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Explanatory notes to the Geological map of Greenland, 1:500 000, Thule, Sheet 5

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North-West Greenland, Baffin Bay, Neoarchaean, Palaeoproterozoic, Mesoproterozoic, Neoproterozoic, Quaternary, shield, intracratonic basin, half-grabens, basic intrusions, economic geology.

Cover
Extract of the central part of the Thule map sheet (Steensby Land) within the Proterozoic Thule Basin. The Thule Supergroup (Nares Strait Group (**N**), Baffin Bay Group (**B**, **Bw**, **Bq**), Dundas Group (**D, Do**)) overlies Archaean shield (Thule mixed-gneiss complex, mainly **og**) and is cut by the Neoproterozoic Steensby Land sill complex (**blue**, $\mathbf{s_1}$) and the Thule dyke swarm (**black**, $\mathbf{d_2}$). The conspicuous WNW–ESE-striking structural grain is caused by $\mathbf{d_2}$ dykes and the Thule half-graben system (see Fig. 35). The structure is essentially two tilted fault blocks – the Itillersuaq half-graben (in the north) and the Moriusaq half-graben – with the shield overlain by a normal, south-westerly dipping section (see Fig. 2). Bounding faults juxtapose the shield against the Dundas Group of the adjacent half-graben (see Fig. 48). Holocene marine and littoral deposits (**blue stippling**), and a prominant uplifted coastal plain (see Fig. 43), characterise the south-western coast. The area shown hosts occurrences of three metalliferous commodities: copper (**Cu**), ilmenite (**il**) and iron sulphides (**py**).

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Contents

Frontispiece. The historical and logistical centre of the Thule region around North Star Bugt, Bylot Sund, in the central part of the Thule map sheet. **Above**: Thule Air Base located in the broad Quaternary-filled valley and now called Pituffik after the valley and river Pituffiup Kuussuaq (visible to the right of the runway and main road), with the region's landmark – table mountain Dundas Fjeld (Uummannaq) – on the extreme right. Photo: 16 September 1975. **Below**: Dundas Fjeld, *c.* 225 m high, and the abandoned sites of the Greenlandic settlement Uummannaq along the outer coast (**U**), the Danish trade station Thule (**T**), radio station Dundas (**D**), and A-Launch, a U.S. Nike-Hercules missile battery (**M**). Photo: 19 July 1982. The region is underlain by shallow-dipping Mesoproterozoic–?Neoproterozoic strata (Thule Supergroup) overlain by prominent surficial deposits, for example the raised beaches in the left foreground and those flanking Dundas Fjeld. Bedrock exposures are: Dundas Fjeld, dark siliciclastic Dundas Group strata capped by a Neoproterozoic basaltic sill; Saunders Ø – identified by its flat erosion surface at 350–390 m a.s.l. – pale carbonates and siliciclastic redbeds of the Narssârssuk Group.

Abstract

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These explanatory notes cover part of North-West Greenland defined by latitudes 75°15′N and 78°N and longitudes 57°W and 73°W, a region with appreciable ice cover. The bedrock is dominated by two Precambrian provinces that extend across Baffin Bay into Canada: the high-grade Archaean–Palaeoproterozoic shield overlain by the intracratonic Mesoproterozoic–?Neoproterozoic Thule Basin. Map units are systematically described and introductory sections cover the physical environment, logistics, data sources and geoscientific research.

The *crystalline shield* embraces seven complexes: three of Archaean age, two of Archaean–?Palaeoproterozoic age and two of Palaeoproterozoic age. Isotopic ages of *c.* 2900 Ma indicate that Neoarchaean orthogneisses are present in part of the region while the existence of Mesoarchaean crust is indicated by *c.* 3200 Ma detrital zircons. The high-grade orthogneisses and paragneisses of the *Thule mixed-gneiss complex* were intruded by two plutonic suites, the *Kap York meta-igneous complex* at *c.* 2700 Ma and the *Smithson Bjerge magmatic association* that includes a major anorthosite body. Subsequent deformation, metamorphism and migmatisation led to the formation of gneisses recognised within the *Melville Bugt orthogneiss complex*. Palaeoproterozoic sedimentation and volcanism represented by the *Prudhoe Land supracrustal complex* took place after *c.* 2250 Ma but had ceased by *c.* 1985 Ma when the *Prudhoe Land granulite complex* was emplaced. Rocks within the *Lauge Koch Kyst supracrustal complex* may correlate with the Palaeoproterozoic Karrat Group of West Greenland. Polyphase deformation with isoclinal folding, and regional metamorphism up to granulite-facies grade, affected the region *c.* 1900 Ma ago, with cooling until *c.* 1650 Ma.

Extensional faulting, intracratonic basin formation and periods of basaltic magmatism occurred during the last 1000 million years of Proterozoic time. After regional dyking at *c.* 1630 Ma (*Melville Bugt dyke swarm*) followed by mature peneplanation, the *Thule Basin* developed as an interior fracture and sag depocentre across the area that is now northernmost Baffin Bay. Defined by the unmetmorphosed Thule Supergroup at least 6 km thick, the basin records fluvial to shallow-marine sedimentation and tholeiitic volcanism at least 1270 million years old. The basin is dissected by the *Thule half-graben system* dominated by WNW–ESE-trending faults thought to have developed during the final tectono-magmatic period dated at *c.* 700–650 Ma. Conspicuous products of this are a major sill complex (*Steensby Land sill complex*) and a regional dyke swarm that parallels the half-grabens (*Thule dyke swarm*). Fault reactivation is probably related to the late Phanerozoic tectonic evolution of Baffin Bay.

In addition to the four metallic commodities included on the map – magnetite, copper, iron suphides, ilmenite – there is potential for gold and other mineralisations. The Neoarchaean magnetite province, traceable for over 400 km through the map region, is spatially the largest in Greenland and it is a correlative of the Mary River iron deposits of Baffin Island, Canada. Several raw materials have potential for local handicraft industries, including soapstone and agate.

The region hosts a multi-event glacial and marine Middle–Late Quaternary stratigraphy dating back to at least the Saalian/Illinoian (pre-130 ka B.P.). The entire region was probably overriden by the Inland Ice during the Weichselian/Wisconsinian glacial maximum and deglaciated in the early Holocene, 11 000 to 9000 years ago.

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Fig. 1. Simplified geological map of southern Nares Strait with an outine of the Thule map sheet (**black frame**) and an inset map showing some regional features. Canadian geology is modified from Okulitch (1991). **Asterisk** qualifying Thule Basin in the legend signifies that the outcrop on Bylot Island, Canada, is part of the coeval Borden Basin. **Inset map**: **orange lines**, Neoarchaean Committee Fold Belt embracing the Mary River – Lauge Koch Kyst magnetite province; **dark blue lines**, Palaeoproterozoic Melville Bugt dyke swarm (MBDS) modified from Nielsen (1990); **pale blue lines**, Neoproterozoic Thule dyke swarm (TDS) plotted from Frisch (1984a, b, 1988 and personal communication 1980), Escher (1985a), Dawes (1991, 1997) and Dawes & Garde (2004), **Blank areas** are ice. Nares Strait (**NS**) is the seaway joining Baffin Bay and the Arctic Ocean. **K**, Kronprins Christian Land; **MG**, 'Mount Gyrfalco'; **Na**, Nanisivik; **NP**, North Pole; **P**, Peary Land.

Introduction

The Thule map sheet encompasses part of North-West Greenland between latitudes 75°15′N and 78°N and longitudes 57°W and 73°W; the island group Carey Øer extends farther west (Fig. 1). The map sheet is bordered on the south by Upernavik Isfjord, Sheet 4 (Escher 1985a) and on the north by Humboldt Gletscher, Sheet 6 (Dawes & Garde 2004). These explanatory notes replace the short map description that was written to accompany the initial presentation of the map (Dawes 1992).

Scope

The notes are designed as an extended map legend providing descriptions of each map unit, furnished with references leading to more information. They are aimed at the practical user of the map needing an introduction to the geology and as a basis for future investigations, rather than the specialist seeking details about one particular aspect. For those active in field geology – such as mineral exploration companies – there are sections on physical conditions and practical aspects like access and logistics.

Since compilation 15 years ago, some revision to the map can be made and age assignments can be refined. To emphasise this, the main revisions are given in a separate section rather than mentioned individually in the map unit descriptions (see *Map revision* under *Map data and geological research*). The photographs chosen as illustrations are, with the exception of Fig. 2, hitherto unpublished and they focus on the lesser known parts of the region such as the Lauge Koch Kyst, Melville Bugt. Throughout the text, citations are given to illustrations in the literature that feature the geological features described.

