and many intervals are richly stromatolitic. Flat to wavy cryptalgal laminites and low-relief dome and mounds are common forms; the broadest mounds seen approach 2 m in diameter (Figs 117B, F; 118B). Columnar and spheroidal stromatolites are less common.

The dolomites can be variously silicified and chert is present in minor amounts particularly in the middle part of the group. It is mostly dark grey to black and occurs as seams and thin beds. Strother *et al.* (1983) regard all chert as early diagenetic in origin, with some chert as thin horizons replacing algal mats.

Evaporite, mainly gypsum, has been noted in all sections examined varying in abundance and form of occurrence. It occurs as seams, nodules, stringers, veins and thin beds, as well as the matrix of breccia beds in which dolomite or shale is broken up and variously gypsiferous (Figs 117C, 118D). Breccia units, up to several metres thick, are commonly very porous with rotten-stone character. The thickest breccia noted, some 14 m thick, is composed of lenticular bedded dolomite in various stages of replacement by evaporite (Fig. 118F). An 8 m thick bed of gypsum is reported in a well log by Davies *et al.* (1963), an occurrence regarded as a bedded evaporite (W. E. Davies, personal communication, 1980).

The Narssârssuk Group is dominated by interbedded cyclic sequences of widely varying lithology and thickness. End members are carbonates and red siliciclastics. Such cycles range from less than 5 to over 20 m; many are between 10 and 15 m thick. Abortive cycles, conspicuous by the absence of red beds or by one or more other lithologies, occur singly or more

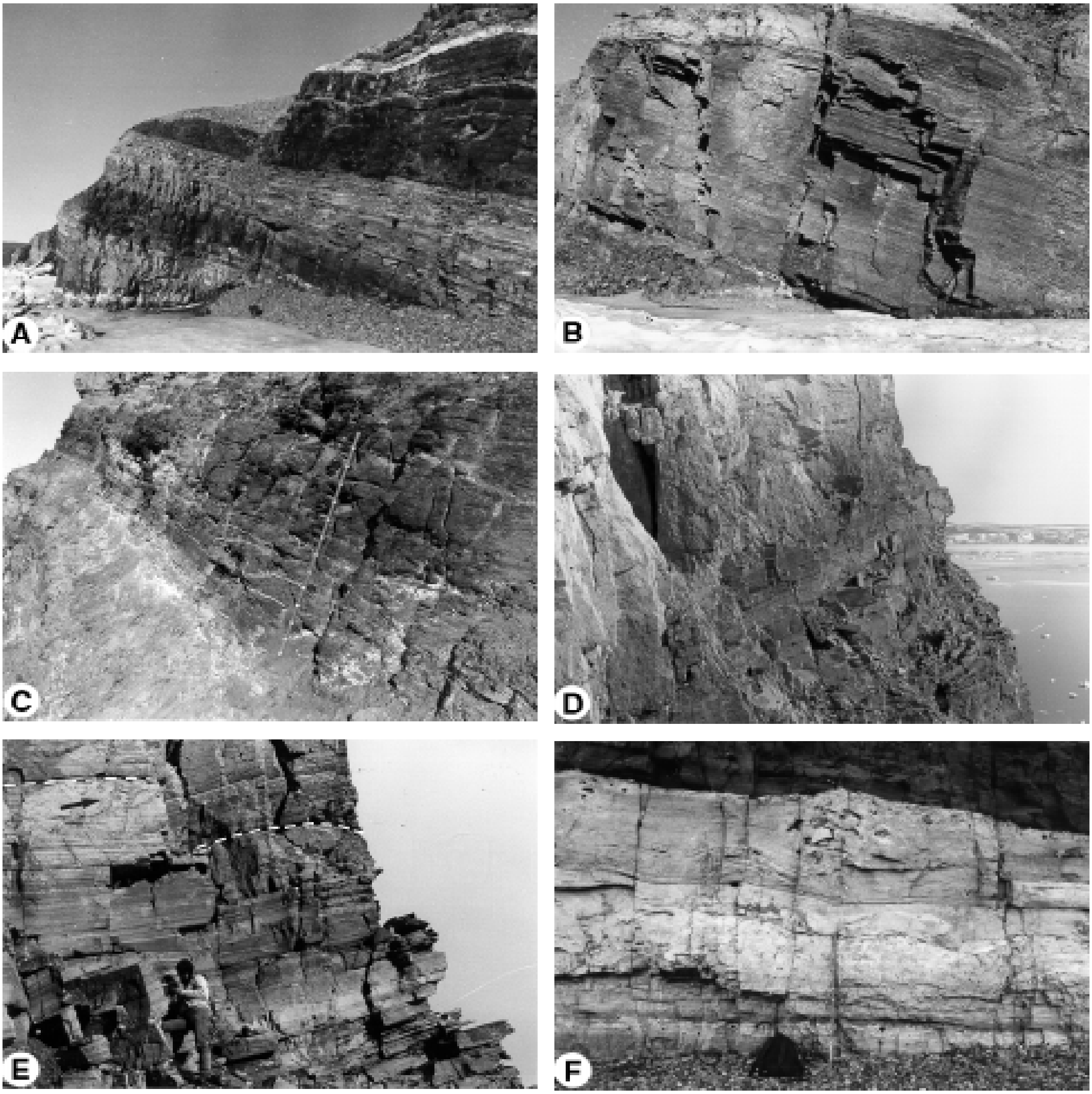


Fig. 117. Cyclic lithologies of the Narssârssuk Group. **A:** progradational cycles capped by red siliciclastic beds. Lowest red bed is 4 m thick; **B:** lower part of progradational cycle showing porous dolomitic limestone passing up into wavy laminated stromatolitic dolomite overlain by pale, variously arenaceous dolomite that contains chert and evaporite. Base of red bed is visible at top left (arrowed). Strata are about 10 m thick; **C:** top of progradational cycle showing laminated dolomites passing up into pale thin bedded siltstone and green calcarenite capped by red sandstone. Evaporite forms white coatings, seams and veins. Staff has 10 cm grid; **D:** part of a regradational cycle with red sandstone below passing upwards into pink and grey interlaminated arenaceous dolomite and at the top grey stromatolitic dolomite. Strata are about 10 m thick; **E:** intergradational siliciclastics and carbonates: red calcareous sandstone at the base passes upwards by interlamination into pink arenaceous and algal dolomites, and finally into red and grey laminated dolomites at the top of which is an eroded algal dolomite bed with tepee structures (arrowed); **F:** algal dolomite sequence with sharp contact with overlying red bed. Planar laminated arenaceous dolomite with some irregular algal beds pass up into paler stromatolitic dolomite with dark algal mat layers, followed by a unit of finely laminated dolomites with algal mounds and a vuggy dolomite top. Wave-ripple lamination is present in the uppermost part (see Fig. 118H). Staff has 10 cm grid. Locations: **A**, **B** and **C**, Pituffik, section 49; **D** and **E**, Saunders Ø, section 50; **F**, Narssârssuk, section 52.