Space priority is given to those rocks about which little has been published, viz. the Precambrian shield and younger basic intrusions that were emplaced at intervals throughout 1000 million years of Proterozoic time. In contrast, the Thule Basin succession is the focus of a richly-illustrated monograph to which the reader is referred for a comprehensive treatment of the Thule Supergroup in terms of formal lithostratigraphy with the establishment of five groups (Dawes 1997). It should be noted, however, that formalisation of the lithostratigraphy post-dated map compilation and there are differences between the map and the monograph regarding the definition and distribution of two groups (see Fig. 4). The stratigraphical age of the Thule Supergroup has also been refined, through reassessment of the age of the microfossil (acritarch) assemblage (Samuelsson *et al.* 1999).

The outcrop pattern of Thule Basin strata is governed by major extensional faults that, apart from early references to their existence and supposed Tertiary age (Koch 1926, 1928a), have not hitherto been synthesised. They are of regional importance with relevance to offshore geology and the tectonic history of northern Baffin Bay (e.g. Jackson & Iannelli 1981; Jackson *et al.* 1992, 2003). Thus, the Thule half-graben system is described in these explanatory notes.

Place names, settlements and terms

Since compilation of the map sheet, the spelling of Greenlandic place names has changed. New orthography is used here irrespective of the form on the map, thus Aafeerneq, Narsaarsuk, Qaqujaarsuaq, Savissivik, Ummannaaq and Ulli rather than Aorfêrneq, Narssârssuk, Qaqujârssuaq, Savigsivik, Umánaq and Uvdle. All names used in the text that differ from the form on the map are given in Appendix 1. Old forms are retained when part of previously formalised geological names, such as lithostratigrahic units, structural names and rock units, for example Aorfêrneq Formation, Uvdle Fault and Qaqujârssuaq anorthosite. The name Cape York meteorite is retained although the authorised name of the historical cape is Kap York, the form used for the more recently named geological feature, the Kap York meta-igneous complex. The spelling Narssarssuk Fault – rather than Narssârssuk – is retained since this was the initial spelling used by Kurtz & Wales (1951).

Pituffik is the authorised Greenlandic name for the U.S. military air base that is known internationally by the name 'Thule' (Frontispiece). With its independent administrative system, it is the largest settlement in the map region, presently with about 1000 residents. The map covers the populated part of Avanersuup municipality that is administered from the capital Qaanaaq (pop. 650) that also bears the authorised Danish name of Thule. Savissivik is the second largest settlement with an indigenous population of over 100; Siorapaluk is the world's northernmost native settlement. Dundas, the Danish station at the original eskimo and trading site of Thule (Ummannaaq) below Dundas Fjeld is deserted (Frontispiece). The history leading to the resettlement of the indigenous population, the establishment of Qaanaaq and the considerable confusion surrounding the name 'Thule' is found in Vaughan (1991).

In these notes, the term 'Survey' is used both for the former Geological Survey of Greenland (GGU) and, from 1995, the Geological Survey of Denmark and Greenland (GEUS). The 'Thule region' refers to the map sheet region, as well as Inglefield Land that covers the northern exposures of the Thule Basin (Fig. 1). 'Thule strata' is used as a general term for rocks of the Thule Basin: a synonym of Thule Supergroup.

The common tectono-magmatic development of North-West Greenland and adjacent Canada led to the practicality of employing on the map sheet, the tectonic subdivisions of the Precambrian contrived by C.H. Stockwell at the Geological Survey of Canada and modified by Douglas (1980), Frarey (1981) and Okulitch (1988). Thus, the terms Aphebian, Helikian and Hadrynian for Early, Middle and Late Proterozoic were used with boundaries at 2500, 1750 and 1000 Ma, as well as the subdivisions Palæohelikian and Neohelikian separated at 1400 Ma. Current practice at the Survey follows present international convention and thus the terms Meso- and Neoarchaean are used in these explanatory notes with a boundary at 3000 Ma, as well as Palaeo-, Meso- and Neoproterozoic with divisions at 2500, 1600 and 1000 Ma. Period names of Precambrian time follow the proposals of Harland *et al.* (1990).

General geology, chronology and regional structure

A glance at the map sheet shows that the largest part of the region is covered by the Inland Ice and local ice caps, with the ice-free land underlain by Precambrian rocks and widespread Quaternary deposits. Two major provinces make up the bedrock: a high-grade Archaean–Palaeoproterozoic crystalline shield overlain by the intracratonic Thule Basin composed of Meso–?Neoproterozoic unmetamorphosed rocks (Thule Supergroup). The profound unconformity between these two provinces is well preserved in many parts of the region (e.g. Dawes *et al.* 1982a, fig. 7; Dawes 1997, figs 13, 51, 53, 93, 95, 97, 103) and one particularly illustrative exposure at Kap Trautwine showing the peneplaned nature of the erosion surface has been in the literature for more than 100 years (Peary 1898, vol. 1, p. 466; Fig. 2). In broad terms, the main part of the ice-free region (corresponding to the *North-western area* as defined later under *Physiography*), represents a faulted margin with the shield mainly forming inland areas adjacent to the Inland Ice, flanked by shallow-dipping Thule Basin strata in coastal areas and on islands. These strata disappear seawards in tilted fault blocks suggesting the presence of considerable outcrops on the continental shelf: an interpretation confirmed by recent geophysical studies (e.g. Jackson *et al.* 2003; Oakey 2005).

On regional geological maps, the southern and main part of the map region is classified as Archaean rocks reworked during the early Proterozoic, with northern Prudhoe Land as belonging to the Proterozoic Inglefield mobile belt (Henriksen *et al.* 2000). Geological relationships, supported by isotopic ages, indicate that the crystalline shield is dominated by Neoarchaean material, with Palaeoproterozoic crust represented by the Prudhoe Land granulite and supracrustal complexes (see *Geological province inset* on the map sheet). Both the Neoarchaean and Palaeoproterozoic provinces, as well as the overlying Thule Basin, continue into Canada. The Palaeoproterozoic rocks crop out on southern Ellesmere Island and the Archaean farther south on Devon and Baffin Islands, whereas the Thule strata are restricted to the outer coast of south-eastern Ellesmere Island bordering Smith Sound and northern Baffin Bay (Frisch & Christie 1982; Frisch 1983, 1988; Dawes 1988a, 1997; Jackson 2000).

Isotopic age information, refining the age determinations given on the map sheet, and including U-Pb SHRIMP and U-Pb IDTIMS analyses, show a range from *c.* 2910 to 1920 Ma, with the oldest detrital zircon grains known being *c.* 3200 Ma (Nutman *et al.* 2004). These ages indicate the presence of a Mesoarchaean source, Neoarchaean sedimentation and plutonism, Palaeoproterozoic sedimentary deposition between *c.* 2250 and 1920 Ma, and high-grade regional metamorphism and recrystallisation around 1900 Ma (for details, see map unit descriptions). Available Rb-Sr whole-rock and K-Ar mineral age determinations indicate widespread reactivation of the crust in late Palaeoproterozoic (Statherian) time, with slow cooling until at least 1650 Ma (Bendix-Almgreen *et al.* 1967; Larsen & Dawes 1974; Dawes *et al.* 1988).

In the latest Palaeoproterozoic (Statherian) and possibly in the early Mesoproterozoic (Calymmian), basic dykes were emplaced (designated $\mathbf{d_1}$) including the Melville Bugt dyke swarm of Nielsen (1987, 1990). Major uplift and peneplanation took place prior to the deposition of the Thule Supergroup, the basal strata of which are older than *c.* 1270 Ma that represents the

Fig. 2. Two Precambrian provinces of the map region separated by the Mesoproterozoic (Calymmian) peneplain: high-grade crystalline shield overlain by unmetamorphosed strata of the Thule Basin. Highly contorted, interleaved grey orthogneiss (**og**) and brownish-weathering paragneiss (**pg**) of the Archaean Thule mixed-gneiss complex, showing fragmented amphibolite layers, lit-par-lit veining, and granite, aplite and pegmatite sheets. **Arrows** mark thin, fragmented amphibolite dykes that cut subconcordant leucocratic veins but are themselves cut by steeply-inclined veins. Thule Supergroup visible is the Nares Strait Group with the basal ferruginous beds of the overlying Baffin Bay Group (Kap Trautwine Formation – **KT**) forming the cliff summit. **No**, Northumberland Formation; **CC**, Cape Combermere Formation; **BB**, Barden Bugt Formation; **CH**, Clarence Head Formation. The locality at Kap Trautwine, Hvalsund, is on the north-eastern side of the Itillersuaq half-graben with the peneplain and its overlying cover dipping shallowly to the south-west. A Neoproterozoic basic dyke of the Thule dyke swarm ($\mathbf{d_2}$) that post-dates the tilting has greenish margins and a reddish core. Height of the sea cliffs is *c.* 800 m.

most reliable radiometric age available on a basic sill from the lower part of the succession (LeCheminant & Heaman 1991). This middle Mesoproterozoic (Ectasian) age is an expression of the Mackenzie igneous event well documented in Arctic Canada. However, the precise age of the upper strata of the Supergroup is uncertain being based on microfossils that are not specifically age-diagnostic but are regarded as late Mesoproterozoic (Stenian) and/or early Neoproterozoic (Tonian) in age (Samuelsson *et al.* 1999; see under *Age of the Thule Supergroup*).

Apart from the physiographically spectacular, ice-overridden, dissected coastal strip of gneisses bordering Melville Bugt (Lauge Koch Kyst; Fig. 3), the two most conspicuous regional features of the map are: (1) the margin of the Thule Basin defined by both sedimentary and faulted contacts, that limits the Mesoproterozoic–?Neoproterozoic strata to western coastal areas and (2) the overall WNW–ESE-striking structural grain (varying to E–W and NW–SE) that characterises the region between Pituffik Gletscher and Prudhoe Land. This grain is composed of three, more or less parallel elements. Firstly, it is the predominant strike direction of the regional foliation in many parts of the shield that is well shown, for example, by the amphibolite (**a**) units immediately north of Pituffik Gletscher and by the outcrop form and structural fabric of the Qaqujârssuaq anorthosite (**an**) at the head of Inglefield Bredning. Secondly, it is the main direction of regional extensional faults (see below), and thirdly, it is the main direction of regional dyking followed by swarms of Proterozoic dykes throughout 1000 million years, the most intense swarm being the 'Thule dyke swarm' (designated $\mathbf{d_2}$) that crosses the entire region (Fig. 1, inset). The latter two features are particularly conspicuous in Steensby Land (see front cover illustration). The $\mathbf{d}_2$ dykes are of late Neoproterozoic (Cryogenian) age and part of a continental-scale swarm that is the eastern expression of the Franklin magmatic event, well known from Arctic Canada (Fig. 1 inset).

The Thule Basin is dissected by the Thule half-graben system controlled by WNW–ESE-striking faults (see Fig. 35) that affect the entire succession including the Neoproterozoic basic sills ($\mathbf{s}_1$). The largest displacements documented juxtapose the youngest strata of the basin (Narssârssuk Group) against the shield indicating vertical movement of several kilometres. The $\mathbf{d}_2$ dykes, that consistently cut the $\mathbf{s}_1$ sills, post-date at least some of the main faults and associated regional tilting, and the half-graben system is thus regarded as originating in the Neoproterozoic. However, some faults register movements of more than one age. Apart from being older than the Inland Ice and Quaternary deposits, the age of fault rejuvenation is unknown but some movements can be correlated with late Phanerozoic tectonism (see section *Correlation within the offshore*).

All land areas within the map region, including the islands of Carey Øer in the west and Sabine Øer in the south, have been overridden by the Greenland Ice Sheet. The region was not deglaciated until the early Holocene with the last recession being 11 000 to 9000 years ago (Bennike & Björck 2002).

Physical environment

Climate, vegetation and field season

The climate of the Thule region is of high-arctic desert type with continuous permafrost and an annual average precipitation at Qaanaaq of 10 cm, mostly falling as snow. Cyclonic storms occur in summer with precipitation highest in July and August. The mean temperature of August, the warmest month, is 3.8°C but occasionally temperatures exceed 15°C. Winter temperatures often drop below –30°C, occasionally below –40°C. There is continual light from May to August. The scarce vegetation, restricted to low herbs, grasses, dwarf shrubs, mosses and lichens, is concentrated below 100 m a.s.l. Lichen growth can be profuse, and on steep bird cliffs such as on Saunders Ø, and those in Parker Snow Bugt, the combination of lichens and bird droppings can camouflage the rocks.

A 2-month period is available for modern geological field work with just 6 weeks normally clear of sea ice and snow. The summer climate is fairly stable with generally calm weather interrupted by spells of strong winds and rain, occasionally snow. The sea ice normally breaks during July, initially in the north, and Siorapaluk can be reached by boat in early July, Pituffik and Qaanaaq a little later. 'Freak' years when the ice breaks earlier or when new ice breaks in the autumn are becoming more frequent**.** Apart from ice-infested waters around Tracy Gletscher at the head of Inglefield Bredning the region between 76° and 78° is navigable during August and early September. However, Melville Bugt with its calf-ice producing outlet glaciers, is a permanent threat to other than ice-strengthened vessels and, although Savissivik can be reached by local boat, clear passage to all parts of the Lauge Koch Kyst is not assured (see Fig. 3). Formation of new ice, a potential problem for small boat operations, can be well advanced near the coast by mid- to late September.

Access and logistics

The two largest settlements Qaanaaq and Pituffik are ideally located as logistic centres being situated in the northern and central parts of the region, respectively. Qaanaaq has a small hotel but permission to reside at Pituffik, including use of airport facilities, needs special authority that must be sought well in advance of arrival. An airport has served Qaanaaq since 2001 and this provides commercial connections to West Greenland towns. A commercial helicopter (Air Greenland) is stationed at Pituffik. A road network, constructed in the 1950s and now best suited for 4-wheel drive vehicles, allows access to the larger Pituffik area including the outer coast 30 km from the airport (see below under *Character of the Survey mapping*). Small boats (up to 25 feet) and outboard motor boats can be chartered locally.

Physiography

The map region is part of the geomorphic 'Thule–Nûgssuaq Region' defined as a well-glaciated coastal strip dominated by uplands and mountainous highlands, with local ice caps (Dawes & Christie 1991).