often in multicycle packages. Prominent, particularly in the lower part, are progradational cycles in which basal carbonates grade into mixed carbonate-siliciclastic lithologies and finally into siltstone-sandstone which is commonly red (Fig. 117A). Typical cycles have at their base coarse, porous, thick-bedded dolomite or limestone that pass upwards into thinner, often wavy-bedded, well laminated dolomite, with wavy laminated, low-relief stromatolites (Fig. 117B). The 'ideal' cycle continues upwards into variously shaly dolomite and calc-siltstone, in places with chert and evaporite and capped by fine-grained, rarely medium-grained, siliciclastics (Fig. 117C). Evaporite, where present, generally increases upwards with incoming of siliciclastic material. An erosional surface, limonitic in places, commonly truncates the upper siliciclastic beds but red beds may also have sharp and locally erosional contacts with lower lithologies. Common in some cycles are units of arenaceous dolomites and algal laminites that may grade or have sharp contact with siliciclastics (Fig. 117F). Some other cyclic variations within the basic shallowing-upwards sequences are mentioned by Jackson (1986).

On Saunders Ø transgressive cycles occur in which red, pink and green siliciclastic rocks grade upwards into pink arenaceous dolomite or buff-grey dolomite and algal dolomite (Fig. 117D, E). Both carbonate and siliciclastic rocks can occur in single units bounded by sharp contacts, although gradation between these rock types is more common. Interbedding between carbonates or carbonate-dominated units and siliciclastic rocks occurs on all scales. The thickest siliciclastic units are more than 30 m thick. The two conspicuous dark-weathering units in south-western Saunders Ø (Fig. 116A) are composed of red-purple, with lesser amounts of green, finely laminated, fine-grained micaceous or silty sandstone with ripples indicating currents from the east.

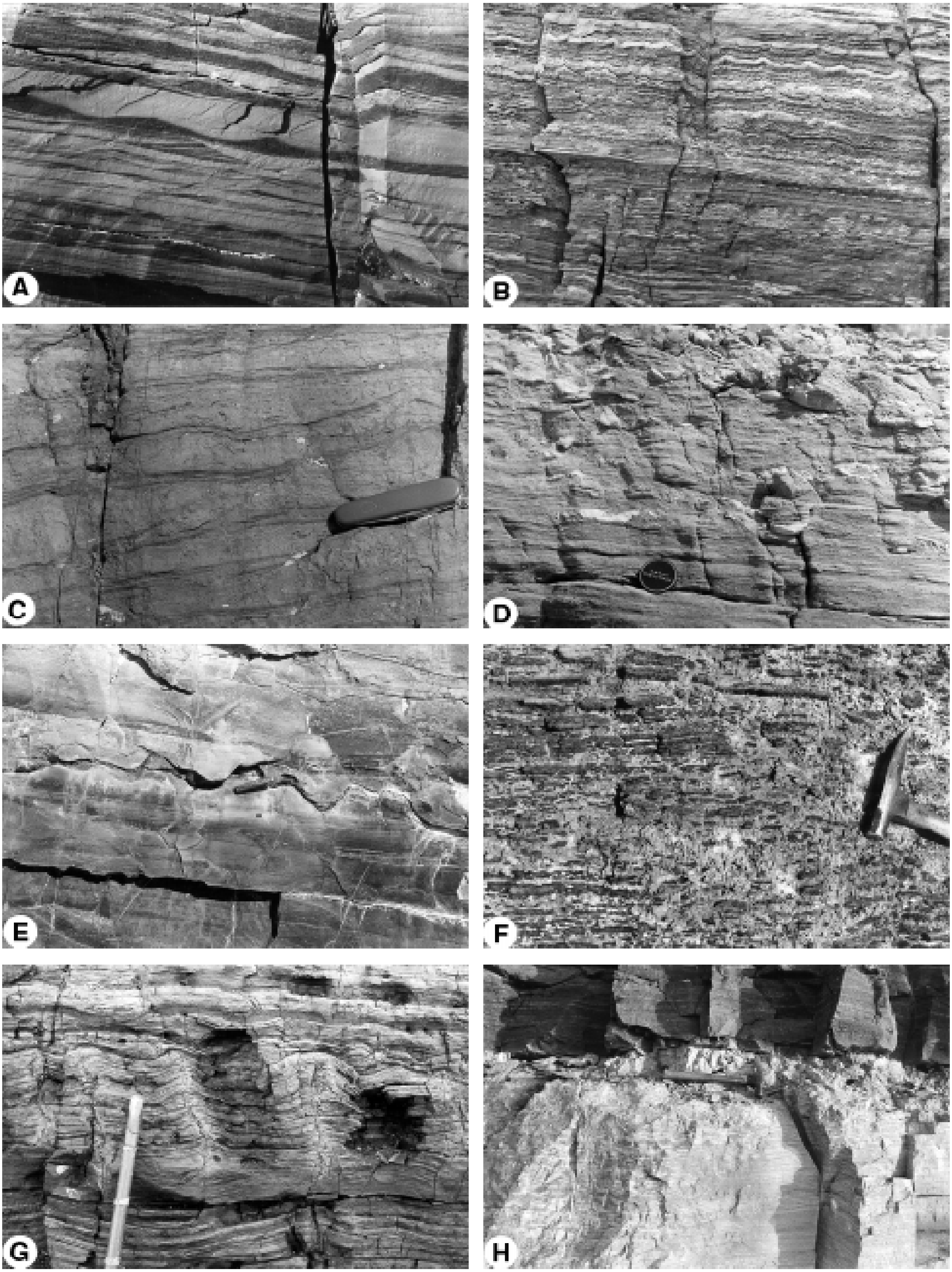
In the type area the group can be divided into three parts: lower and upper successions (Imilik and Bylot Sund Formations), characterised by cycles involving red siliciclastic strata, are separated by a carbonate-dominated, generally thicker bedded unit (Aorfêrneq Formation) in which dolomites are generally clean, and siliciclastic rocks are restricted to sporadic thin red beds. The Aorfêrneq Formation contains considerably more evaporite than the sequences below and above. The strata on Saunders Ø in gross terms reflect this tripartite subdivision (Fig. 113), although the rather massive pale dolomite units that characterise the western end of the island – overlain and underlain by cyclic red bed sequences – show clear differences from the Aorfêrneq Formation; for example, important clastic intervals occur. The lateral facies and thickness variations seen locally are expected to be reflected regionally in differences between the type area and more basinal strata to the west.

Depositional environment. Previous studies of the Narssârssuk lithologies conclude that the very shallow water strata represent subtidal to supratidal deposition in an arid or semi-arid environment (Dawes, 1979a; Strother *et al.*, 1983; Jackson 1986).