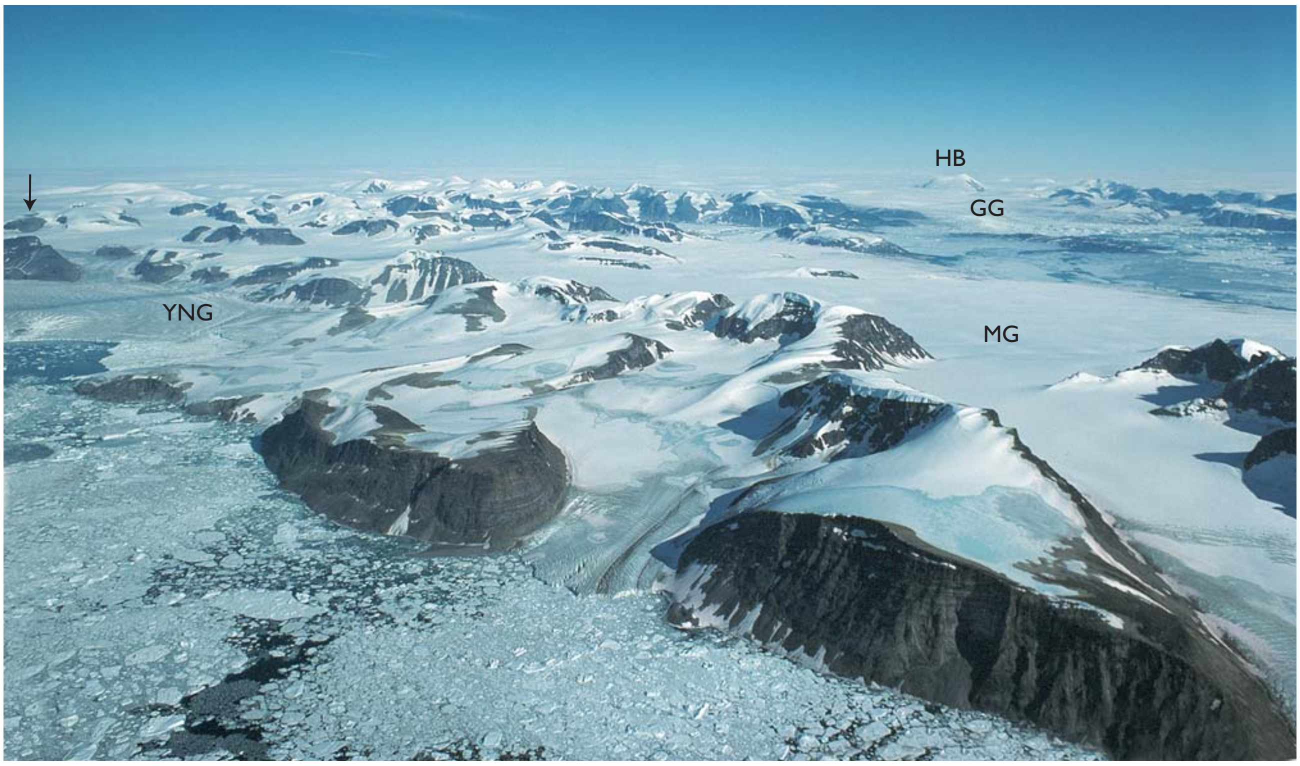


Fig. 3. Typical landscape of the Lauge Koch Kyst showing restricted ice-free land and ice-choked sea. View is north-east over northern Meteorbugt with Haffner Bjerge (**HB**) at 1462 m about 60 km distant. **Arrow** on left marks the nunatak featured in Fig. 6. **GG**, Gade Gletscher; **MG**, Mohn Gletscher; **YNG**, Yngvar Nielsen Gletscher. Height of the sea cliffs in the foreground is 860 m. Photo: 14 August 1978.

The few lowland areas present are narrow coastlands like the uplifted coastal plain of Steensby Land (see Fig. 43) and Quaternary-filled valleys, for example between the heads of McCormick and Bowdoin Fjords and the site of the air base, Pituffik (Frontispiece). Physiographically, the region can be readily split into north-western and south-eastern areas along a dividing line striking north-east from Parker Snow Bugt. The former, underlain by shield rocks overlain by Thule Basin strata, contains the majority of the ice-free land, the most varied topography and the most accessible exposures; the latter, underlain by shield lithologies, forms the ice-dominated, dissected and relatively inaccessible coast of Melville Bugt.

North-western area

The inner part of this area, composed of shield rocks and flanked on the east by the Inland Ice, has an undulating dissected plateau character with dome-shaped mountains rising above a general elevation of 700–800 m and steep to precipitous fjord coasts (see Figs 26A, 32, 37, 41). The highest ice-free summit is 1133 m in eastern Steensby Land at the Inland Ice margin east of the lake Tasersuaq. The outer (western) part is the 'Thule Upland' of Dawes & Christie (1991), etched from tilted fault blocks of Thule strata, in which the varying topography is to a high degree due to the variable lithologies. Thus, the resistant strata dominated by sandstone, volcanic rock and dolomite commonly form spectacular, steep-cliffed coasts, as for example the 900 m high sandstone cliffs east of Qaanaaq and the steep shores of Bylot Sund and Hvalsund (Fig 2; Dawes 1997, figs 98, 112, 114). Ice-topped mountainous terrain up to 1000 m high, with cirques, occurs on Northumberland Ø. The more recessive, argillaceous rocks of the Dundas Group, form more moderate slopes but where sills are interspersed, for example as in the NW–SE belt stretching through southern Steensby Land and into the Dundas area, ridged slopes with mesas and cuestas are common. One mesa is the celebrated landmark Dundas Fjeld (see Frontispiece, also Dawes & Rex, 1986, fig. 3; Dawes 1997, fig. 105). Many valleys and fjords are fault-controlled and many coastlines have trends to the WNW or NW, parallel to the main structural blocks of the region (see under *Thule half-graben system*).

South-eastern area

This area corresponds to the Lauge Koch Kyst and Kap York peninsula where the Inland Ice reaches

Melville Bugt as broad glaciers with floating tongues and with islands, peninsulas, semi-nunataks and nunataks representing the ice-free land (Fig. 3; also Dawes *et al.* 1988, fig. 5). Elevation rises sharply inland and steep-sided nunataks produce an almost alpine topography with summits between 800 and 1000 m a.s.l. (see Dawes & Christie 1991, fig. 3.2). Heavily ice-clad Haffner Bjerg at 1462 m is the highest rock summit of the map region (Fig. 3).

Erosion surfaces

Flat-lying to shallow-dipping palaeosurfaces characterise many parts of the map region, for example the conspicuous surfaces on Carey Øer and and that forming the summit level of Saunders Ø (Frontispiece; Wordie 1938; Davies *et al.* 1963; Bendix-Almgreen 1967, and other references in Dawes & Christie 1991). Reliable correlation is lacking but the surfaces have been referred to Precambrian and Neogene–Pleistocene planation levels.

The oldest surface is the conspicuous undulating dissected plateau of the 'Thule Upland' (see above, under *North-western area*) that corresponds to the Mesoproterozoic (Calymmian) peneplain below the Thule Basin. Although highly faulted, it is recognisable as a westerly-inclined surface around the heads of Inglefield Bredning and Olrik Fjord, and along the south side of Hvalsund it disappears below sea level west of Kap Trautwine (see Figs 2, 26A, 41). This peneplain is preserved throughout the map sheet and to the north in Inglefield Land. This mature surface probably correlates with the main summit level along the Lauge Koch Kyst and a level recognised farther south by Paterson (1951) in the region of the adjoining map sheet (Escher 1985a).

The prominent flat-lying surface on Saunders Ø and the flat to sloping surfaces of the Carey Øer are at least 1000 million years younger. The former is etched on Thule Basin strata of late Mesoproterozoic or early Neoproterozoic (Stenian or Tonian) age and on late Neoproterozoic (Cryogenian) basic dykes, while on Carey Øer erosion cuts into shield rocks invaded by dolerite intrusions of similar age (see respective sections on *Narssârssuk Group* and *Palaeoproterozoic?, Mesoproterozoic and Neoproterozoic sills and sheets (**s**)*). These palaeosurfaces are generally correlated and regarded as remnants of late Phanerozoic peneplanation (e.g. Bendix-Almgreen *et al.* 1967). However, theoretically they may be partly of latest Precambrian age corresponding to the post-Cryogenian peneplain preserved below the early Cambrian (Atdabanian) of the Franklinian Basin. This erosional feature is traceable for thousands of kilometres across Greenland and the Canadian Arctic. The southernmost Franklinian strata preserved in Greenland are in Inglefield Land just 50 km beyond the map sheet and a natural assumption is that the Franklinian Basin once covered the entire Thule region.

Exposure

Good bedrock exposures are restricted to coastal cliffs, nunataks, the sides of glaciers and along valley walls. With its closely-spaced cirque glaciers, Northumberland Ø provides good inland exposures, some of which can be reached from the ice fields. The steep-cliffed coasts in many parts of the region enable the homoclinal Thule strata to be followed over appreciable distances, as for example along the outer headlands of northern Prudhoe Land and along Bylot Sund but many such illustrative sections are precipitous and inaccessible. Similarly, the steep to precipitous ice-scoured rock faces of nunataks of the Lauge Koch Kyst, provide illustrative exposures revealing the structure of the shield rocks (see Figs 15, 18).

Commonly, steep slopes have talus fans, moderate slopes a scree cover. On the rolling upland and plateau terrain there is a widespread surficial cover of boulder-rich glacial deposits modified by frost shattering and solifluction. The Inland Ice margin has retreated during the last century (see under *Recent glacial history*). Recently deglaciated land is often covered by a continuous blanket of drift.

Map data and geological research

Data sources, field work and map quality

The main sources behind the Thule map sheet are unpublished Survey maps and three printed maps, viz. two 1:100 000 maps around Pituffik (Davies *et al.* 1963; Fernald & Horowitz 1964) and a 1:50 000 map of Smithson Bjerge at the head of Inglefield Bredning (Nutman 1984; see inset on the map sheet). The unpublished maps, in the archives of the Geological Survey of Denmark and Greenland, Copenhagen, comprise six sheets at 1:100 000 covering the main Thule Basin outcrops and five 1:200 000 sheets covering the Precambrian shield (Dawes 1988b).

Character of the Survey mapping

The variable logistics behind the Survey field work – mainly shoreline mapping with limited helicopter traversing – determined that overall map quality is not uniform. The regional mapping was carried out during five summers between 1971 and 1980, and stretched as far north as 78°40′N in Inglefield Land (Dawes 1972, 1975, 1976a, 1979; Dawes & Frisch 1981). During the first three seasons from end-July to mid-September shoreline investigation of the entire region north of Kap York was by locally hired boat with Inuit crew. In 1978 and 1980, emphasis was on the relatively inaccessible Lauge Koch Kyst, supported by the Survey cutter *K.J.V. Steenstrup* with Jan C. Escher (in 1978) and Thomas Frisch (in 1980) assisting. This phase of mapping was supported by two, 5-hour fixed-wing flights (Twin Otter) from Pituffik during which the entire inner part of the Lauge Koch Kyst was surveyed (see Mikkelsen 2006, p. 191). In 1978, with helicopter time available, the chance was taken to support what still remains the only detailed mapping of shield rocks in the map region, namely 1:25 000 mapping of the Qaqujârssuaq anorthosite and adjoining rocks of Smithson Bjerge (Nutman 1979, 1984). During stop-overs at Pituffik between 1971 and 1983, the roads to satellite stations and installations gave access to Wolstenholme Fjord (Dundas–Ulli), the Inland Ice margin at Store Landgletscher (J-site and Camp Tuto), Aafeerneq, Pingorsuit (P-Mountain station) and Quaraatit Nuna (Cape Atholl Coast Guard station). The island Nordvestø of the Carey Øer was briefly visited in 1983 on an opportune helicopter flight.

From the above, it can be seen that much of the mapping was accomplished from boat, shore camps and on inland foot traverses: helicopter support was limited to a few days in each of the last three seasons (1975, 1978, 1980). Consequently, the inland areas, and thereby generally the Precambrian shield, was not given the attention afforded the coastlands. Moreover, the inland plateau with its heavy surficial cover did not warrant use of the limited helicopter time. Thus, many gneiss areas, particularly those flanking the Inland Ice, were mapped from the air with sparse ground checks, aided by photo-interpretation. This approach was not adequate to consistently differentiate between the varied gneiss lithologies, for example mapping out of ortho- and paragneiss units could not be achieved consistently (see under *Thule mixed-gneiss complex*). Also, the inaccessible Lauge Koch Kyst has only been mapped in reconnaissance style (see under *Melville Bugt orthogneiss and Lauge Koch Kyst supracrustal complexes*). Concentration on coastal areas focussed attention on the Thule Basin that was mapped in its entirety at formational level and followed north onto the adjoining map sheet where the basin margin facies is exposed (Dawes & Garde 2004).

History of geoscientific investigations

The first geological observations recorded from the map region pertain to 'primary' shield rocks collected during John Ross' visit to Melville Bugt and the Kap York peninsula in 1818 (M'Culloch 1819). A history of research pertaining to the Thule map region, albeit focussed on Thule Basin stratigraphy, is given by Dawes (1997) based on three periods of exploration: "Ship-borne exploration (1852–1909)", "Exploration from stations (1910–1945)" and "Modern investigations (1946 and onwards)". Only milestones are mentioned here. Investigations of surficial deposits and glacial geology are dealt with in the *Quaternary* section, including *NORDQUA 86* that, with more than 30 participants in the Pituffik – Wolstenholme Fjord area in 1986, is the largest geoscientific party to operate within the map region (Funder 1990).

Local and often cursory observations made during the ship-borne exploration period established the presence of a Precambrian shield overlain by a 'secondary' series including sandstones and greenstones (e.g. Sutherland 1853a, b; Haughton 1858, 1859; Nathorst 1884; Chamberlin 1895a, b, c; Peary 1898; Low 1906; Hovey 1918). Many of the early observations are summarised in Koch (1920; for map summary, see Dawes & Christie 1982, fig. 5). The first regional survey was undertaken by Lauge Koch between 1916 and 1923 resulting in the 'The Kap York District' geological map at *c.* 1:1 000 000. Although printed in 1931 this was not released until much later (Dawes & Haller 1979, plate 1). The Thule region (known earlier as the Kap York District) featured in many of Koch's papers but mostly in regional appraisals (e.g. Koch 1920, 1925, 1929), although one paper deals specifically with fault tectonics within the Thule map sheet (Koch 1926). The pre-Second World War era was based on boat and sledge investigations mainly of coastlands and thus Thule Basin strata. Of note is Munck's (1941) work that represents the first stratigraphic logging.

Post-war establishment of military facilities at Pituffik (Thule Air Base, see Frontispiece) allowed for work by helicopter, icebreaker and tracked vehicles, and a wide range of geoscientific and geotechnical investigations involving both land and ice studies were carried out in the late 1940s and throughout the 1950s (e.g. Kurtz & Wales 1951; Nichols 1953; Davies 1954; U.S. Army 1954; Schytt 1955, 1956; Gregory 1956; White 1956, Goldthwait 1960; Holmes & Colten 1960, Swinzow 1962; Davies *et al.* 1963; Fernald & Horowitz 1964). Pertinent to the Thule map sheet is the field work leading to the two 1:100 000 geological maps previously mentioned, the coverage of which is shown on the inset on the map sheet.

Following the reports of iron sulphides and black sands in southern Steensby Land (Koch 1920) and ilmenite-rich placers at Pituffik in 1950 (Ghisler & Thomsen 1971, 1972), the first economic survey of the map region was made in 1969 by Greenarctic Consortium, as part of a programme throughout northern Greenland (Stuart-Smith & Sproule 1970; Stuart-Smith & Campbell 1971). The mineralised localities discovered, as well as occurrences of banded iron-formation found by Davies *et al.* (1963), the Survey (Dawes 1975, 1976a) and Cominco Ltd (Gill 1975), were evaluated in 1975 and 1977 (Cooke 1978). Apart from the mapping mentioned earlier under *Data sources, field work and map quality*, other work in the 1970s and 1980s included stratigraphical, palaeontologial and organic geochemical studies of Thule strata aimed at comparison with Canadian sections (e.g. Ponnamperuma 1978; Vidal & Dawes 1980; Strother *et al.* 1983; Dawes & Vidal 1985; Jackson 1986; Hofmann & Jackson 1996), and brief interest in ilmenite placer deposits in the Pituffik–Moriusaq area (e.g. Christensen 1985; Dawes 1989). In the mid-1990s a regional gravity survey was undertaken (Forsberg *et al.* 1994, 1995) and mineral exploration including geochemical stream-sediment sampling was carried out between Parker Snow Bugt and Siorapaluk (Gowen & Sheppard 1994; Gowen & Kelly 1996). During the Survey's mineral exploration project *Upernavik 98*, the south-eastern part of the map region around Kap Seddon was reached from the south (Thomassen *et al.* 1999a, b).

The year 2001 saw renewed geological activity in the map region. During *Cruise 2001 Louis S. St. Laurent*, samples were collected in the Thule region for various analytical procedures, including palaeomagnetism and fission track dating (Jackson *et al.* 2003; Grist & Zentilli 2004). With *Qaanaaq 2001*, the Survey continued its mineral potential assessment of North-West Greenland and embarked on systematic drainage sampling covering the *northern* part of the map sheet (north of Olrik Fjord), as well as one specific area in southern Steensby Land (Steenfelt 2002; Steenfelt *et al.* 2002; Thomassen *et al.* 2002a, b). In 2003, the most promising mineral and geochemical anomalies were checked in the field (Thomassen & Krebs 2004) and, in preparation for a sequel mineral resource project covering *southern* part of the map sheet, a Landsat study was directed at pin-pointing mineral exploration targets (Krebs *et al.* 2003).

Map revision

No *mapping* projects have been undertaken since compilation but revision of map geology and legend information can be made from new field observations and laboratory data. For example, project *Qaanaaq 2001* (see above) provided an opportunity to revisit inland areas of Prudhoe Land and the area around Inglefield Bredning and Olrik Fjord, otherwise only seen on widely-spaced helicopter traverses in the 1970s. As noted in Thomassen *et al.* (2002a), the information so gained led to adjustments of map unit distribution some of which are depicted on fig. 1 of that account.

Changes in the stratal definition of the map units of the Thule Supergroup (based on formations and groups) were made during the definitive lithostratigraphic subdivision that was finalised *after* the map sheet was issued (Dawes 1997; Fig. 4). Those observations that radically change the outcrop pattern of the map and/or the composition of units given in the legend are listed below.