A low-energy environment sheltered from the open influence of the sea is suggested, such as a large protected embayment with lagoonal conditions. The cyclic sedimentation indicates regular fluctuations of the shallow, quiet water in which for the most part only rip-up clasts indicate sedimentary reworking. Deposition must have been on a wide carbonate shelf with very gentle bottom slopes. Stromatolites and evaporites occur at all levels of the group indicating persistence of warm hypersaline conditions. Evaporite is conspicuous as a diagenetic phase (disrupting and replacing other lithologies and as fracture infillings) but primary nodules, seams and thin beds point to arid or semi-arid evaporitic environments. The overall depositional environment is perhaps analogous to modern coastal sabkhas.

The lower and upper parts of the Narssârssuk Group characterised by red beds in regressive cycles, indicate repeated progradation from intertidal carbonates to supratidal siliciclastics. The transgressive cycles noted in the west may reflect coeval allocyclic sedimentation. Cross-bedding and ripple marks in clastic lithologies (particularly in the upper part in the east) evince periods of stronger current action and a consistent transport of clastic material from the east. The middle part of the group, characterised by cleaner and thicker carbonate units and appreciably more evaporite, is taken to represent a protracted stable period in which broad carbonate tidal flats persisted and in which algal growth was rife. Some subtidal carbonates are suggested by Jackson (1986) to be represented in the group, a view supported by the micro-organism habitats studied by Strother *et al.* (1983).

The role of faulting – penecontemporaneous faults were recorded initially by Kurtz & Wales (1951) – in the generation of the cyclic sequences is uncertain, but the gross lithological character suggests that deposition was in a shallowly subsiding basin with complimentary migration of the shoreline, rather than a tectonically controlled shelf sea.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Fossils. Algal associations including algal mats and stromatolites of varying types (domes, columns, oolites, low-relief algal laminites) and microbiota – both acritarchs and cyanobacteria. Shales have yielded filamentous microfossils and an acritarch assemblage of five taxa, the most stratigraphically significant being *Vandalosphaeridium varangeri* (Vidal & Dawes, 1980; Dawes & Vidal, 1985; see below under *Geological age*). Twenty entities of planktonic micro-organisms from carbonaceous cherts have been described by Strother *et al.* (1983), including five new taxa. The microfossils represent four distinct microbial associations and one allochthonous assemblage.

Boundaries and correlation. Lack of exposure and erosion determine that the stratal limits of the Narssârssuk Group are unknown. The only observed boundary is the fault contact with the crystalline shield that bounds the group to the south (Fig. 105). The northern boundary is concealed below the valley of Sioraq and the group is preserved in a WNW-trending half graben or graben. The group is limited upwards by the present erosion surface. The nearest strata (both geographically and stratigraphically) are those of the Dundas Group exposed in the valley of Sioraq. As described under that group, these strata dip south and most likely underlie the Narssârssuk Group.

Geological age. Late Hadrynian – Vendian, an age based on microfossils and on the whole-rock isotopic dating of basic intrusions. The K-Ar age of dolerite from a dyke that cuts the uppermost strata (Bylot Sund Formation) is 645 ± 26 Ma. This dyke is part of the regional WNW-trending swarm that has a K-Ar age range of 675–630 Ma (Dawes, 1991a). An acritarch assemblage from the Narssârssuk Group contains Late Riphean – Vendian species which also occur in the Baffin Bay and Dundas Groups. Only one species, *Vandalosphaeridium varangeri*, is stratigraphically significant within the limits discussed here, and it has been found elsewhere in the Thule Supergroup only in the Olrik Fjord Formation of the Dundas Group. This species is only known from one sample from the lowermost strata (Imilik Formation) and it is considered indicative of an early Vendian age (Vidal & Dawes, 1980). The microbes described by Strother *et al.* (1983) are consistent with this early Vendian age, viz. around 700 Ma. The K-Ar age of the WNW-trending and cross-cutting basic dyke swarm suggests that substantially younger strata are probably not present.

Subdivision. The three subdivisions established in the type area and mentioned under *Lithology* have been mapped as formations and their distribution tentatively extended to Saunders Ø (Figs 105, 113). From base upwards these are: Imilik Formation, Aorfêrneq Formation and Bylot Sund Formation. Precise correlation between the type area and Saunders Ø is problematic (see earlier, under *Thickness*). In any case there are distinct lithological packages in many parts of the group that warrant formal recognition. Pending further field work, formal definition at formation level is not made in this bulletin.

←

Fig. 118. Characteristic lithologies and structures of the Narssârssuk Group. **A:** interlaminated arenaceous dolomite and darker sandy material showing wave ripples and ripple-bedded sand lenses. Distance between central ripples is about 15 cm; **B:** wavy algal laminite. Penknife, upper centre, is 7 cm long; **C:** pink arenaceous dolomite with fine algal laminae and rip-up flake/clast layers. Penknife is 9 cm long; **D:** gypsum nodules and stringers in a red bed at top of shallowing-up cycle showing increased concentration upwards; **E:** stylolite in fine-grained dolomitic limestone; dark shale is present in the plane. Penknife is 9 cm long; **F:** carbonate-evaporite breccia showing invasion and replacement of dolomite; **G:** tepee structures in dolomite showing central deeply penetrative cracks cutting darker arenaceous dolomite layers, photo: B. O'Connor; **H:** detail of algal dolomite and overlying laminated red sandstone shown in Fig. 117F. Wave-ripple laminated dolomite showing lateral passage to planar lamination capped by coarser vuggy dolomite that contains red chert and evaporite clots. Locations: **A**, **B** and **C**, Saunders Ø, section 50; **D** and **E**, south of Pituffik; **F**, Aorfêrneq Dal, section 51; **G** and **H**, Narssârssuk, section 52.

Basin characterisation, limits, development: a summary

Thule Basin: onshore – offshore

The Thule Supergroup defines a depocentre on the northern margin of the North Atlantic craton. The outcrops, forming coastal exposures disappearing under the sea in down-faulted blocks, are the preserved fragments of a large sedimentary and volcanic province. Gravity, magnetic and seismic reflection data indicate the presence offshore of a thick, faulted sedimentary section between south-east Ellesmere Island and North-West Greenland (Keen & Barrett, 1973; Hood & Bower, 1975; Ross & Falconer, 1975; Newman, 1982a; Jackson *et al.*, 1992). A sedimentary section several kilometres thick is interpreted to fill these offshore down-faulted basins; for example from magnetic data between 77º and 78ºN, Hood & Bower (1975) suggest thickness variation between 10 and 20 km.

Farther south, between 74º and 76ºN, reflection seismic data indicate that a thick sedimentary succession is preserved in graben structures in the Melville Bugt – Kap York region, with one small basin south-west of the Carey Øer (Whittaker & Hamann, 1995). The offshore section here is up to 8 km thick.