1. **Thule mixed-gneiss complex: lithological diversity**. The homogeneity of many parts of the Thule mixed-gneiss complex shown on the map sheet, for example the inland plateaux at the head of Olrik Fjord and Inglefield Bredning (including Nunatarsuaq and Anngiusalipaluk), is more a mark of poor exposure and limited investigation, than a sign of the paucity of other lithologies within gneisses **og** and **pg**. Thus in 2001 during helicopter traverses, further outcrops of map units **gf, a**

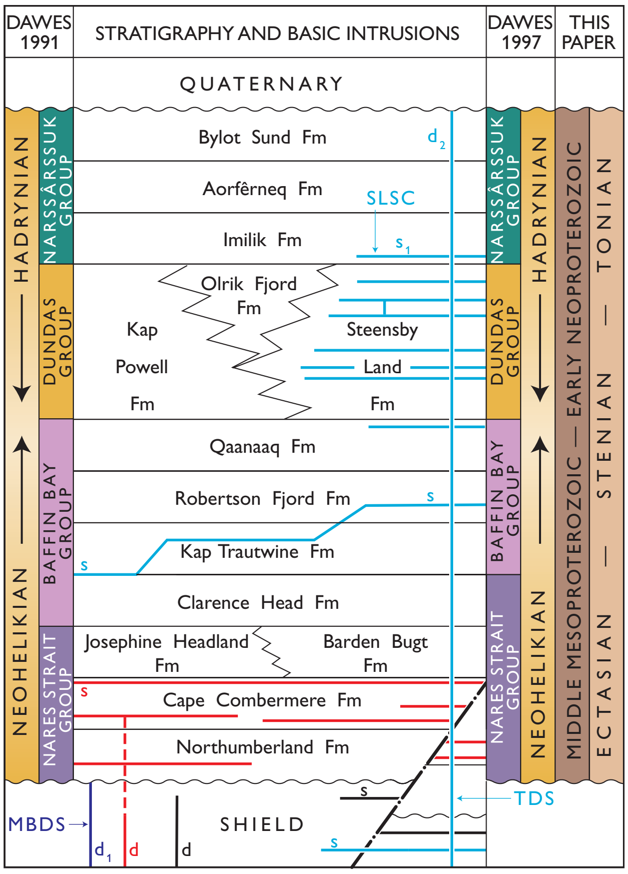


Fig. 4. Generalised stratigraphic chart of the Thule Supergroup succession (central basin) showing the relationship of the five groups of Proterozoic basic intrusions differentiated on the map sheet (**d**, $\mathbf{d}_1$, $\mathbf{d}_2$, **s** and $\mathbf{s}_1$). Note the formational revision of the Baffin Bay and Nares Strait Groups since map compilation (Dawes 1991) and the revised age of the Thule Supergroup since establishment of the formal lithostratigraphy (Dawes 1997). Colour scheme of the four stratal groups is based on the map sheet; no stratigraphical thicknesses are implied. Colour scheme for the main ages of intrusions corresponds to Fig. 40: Palaeoproterozoic–Mesoproterozoic (**dark blue**); Mesoproterozoic (**red**); Neoproterozoic (**pale blue**); with sills and dykes of uncertain age **black**. The fault block at the bottom right illustrates that the youngest sheets (**s**) and the Thule dyke swarm ($\mathbf{d}_2$) post-date regional extensional faulting. The 'feeder' relationship (**dashed**) between the **d** dyke and Mesoproterozoic volcanic rocks of the Cape Combermere Formation is inferred. **MBDS**, Melville Bugt dyke swarm; **SLSC**, Steensby Land sill complex; **TDS**, Thule dyke swarm.

and **u** were found. The mafic outcrops are of foliated or schistose amphibolite, as well as apparently younger gabbro and metagabbro. The two largest finds are an ultramafic mass within orthogneiss on the northern side of Academy Bugt near its head (see Fig. 26A) and a metagabbro body in the central part of the nunatak between Leidy Gletscher and Marie Gletscher that is a possible relative to the basic components of the Heilprin Gletscher complex (**gf**).

2. **Iron-formation: new occurrences**. The symbol **mg**, indicative of magnetite-bearing rocks, including banded iron-formation (BIF), is shown on the map in three complexes: Thule mixed-gneiss complex, Melville Bugt orthogneiss complex and Lauge Koch Kyst supracrustal complex. In the first-named complex, new occurrences of both oxide- and silicate-facies iron-formation were discovered in 2001 and 2003 (see under map unit *Magnetite (**mg**)*). The largest is a BIF occurrence, cm-banded, 20 m thick and associated with a rust zone, 5 km east-north-east of the amphibolite shown on the map sheet on the northern shore of Olrik Fjord – the 'Mount Gyrfalco showing' of Thomassen *et al.* (2002a, fig. 5; 2002b, figs 7–10). A second occurrence is in Prudhoe Land along the Hubbard Gletscher where garnet quartzite within paragneiss contains iron concentrations (Thomassen & Krebs 2004, figs 2–4).

3. **Map unit (tg) contains granitoids**. The rock name 'tonalite' given in the map legend to describe map unit **tg** in easternmost Steensby Land is misleading. Granitoid rocks containing appreciable alkali feldspar are now known and tonalite *sensu stricto* appears to be a subordinate rock type restricted to intrusive material contaminated by amphibolite-rich gneiss xenoliths.

4. **Prudhoe Land supracrustal complex: wider distribution**. Outcrops of this complex are more extensive than shown on the map sheet. Dominated by paragneiss and schist, the rocks are mostly conspicuous at a distance because of their recessivity and rusty-weathering character. Additional outcrops large enough to be depicted on the map occur in three main areas. *Bowdoin Fjord*: several outcrops of garnetiferous, graphitic schist and paragneiss, often weathered out in gullies, are present within orthogneiss (**og**) on the north-western side of the fjord, and rusty rocks also are an important component of the 'new' shield exposures described below in section 6, south of Tuttu Gletscher. In addition, rusty paragneiss form nunataks on the east side of the ice cap south of the major fault (see below in section 8) that on the map sheet are shown as redbeds of the Baffin Bay Group (**B**). *Robertson Fjord:* recessive units of garnet-rich paragneiss and schist, in places with amphibolite layers, occur within the gneiss (**grn**) in the steep fjord walls west of Verhoeff Gletscher. *Morris Jesup Gletscher*: prominent outcrops of rusty paragneiss, with some thinner paler units, occur interleaved with isoclinally folded grey gneiss of unit **grn** on all nunataks forming the south-east-

ern side of the glacier. These rocks are equated with the succession shown on the map on the north-western side of the glacier. It is assumed that pale units seen from the air are quartzite and/or marble (see below, section 5).

5. **Prudhoe Land supracrustal complex: additional lithologies.** In addition to the rock types mentioned in the map legend, marble and ultramafic rocks were discovered in the succession in 2001 (Thomassen *et al.* 2002a). Where seen on the ground – in the outcrops east of Bowdoin Fjord and north-west of Morris Jesup Gletscher – marble and associated calc-silicate rocks are subordinate rock types occurring sporadically as thin beds interleaved with paragneiss (**ps**), quartzite (**qz**) and amphibolite (**a**) (see Fig. 29). During the initial mapping in the 1970's, pale units mapped from the air or seen from vantage points were, against the background of ground observations made elsewhere, interpreted as quartzite or quartz-rich rocks, a practice no longer tenable. Thus, re-examination of the successions may indicate more marble than the 'subordinate' tag attached here. At Morris Jesup Gletscher, the succession contains mafic rocks that grade into hornblendite.

6. **Thule Basin unconformity: new exposures**. Apart from the outcrops at the Scarlet Heart Gletscher described in section 8 below, the contact between the Thule Supergroup and the shield is exposed through the surficial cover in several places on the south side of the Quaternary-filled valley between McCormick and Bowdoin Fjords. For example, an illustrative block-faulted section borders the outlet glacier that coalesces with the front of Tuttu Gletscher. Here rusty-weathering paragneiss and associated rocks composing the shield are overlain by the Nares Strait and Baffin Bay Groups representing a faulted basin margin that simulates the contact at the head of McCormick Fjord illustrated in Fig. 37.

7. **Nares Strait Group – Baffin Bay Group relationship**. The Nares Strait Group (as now defined) has a larger distribution than shown on the map sheet, with that of the Baffin Bay Group correspondingly smaller (Fig. 4). White sandstone (Clarence Head Formation) included on the map as the basal strata of the latter group were later redesignated the upper beds of the Nares Strait Group (Dawes 1997). Thus, for example, Hakluyt Ø depicted as undivided Baffin Bay Group on the map sheet is composed of Clarence Head Formation overlain by the redbeds of the Baffin Bay Group (Kap Trautwine and Robertson Fjord Formations; see Dawes 1997, fig. 48). This cited figure also shows that the Nares Strait Group crops out at two places along the south coast of Northumberland Ø; the western of these is illustrated in fig. 9 of Dawes *et al.* (1982a).