There is clear correlation between offshore geological features and onland strata and tectonics. Thus the offshore sedimentary tract trending north-west from the Bylot Sund region – the Steensby Basin of Newman (1982a; Fig. 119) – is online with the major graben structure that preserves the Narssârssuk Group with a throw on the southern boundary fault (Narssârssuk Fault) of several kilometres. However, the age of the offshore strata in the North Water and Steensby Land Basins (Fig. 119), as well as in the Melville Bugt basins farther south, is unknown. From comparison with the offshore geology of Baffin Bay (cf. Balkwill *et al.*, 1990), it is predicted that a thick late Phanerozoic (Cretaceous–Tertiary) section is preserved. But it is very conceivable that Proterozoic strata form an important part of the offshore successions although as yet only qualified guesses can be made as to the extent and thickness of Proterozoic versus Phanerozoic rocks.

Also uncertain, is the structure of northern Baffin Bay and Smith Sound; the origin of this seaway, and its continuation northwards as Nares Strait, have been the subject of considerable debate (Dawes & Kerr, 1982). Some authors, working with plate kinematic models, interpret the seaway as the site of a Cenozoic plate boundary: a major suture zone representing a subducted ocean, substantial transcurrent motion, massive crustal shortening with continental collision (e.g. Srivastava & Tapscott, 1986; Jackson *et al.*, 1992). However, the regional geology, including the presence of the intracratonic Thule Basin straddling the seaway, and the overlying undisturbed Palaeozoic strata bordering Smith Sound and Kane Basin, militate against such a dynamic crustal history (e.g. Dawes, 1986; Higgins & Soper, 1989). Clearly, information on the tectonic setting of the offshore strata in the northern Baffin Bay – Smith Sound region must await renewed and more refined geophysical data.

Geological setting

Dominated by continental, littoral and shallow marine sedimentary facies, coupled with continental tholeiitic magmatism, the Thule Supergroup is an expression of the evolution of a rifted continental margin or intracratonic basin. The spatial relationships and thicknesses of the described lithostratigraphic units define two major structural margins: one in the north across Smith Sound, the other in the east and south-east between Inglefield Bredning and Wolstenholme Fjord. Marked thickness changes with the cut-out of basal strata and overlapping of younger Thule strata onto the crystalline shield characterise these margins (Fig. 119, see below). They evince that the Thule Supergroup represents the fill of a restricted or semi-restricted intracratonic basin rather than a one-sided wedge on a shallow continental margin.

Basin geometry

The regional extent of the Thule Basin, from Canada to Greenland and over 300 km in a north–south direction, is defined by the lower Thule Supergroup, viz. the Nares Strait, Smith Sound and Baffin Bay Groups. These groups have preserved sedimentary contacts with the crystalline shield. Overlying strata of the Dundas and Narssârssuk Groups are only preserved in Greenland, and the strata outcrop within the limits of the basin as defined by the older rocks, viz. there is no overlap of upper Thule strata onto the crystalline shield.

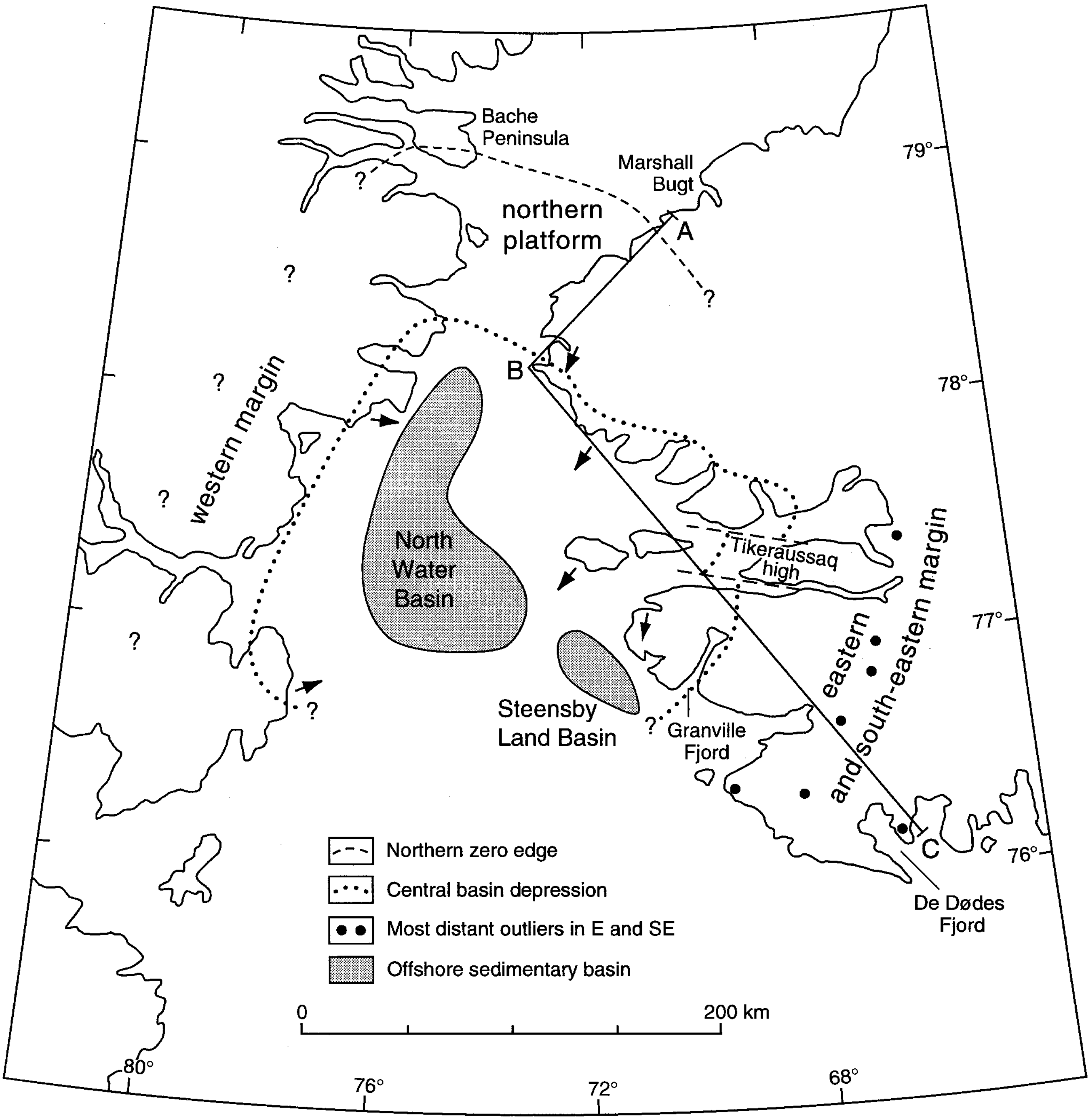


Fig. 119. Map of the northern Baffin Bay – Smith Sound region showing the extent of the central and marginal parts of the Thule Basin in Neohelikian time. This corresponds to the evolution stage shown in the cross-section given in Fig. 120 (line A–B–C). The central basin depression corresponds to the Nares Strait Group and correlative strata of the Smith Sound Group over the northern basin margin. The arrows indicate prominent palaeocurrent directions for the Nares Strait Group and lower strata of the Smith Sound Group mainly from Dawes *et al.* (1982a), Frisch & Christie (1982) and Jackson (1986), as well as unpublished data. The offshore sedimentary basins are based on geophysical data from Newman (1982a). For bedrock outcrops and ice cover, see Fig. 2.