8. **Scarlet Heart Fault, McCormick Fjord**. A NW–SE-trending fault with major downthrow to the north-east is located under the Scarlet Heart Gletscher: it juxtaposes shield rocks with sandstones of the Baffin Bay Group (Robertson Fjord and Qaanaaq Formations). The unconformity below the Thule Basin is now known to be exposed west of the glacier. Sheared, dark gneiss, reddened and rubbly weathered at the unconformity, are overlain by pale sandstone, basaltic rocks and redbeds (with a basic sill) that can be referred to the Nares Strait Group, with at least the Northumberland, Cape Combermere and Barden Bugt Formations present. The Scarlet Heart Fault must link up with the fault shown on the map sheet on the north-west coast of Bowdoin Fjord that strikes westwards under the ice cap (for fault positions, see Thomassen *et al.* 2002a, fig. 1). To the north of McCormick Fjord, the Scarlet Heart Fault lies in the N–S-striking Quaternary-filled valley (Five Glacier Dal) where shield rocks (not shown on the map sheet) are exposed on the west side of the valley both in faulted and unconformable relationships with Thule strata. It is noteworthy that this major fault has the opposite polarity to the bounding faults of the regional half-grabens (see later under *Thule half-graben system*).

9. **Piulip Nunaa – Hubbard Gletscher: basaltic rocks**. The map legend states under the map unit *Baffin Bay Group, undivided* that the Nares Strait Group is present at Bowdoin Fjord. However, it is now known that this group is present throughout Piulip Nunaa, on both sides of Bowdoin Fjord, and as far east as Hubbard Gletscher (Fig. 5; also Dawes 1997, fig. 98). The thin basic sill marked '**s**' on the map sheet, shown in the lower part of the undivided Baffin Bay Group (**B**) from McCormick Fjord to Bowdoin Fjord, is the Cape Combermere Formation of the Nares Strait Group. In contrast, the basic sill at the coast west of Hubbard Gletscher is stratigraphically higher and depicted correctly on the map sheet within redbeds of the Baffin Bay Group (see Thomassen & Krebs 2004, fig. 5). Both these basaltic units occur in the Castle Cliff fault block 15 km west of Hubbard Gletscher as shown in Fig. 5. Loose blocks of vesicular basalt collected near the glacier by J.D. Krebs (per-

Fig. 5. Castle Cliff fault block with downdrop to the north-east seen from Bowdoin Fjord. Pale sandstones of the Qaanaaq Formation (**Bq**) juxtaposed against older redbeds and basaltic rocks of the Nares Strait and Baffin Bay Groups. These outcrops, together with those at Hubbard Gletscher, represent the thin basin margin facies of the Nares Strait Group. **No**, Northumberland Formation; **CC**, Cape Combermere Formation; **BB**, Barden Bugt Formation; **CH**, Clarence Head Formation; **RF**, Robertson Fjord Formation with Kap Trautwine Formation at the base of the Baffin Bay Group visible as thin dark beds (**KT**); **s**, basic sill (not marked on map sheet at this locality but to the east at Hubbard Gletscher). **KM,** Kap Milne. Main summit is at *c.* 600 m a.s.l.

sonal communication 2001), are taken as confirmation that the Cape Combermere Formation is also present in the basal part of the poorly exposed section there.

10. **Tikeraussaq High, Inglefield Bredning: revised stratigraphy**. On the map sheet, the Wolstenholme Formation is shown overlying the shield at Tikeraasaq on the southern coast of Inglefield Bredning. The suggestion that a WNW–ENE-trending horst between Inglefield Bredning and Olrik Fjord existed in the early evolution of the Thule Basin was based on the interpretation that the Nares Strait Group was absent or extremely thin, and that the shield was draped by redbeds of the Baffin Bay Group (see Dawes 1997, fig 119). The poorly exposed section directly above the shield at Tikeraasaq, that is dominated by redbeds, was examined in 2001 and it is now referred to the Nares Strait Group. It can be correlated with the sections to the north at Bowdoin Fjord and to the south in Steensby Land, for example in Barden Bugt and Granville Fjord. Basal varicoloured sandstones (Northumberland Formation) are overlain by a greenish basaltic unit at least 20 m thick probably containing both intrusive and extrusive rocks (Cape Combermere Formation) above which is an unexplored multicoloured sandstone section topped by the thick, pale-weathering Qaanaaq Formation and the Dundas Group (see Dawes 1997, fig. 95).

11. **De Dødes Fjord outlier: Qaanaaq Formation**. The southernmost outcrops of the Thule Basin occur north of Kap York on the eastern side of De Dødes Fjord. Several exposures at the top of the sea cliffs above the shield are dominated by redbeds and partly covered by ice fields that are receding. On the map sheet all the strata are referred to the Wolstenholme Formation. The presence of pale-weathering beds fringing the ice fields suggests that the upper part of the succession in these exposures reaches into the Qaanaaq Formation (Dawes 1997, fig. 13).

12. **Itilleq Fault: extension to the east**. The master fault of the WNW–ENE-trending Olrik half-graben is conspicuous on the south side of Olrik Fjord where the Dundas Group is downdropped against the shield (see Fig. 48; Dawes 1976b, fig. 231; 1997, fig. 109; see later under *Thule half-graben system*). In the east, it splays inland into several faults and is crossed by northerly trending faults. Farther east, the master fault is not shown on the map but it is now known to flank the northern margin of the large unnamed ice cap striking towards lake Tasersuaq. This modifies the outcrop pattern in the fault block *west* of the large expanded-foot glacier, where shield rocks on the *south* are juxtaposed against the Baffin Bay Group that, like the section to the east of the glacier, reaches up into the Qaanaaq Formation (Dawes 1997, fig. 103 needs modification). Farther west in the region of lat.

68°W around the small outlet glacier, there is more Dundas Group exposed and less Qaanaaq Formation, than shown on the map sheet. Small downfaulted blocks of Dundas strata exist. To the north, on the massif Qaqqarsuaq (not named but marked '**Bq**' on the map sheet), the intricate fault-block pattern not only includes the downdropping of Baffin Bay Group against shield as shown in Fig. 36, but faults on the north-eastern side downdrop Dundas Group against the Baffin Bay Group (Qaanaaq Formation). However, the Dundas Group may have been draped over an early manifestation of this horst.

13. **Downfaulted outlier of Thule strata at Magnetitbugt**. Such an outcrop was initially shown on a sketch map by Kurtz & Wales (1951, fig. 1). On the geological map compiled by W.E. Davies (Davies *et al.* 1963, plate 1) Thule strata crop out from *beach* level to the *top* of the sea cliffs at an altitude of *c.* 400 m inland, with a preserved contact to gneisses, bounded on the south by a fault, named the Magnetitbugt Fault. The geology on the Thule map sheet is based on these sources modified during shoreline mapping and photogeology, and supplemented by information from W.E. Davies (personal communication 1980). Views from the sea and from the beach at Magnetitbugt by the present author, and independently by Cooke (1978; personal communication 1977), failed to locate the Thule strata and at least the lower cliffs are composed solely of crystalline rocks. Since compilation the present author has seen the locality from an airplane and backed by Landsat images, he now favours the presence of a single outlier of Baffin Bay Group (Wolstenholme and ?Qaanaaq Formations) on the plateau surface in conjunction with a fault with downthrow to the north. The outcrop is identifiable on a so-called 'Crosta image' of the Magnetitbugt area featured in Krebs *et al.* (2003, fig. 1).

14. **Ages of basic dykes: revision**. Two main ages of Proterozoic dyking are portrayed on the map, represented by dykes designated $\mathbf{d_1}$ (Palaeoproterozoic–Mesoproterozoic) and $\mathbf{d_2}$ (Neoproterozoic), with all dykes of uncertain age designated **d**. Although the precise age of many basic dykes cutting the shield is still unknown, refined laboratory data make it possible to reclassify some **d** dykes into the two other groups, as well as identify a period of Mesoproterozoic dyking not identified on the map but with the same general direction as the main $\mathbf{d_2}$ swarm (see Table 1 and under map unit descriptions).

15. **Age of Thule Basin: revision**. The ages given in the map legend related to the Thule Basin history have been revised. The new information suggests a somewhat earlier onset of sedimentation in the middle Mesoproterozoic (Ectasian) and an earlier closure in the *early* rather than *late* Neoproterozoic (Tonian; see Fig. 4 and under *Age of the Thule Supergroup*).