The present limits of the Thule Supergroup on land are defined by both sedimentary and tectonic contacts (Figs 1, 2, 5). The most extensively preserved sedimentary contacts marking the outer limits of the basin occur in Greenland, in the east and south-east between Inglefield Bredning and Wolstenholme Fjord, and in the north in Inglefield Land. In the former region, scattered outliers on the shield show easterly stratal thinning; in the north, a thin platform cover of Smith Sound Group over structurally high shield (Bache Peninsula arch) thins to the north and north-east in Inglefield Land and to the west in Bache Peninsula, finally petering out at the unconformity between the shield and Cambrian strata of the Franklinian Basin (zero-edge in Fig. 119).

The present north-eastern limit in Prudhoe Land is fault-controlled. In the north a major NW-trending block fault system, characterised by down dropping to the south-west, limits Thule strata to the coastal area. The Dodge Gletscher Fault, as the main outer fault of the system, juxtaposes the basal Thule strata (Nares Strait Group) against the shield (Figs 1, 5B, 27, 111). Farther south, the unconformity involving Nares Strait Group, although extensively faulted, marks the basin limits. The Inland Ice hides the geological relationships inland but overlapping of younger strata (Baffin Bay Group) on the basin substratum is not seen. This contrasts with conditions farther south where outliers of the Baffin Bay Group stretch far beyond the faults that limit the Nares Strait Group. The outlier at De Dødes Fjord, representing the most distal strata of the marginal succession, is over 100 km south-east of the central basin limit at Granville Fjord (Figs 13A, 119).

Based on the Greenland sections, the lower Thule Supergroup shows progressive thinning to the north, east and south defining a central depression with a section exceeding a thickness of 2 km, e.g. in the Northumberland Ø area (Figs 12, 120). The Canadian outcrops, although relatively small and isolated, and being truncated by the present erosion surface (apart from the Smith Sound Group at Bache Peninsula in the north), show corresponding thinning to the north and south. Comparison with the Northumberland Ø section suggests an overall westerly thinning, but narrowness of the coastal sections between Clarence Head and Johan Peninsula (Fig. 2) restricts meaningful inferences on regional east–west trends. These outcrops disappear under the ice cap or are in fault contact with crystalline shield. They show no sign of westerly thinning or overlapping of younger strata onto crystalline basement. It should be mentioned here that the overlapping of the crystalline shield by 'Upper beds' shown by Frisch (1988, map 1572A) in western outcrops at Gale Point, is reinterpreted in this bulletin as an unconformity involving basal sandstones (Northumberland Formation, see Fig. 54).

In general terms the palaeocurrent pattern supports the basin geometry devised from the regional thickness variations. In Greenland, lower Thule Supergroup data indicate prominent transport directions to the south and south-west away from the fringing outcrops of crystalline shield (Dawes *et al.*, 1982a), while in Canada easterly transport directions prevail with more local westerly and northerly components (Frisch & Christie, 1982; Jackson, 1986). In terms of the primary basin geometry, the Canadian provenance data are particularly significant since the western boundary is only fragmentarily preserved (compared with the eastern side in Greenland). The data indicate that in Neohelikian time the basin was closed to the west, i.e. a land source area lay in that direction. This is supported by volcanic flow direction where determinable, e.g. the emplacement of a terrestrial basaltic flow at Goding Bay (Cape Combermere Formation) is from the west (Jackson, 1986). How far to the west the original margin of the Thule Basin was situated is conjectural (Fig. 119).

The central fill of the Thule Basin is formed mainly of the Nares Strait Group that in Greenland shows a regional thinning to the north, east and south (Fig. 12). Equivalent strata of the Smith Sound Group (Pandora Havn and Kap Alexander Formations) show overlapping relationships with crystalline shield, tapering and petering out northwards; basal strata of the Nares Strait Group are abruptly cut out by faults (Figs 26, 27, 120). The present expression of this basin margin is as a post-deposition fault zone. Coeval sedimentation may have taken place beyond the central basin depression in shallows on the eroded crystalline shield or in local sags. Such deposition is probably represented by the basal clastic strata of the Smith Sound Group (Cape Camperdown Formation).

The presence of similar marginal faults in the east and south-east limiting the Nares Strait Group can be surmised from outcrops in the Inglefield Bredning area and Steensby Land (see Fig. 95). It is noteworthy that this margin, delimiting the central basin depression and projected to reach the outer coast at Granville Fjord (Fig. 119), is on strike with a major offshore fault deemed by Okulitch & Trettin (1991, fig. 17.12) to have been active during the late Phanerozoic development of Baffin Bay.

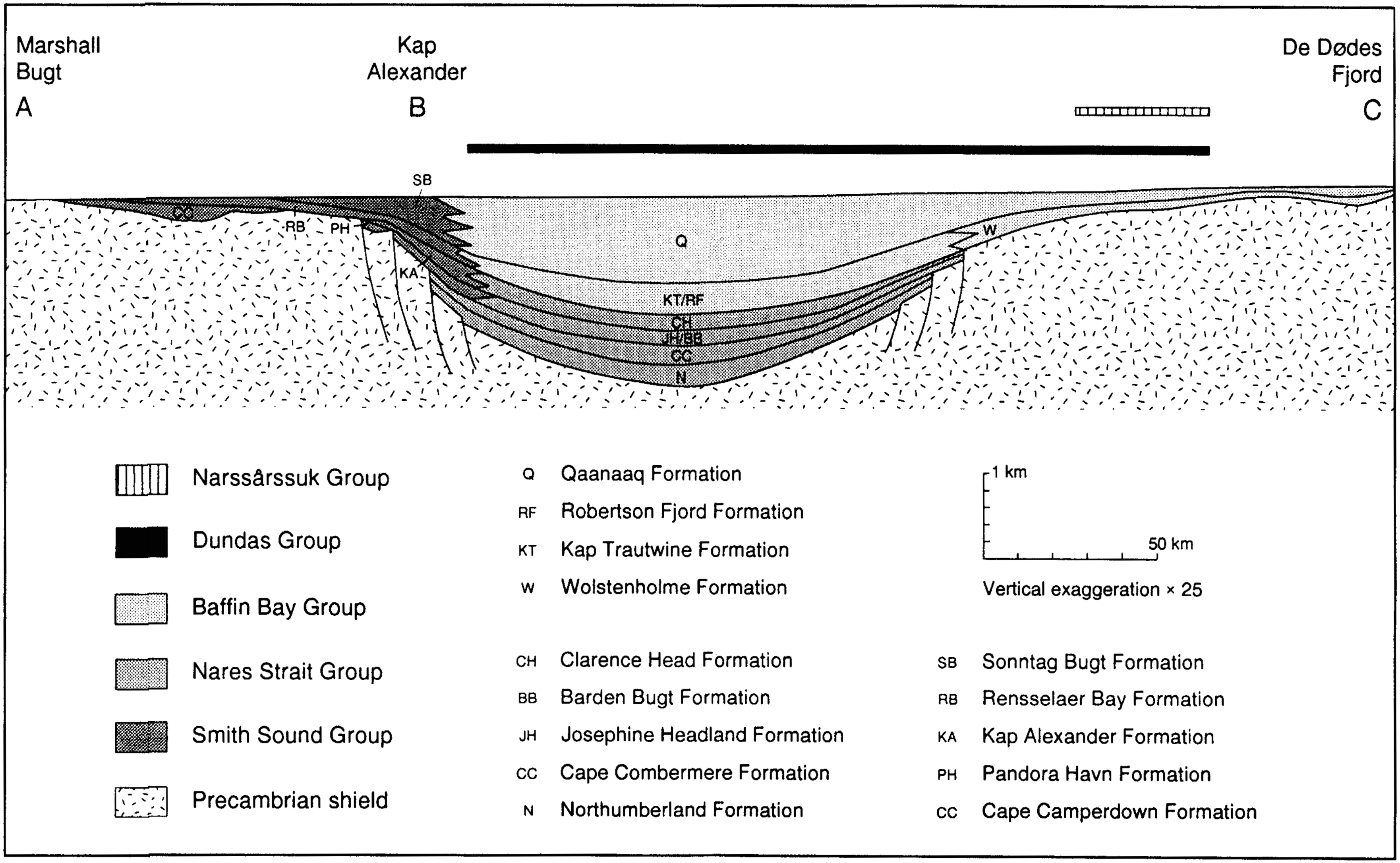


Fig. 120. A cross-section through the Thule Basin with the lower Thule Supergroup as basin fill, showing the relationships of groups and their formations. The spatial relationship of the Dundas and Narssârssuk Groups superimposed on this Neohelikian evolutionary stage is shown by bars. The location of section line A–B–C is shown in Fig. 119.

Major basin expansion is indicated by the Baffin Bay Group and upper strata of the Smith Sound Group with sedimentation across the early basin margin and with overlapping of the crystalline shield beyond. This expansion defines the maximum limits of the Thule Basin as preserved today. As described above, a thinning of both these groups away from the depocentre is evident.

A polyhistory interior fracture basin

The Thule Supergroup is notably lacking in regional or intra-basinal unconformities. Taken on face value this field observation suggests that deposition more or less kept pace with slow and steady subsidence. However, in the absence of more precise biostratigraphical control, any paraconformities in the succession remain undetected. The only major stratigraphic junction that has not been observed is that limiting the Hadrynian Narssârssuk Group and a major unconformity representing an appreciable time gap may exist at this level. On the other hand, the succession does show marked changes in vertical lithologies and depositional environments, for example from continental to shallow marine, and there are pronounced changes in transport directions (e.g. Jackson, 1986); these features suggest that penecontemporaneous faulting may have been important.

The recognition of faulted basin margins delimiting an early central depression (Nares Strait Group) from surrounding marginal areas with thinner successions point to a Neohelikian evolution in which vertical horst and graben faulting played an important role. This early rift development included basaltic magmatism, with outpouring of lavas, injection of sills and some explosive volcanism. This magmatic activity is regarded as indicative of an overall extensional environment (rather than a specific high geothermal gradient) in much the same way as Cox (1970), in the case of the Karoo region of South Africa, viewed the tholeiitic volcanism in association with sedimentary basins and extensional faulting. Rifting of the continental crust is seen as the initiator of basin development with early sediments filling depressions within the block fault system and with contemporaneous volcanism.

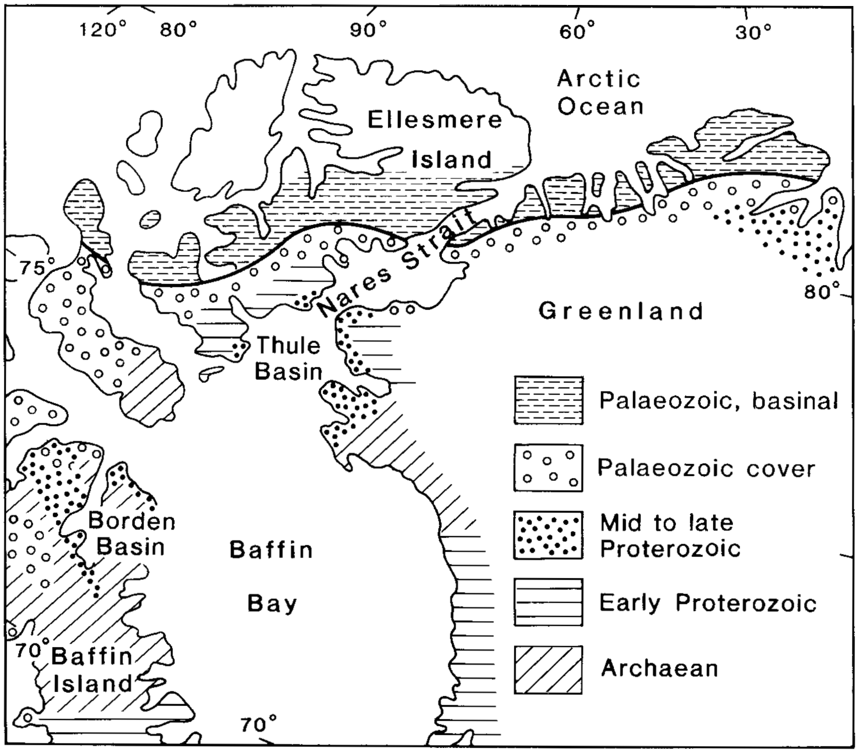
Fault blocks can be expected in the central part of the basin; at Thule, however, this segment of the basin is submarine. Predicted fault blocks are not portrayed on the cross-section given here (Fig. 120), although Northumberland Ø, representing today an uplifted block and the most central section of the basin (Fig. 48), may well be flanked by fault depressions with thicker successions. One well-defined fault block – here called the Tikeraussaq High – is preserved in the eastern part of the basin (Figs 95, 119). This is a WNW-trending horst that must have been a positive feature during the deposition of the basal strata of the basin: strata of the Nares Strait Group are present north and south, while the horst is draped by strata of the Baffin Bay Group.

A main stage of basin expansion, heralded by the Baffin Bay Group and coeval strata of the Smith Sound Group, was presumably due to renewed block faulting and foundering of the early basin margin. At that time faults such as that delimiting the Tikeraussaq High were active.

Passage from lower to upper Thule Supergroup – from continental and littoral Baffin Bay Group to more basinal Dundas Group – marks environmental changes indicating accelerated basin subsidence, presumably by increased tensional faulting accompanied by basin sagging. In Canada, transitions in the uppermost Baffin Bay Group towards more basinal lithologies suggest that the Dundas Group may once have had a much wider distribution. On the other hand, nothing can be said about the original extent of the Narssârssuk Group, which is now restricted on land to the Bylot Sund area. In any case, the upper Thule Supergroup signifies consolidation of the previous basin expansion with youngest deposition on the south-east margin of the basin. The answer to the question of whether the Narssârssuk Group represents a local successor basin developed, for example, in a narrow fault-controlled trough or represents a fragment of a larger province, such as a carbonate platform, must await data from the offshore regions.

Dislocations in the Narssârssuk Group provide some evidence for syndepositional faulting which may be responsible for the prominent cyclicity characterising the sedimentation. The strata are preserved in one of several graben structures that cut the Thule Supergroup and that are also known offshore. Many of these faults, including those bounding the Narssârssuk Group, are parallel to a regional swarm of Hadrynian basic dykes that have given K-Ar ages between 645 and 725 Ma (Dawes & Rex, 1986; Figs 70, 105). These dykes are seen as the waning phase of the Franklin magmatism that released appreciable amounts of basaltic material into the basin and produced the sill complex penetrating the Dundas Group in central and south-eastern exposures (Fig. 106).

Fig. 121. Simplified geological map of northern Greenland and adjacent part of Canada, showing the locations of the Thule and Borden Basins of northern Baffin Bay. The middle to late Proterozoic strata shown in eastern North Greenland define the Independence Fjord and Hagen Fjord Basins (Sønderholm & Jepsen, 1991). The one geological boundary highlighted corresponds to the southern limit of basinal rocks of the Palaeozoic Franklinian Basin. Shelf carbonates bordering this basin (part of the 'Palaeozoic cover') overlie the northern exposures of the Thule Supergroup in Bache Peninsula, Ellesmere Island, and in Inglefield Land, Greenland (see Fig. 2). Modified from Frisch & Dawes (1994).



Many post-depositional faults that cut the Thule Basin and that are associated with tilting, local folding and broad flexuring, may represent a long Proterozoic history and may have been active during sedimentation. Clearly, an overall extensional environment persisted during the Hadrynian development of the basin, as indicated by the Franklin dykes that follow such faults. (Fig. 70).

The Thule Basin records a long history of sedimentation, magmatism and tectonism possibly spanning as much as 650 Ma. While continuous sedimentation through such a long period of time is improbable, unconformities in the succession have yet to be documented. In terms of global basin classification such as that proposed by Kingston *et al.* (1983), the basin can be categorised as a multicycle, polyhistory, interior fracture basin, characterised by block faulting and subsidence and followed by basin sagging. Divergent plate movements are deemed to be the underlying cause of this type of basin.

Regional comment

The Thule Basin is one of several mid to late Proterozoic depocentres that fringe the northern margin of the Canadian–Greenlandic shield stretching from the western Cordilleran region to East Greenland (Young, 1979). These intracratonic basins were influenced to varying degrees by the Neohelikian Mackenzie, and Hadrynian Franklin, magmatic episodes, and they share many features in stratigraphic sequence and tectonic setting.

The nearest basin to Thule is the Borden Basin of northern Baffin Island (Fig. 121). This basin contains a comparable thickness of shallow water sediments with an interval of Neohelikian volcanics and it has a conspicuous NW tectonic grain (Jackson *et al.*, 1978, 1985; Jackson & Iannelli, 1981, 1988). Faults were active during Neohelikian sedimentation and they reflect a long history from the Paleohelikian to Recent. The parallelism of the main fault trends in the Borden and Thule Basins led Jackson & Iannelli (1981) to propose a tectonic model for the development of both depocentres as rift basins generated during the Neohelikian (1250–1200 Ma) opening of a Proto-Atlantic (Poseidon) Ocean. Impressed by the similar evolution and apparent coevality of the depocentres, Fahrig *et al.* (1981) introduced the name 'Bylot basins' to cover them.

Several authors, searching for geological evidence to support plate tectonic models that predict substantial transcurrent movement along a hypothetical plate boundary in Nares Strait, match the Proterozoic strata of the Thule and Borden regions as separated parts of a single basin (e.g. Newman & Falconer, 1978; McWhae, 1981; Newman, 1982b; Jackson *et al.*, 1992). These reconstructions ignore the certainty that the Neohelikian strata of Ellesmere Island are an intrinsic part of Thule stratigraphy and form the western margin of the Thule Basin.

However, the southern margin of the Thule Basin is not exposed and it remains conjectural whether Proterozoic sedimentation of the depocentres of the Thule and Borden Basins was linked (Dawes *et al.*, 1982a). Jackson & Iannelli (1981) and Jackson (1986) speculate that the two depocentres were interconnected at some stage, the most likely period being during deposition of platform carbonates late in the sedimentary history, viz. the Narssârssuk Group at Thule. These authors also suggest that some displacement of Greenland relative to Canada occurred as early as Neohelikian time (1250–1200 Ma). As suggested in the previous section, the Narssârssuk Group may be a fragment of a regional carbonate-siliciclastic province (parts of which are preserved offshore) and part of a broad, shallow embayment extending far to the south-west.

However, there are also pertinent differences in both sedimentary and tectonic history between the Thule and Borden Basins. For example, the entire fill of the Borden Basin accumulated in Neohelikian time: more precisely, over an 18 million year period starting around 1220 Ma ago (Fahrig *et al.*, 1981; Jackson & Iannelli, 1988). The Thule Supergroup appears to have a much longer depositional history, and although the presence of important paraconformities in the succession cannot be discounted, the Narssârssuk Group appears to have closed the Proterozoic sedimentary record possibly as late as the end of the Hadrynian (Vendian; Fig. 4). This simulates the geological record seen in other Proterozoic basins farther east in northern Greenland (cf. Sønderholm & Jepsen, 1991; Clemmensen & Jepsen, 1992). Tectonically, the Thule Basin is a restricted or semi-restricted ‘symmetrical’ depocentre that in the Neohelikian was closed to the west. This contrasts with the Borden Basin, which was open to the north-west in the Neohelikian and is thought to have developed as an aulacogen within a 1200 km long, NW-trending fault zone (Jackson & Iannelli, 1981).

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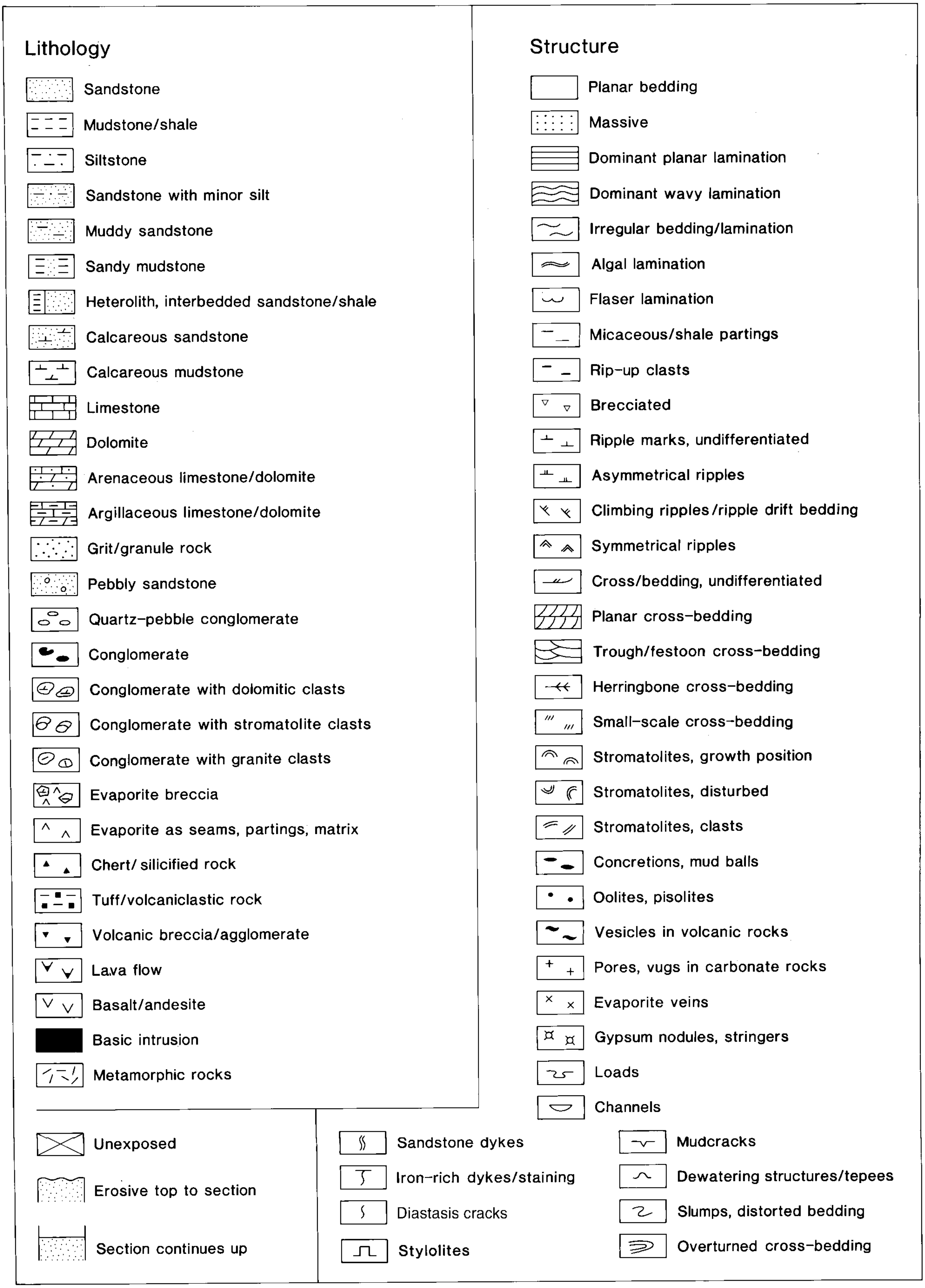

Plate 1. Legend covering all stratigraphic logs and generalised sections for which no other signature is given.

Note added in proof

An important paper on the micropalaeontology of the Thule Basin was published last year by the Geological Survey of Canada (GSC). The paper – Hofmann & Jackson (1996) – is based on samples from sections that are formally redefined in this *Geology of Greenland Survey Bulletin*. Hofmann & Jackson note that the Thule Group is raised to supergroup status by Dawes (in press), and state that since "the new nomenclature awaits publication, we retain the old terminology, referring to Dawes' new nomenclature where appropriate to facilitate comparisons". The citation to "Dawes (in press)" refers to a preprint version of the present Bulletin sent to GSC for critical review in 1994.

As well as mentioning the supergroup terminology in their main text, Hofmann & Jackson (1996) refer to it in an appendix and in their cover illustration. They also cite three figures in Dawes (in press) as the source for sketch maps used in their Fig. 1. Regrettably, Hofmann & Jackson's citations are premature. *Geology of Greenland Survey Bulletin* 174 is a revised version of the 1994 text and there are several important differences. For example, the so-called "new nomenclature" quoted by Hofmann & Jackson does not equate totally with the formal terminology presented in this Bulletin; neither do the figure numbers cited equate with the figures as they appear in this Bulletin.

It needs to be stressed that the formal stratigraphic nomenclature presented in this Bulletin supersedes the supergroup terminology mentioned by Hofmann & Jackson (1996). Corrections have already been made by Hofmann & Jackson in a corrigendum distributed with the GSC Bulletin but for practical reasons the most pertinent differences in stratigraphic terminology are given below.

Cover illustration of Hofmann & Jackson (1996)

View of Paine Bluff, eastern Goding Bay, Canada; these cliffs are also featured in Fig. 81B of this Bulletin. The conspicuous dark coloured unit in the middle part of the cliffs is the Goding Bay Formation of this Bulletin, not the Paine Bluff Member. The middle sub-unit of this formation that yielded microfossils is the Paine Bluff Member.

Appendix in Hofmann & Jackson (1996)

a) The Ekblaw Member does not exist; the unit equates with the Sparks Glacier Member of this Bulletin;
b) The Sparks Glacier Member as used by Hofmann & Jackson is equivalent to the Cape Dunsterville Member of this Bulletin;
c) The Sparks Glacier Member of this Bulletin is part of the Cape Combermere Formation and not part of the Josephine Headland Formation;
d) The Troelsen Member is stated by Hofmann & Jackson to occur at Clarence Head. The Troelsen Member of the Goding Bay Formation of this Bulletin is not recognised at Clarence Head; the strata in question are referred to the Siorapaluk Member of the Robertson Fjord Formation.

Reference

Hofmann, H. J. & Jackson, G. D. 1996: Notes on the geology and micropaleontology of the Proterozoic Thule Group, Ellesmere Island, Canada, and North-West Greenland. *Geological Survey of Canada Bulletin* **495**, 26 pp

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