Precambrian shield

As outlined earlier under *Character of the Survey mapping* in the section *Map data and geological research*, the Precambrian shield has been mapped in reconnaissance fashion with detailed mapping being restricted to an anorthosite body (the Qaqujârssuaq anorthosite), associated magmatic rocks and their host rocks on the semi-nunatak Smithson Bjerge at the head of Inglefield Bredning (Nutman 1984). This condition, and the limited isotopic age determination work that has been carried out (see below), provide only a general insight into the geochronology and tectono-magmatic evolution of the Archaean and Palaeoproterozoic rocks composing the shield.

Isotopic ages

Prior to map compilation seven isotopic dates giving indication of protolith age were available from the map region demonstrating the presence of Neoarchaean crust. These seven dates are: two Rb-Sr errorchron ages from localities in Melville Bugt, Kap York and Kivioq Havn (*c.* 2700 Ma, Dawes *et al.* 1988), U-Pb isotopic work on zircons from two other localities in Melville Bugt, Sabine Øer and Fisher Øer (*c.* 2620 Ma, R.T. Pidgeon, personal communication 1984; Kalsbeek 1986) and three unpublished Sm-Nd model ages from widely spaced localities: from south to north, Gade

Gletscher, Melville Bugt (2840 Ma), Olrik Fjord (2910 Ma) and Verhoeff Gletscher, Prudhoe Land (2570 Ma) (P.N. Taylor, personal communication 1990). The one Palaeoproterozoic age cited on the map for the northernmost rocks (*c.* 2000 Ma; Prudhoe Land granulite complex) is based on correlation with meta-igneous rocks and orthogneisses of Inglefield Land on the adjoining map sheet that were known to be Palaeoproterozoic (Dawes 1988a; Dawes *et al.* 1988).

SHRIMP U-Pb zircon dating of six rocks from Prudhoe Land has been undertaken in connection with an age determination programme focused on the Palaeoproterozoic rocks of the adjoining map sheet (Nutman *et al.* 2004). Two of these ages are located just beyond the map at Sonntag Bugt (Fig. 1; Dawes 2004). These six ages – from the Thule mixed-gneiss, Prudhoe Land supracrustal and Prudhoe Land granulite complexes – support the map chronology, confirm the presence of both Neoarchaean and Palaeoproterozoic crustal material and indicate metamorphism and strong recrystallisation with zircon growth at *c.* 1900 Ma (for details, see map unit descriptions).

K-Ar mineral ages of rocks from the map region (seven ages) and from Inglefield Land to the north (three ages) mostly fall between 1850 and 1610 Ma and record a regional tectono-metamorphic event with slow cooling that is correlated with the Hudsonian Orogeny of the Canadian shield (Bendix-Almgreen *et al.* 1967; Larsen & Dawes 1974).

Map divisions, boundaries and map unit descriptions

The first-order subdivision of the shield is into two provinces: (1) *Archaean and ?Palaeoproterozoic* and (2) *Palaeoproterozoic*, represented by five and two complexes, respectively. As explained in the *Introduction*, the term Palaeoproterozoic replaces Aphebian of the map legend. The distribution of five of the seven complexes can be seen in the *Geological province* inset on the map sheet. The remaining two – the Lauge Koch Kyst and the Prudhoe Land supracrustal complexes – are interleaved with other complexes and therefore for simplicity are not shown on the inset. All map units are pre- to synkinematic and the rocks are thus tectonised to some degree, exemplified by mineral foliation and gneissosity. Primary features, such as igneous textures and contacts are sporadically preserved. Post-tectonic intrusions represented by minor acidic intrusions – pegmatites, aplites and quartz veins – are too small to be shown on the map sheet.

In the map legend, the complexes are arranged in general younging order, although it will be obvious from the earlier discussion about mapping style and isotopic dating work, that complete geochronological order is uncertain. Furthermore, the large expanses of ice within the map region hide the contact relationships of some complexes and regional structure and rock relationships in several areas have been pieced together in nunatak country.

Descriptions of the map units are designed to highlight their essential characteristics based mainly on field criteria. Thus, while laboratory data, including major element chemical analyses, are available in Survey archives, systematic analysis and presentation of these data are outside the scope of these explanatory notes. Published petrologic and chemical data for parts of the region north of Pituffik Gletscher are found in Davies *et al.* (1963), Fernald & Horowitz (1964), Bendix-Almgreen *et al.* (1967), Larsen & Dawes (1974), Kalsbeek & Dawes (1980), Nutman (1984), Dawes *et al.* (1988) and Steenfelt *et al.* (2002).

Relationships of the complexes

Critical field relationships for the geochronology and ordering of the complexes in the map legend are listed below. The Thule mixed-gneiss complex forms the central part of the Thule region and has boundaries with all other complexes. Although boundary information can be fragmentary because of poor exposure and ice cover, it suggests – in conjunction with the deformational status and metamorphic grade of the complexes – that the Thule mixed-gneiss complex contains the oldest crustal material of the region (2.91 Ga), a conclusion supported by the available isotopic ages. Archaean rocks of similar age (2.84 Ga) are also known to be present in the multiphase Melville Bugt orthogneiss complex (Dawes & Frisch, 1981, table 1).

1. **Thule mixed-gneiss complex / Smithson Bjerge magmatic association**. The Thule mixed-gneiss complex pre-dates the Smithson Bjerge magmatic association (see Fig. 10). The main components of the association – the Qaqujârssuaq anorthosite (**an**) and the Heilprin Gletscher complex (**gf**) – are considered to be products of the same chronological interval that were emplaced into highly deformed paragneiss (**pg**) and multiphase orthogneiss (**og**). Complex relationships exist between anorthosite and the gneisses of the Thule mixed-gneiss complex but Nutman (1984) lists four relationships, including enclaves of paragneiss within anorthosite, that indicate emplacement of the anorthosite into paragneiss. This rock package was then strongly deformed by several phases of folding, including regional isoclines, and subjected to granulite-facies metamorphism.

Fig. 6. Basement–cover relationship between the Melville Bugt orthogneiss complex (**gn**) and rusty-weathering Lauge Koch Kyst supracrustal complex (**ms**). **Arrows** mark thin, fragmented amphibolite dykes that are discordant to gneiss foliation and compositional layering but that do not penetrate the supracrustal cover. Like many occurrences along the Lauge Koch Kyst, the age of these supracrustal rocks remains uncertain: Archaean or Palaeoproterozoic? Nunatak at the proximal part of Yngvar Nielsen Gletscher marked **ms** on the map sheet and located in Fig. 3. Gneiss section is *c.* 200 m thick.

2. **Kap York meta-igneous complex / Thule mixed-gneiss complex / Lauge Koch Kyst supracrustal complex**. The Kap York meta-igneous complex was emplaced into the Thule mixed-gneiss complex and at least some of the rocks mapped as the Lauge Koch Kyst supracrustal complex (Davies *et al.* 1963; Dawes 1976a). The northern contact with the Lauge Koch Kyst supracrustal complex is ice-covered but small nunataks define a WNW–ESE-trend from De Dødes Fjord to the head of Parker Snow Bugt where Davies *et al.* (1963, p. 6) mapped a sharp contact between quartz diorite (**gt**) and the 'surrounding rock'. According to W.E. Davies (personal communication 1980), the latter term covers highly-deformed amphibolite-facies gneisses that on the Thule map sheet are placed within the Thule mixed-gneiss complex (**og**). However, apart from one sharp contact indicating intrusion of granite (**gr**) into orthogneiss (**og**) and amphibolite (**a**) (Dawes 1975), most contacts seen by this author have been tectonised to varying degrees and are characterised by overgrowth by feldspar porphyroblasts and invasion by leucocratic veins. Such relationships have also been described north of Pituffik Gletscher by Gowen & Kelly (1996). The mylonite zone mapped and described by Davies *et al.* (1963, p. 26) in the south-eastern part of Parker Snow Bugt also obscures relationships. Nevertheless, map units **gt** and **gr** are considered to post-date the regional banding of the Thule mixed-gneiss complex, and some pelitic and amphibolitic lithologies of the Lauge Koch Kyst supracrustal complex.

3. **Melville Bugt orthogneiss complex / Kap York meta-igneous complex / Thule mixed-gneiss complex**. The western boundary of the Melville Bugt orthogneiss complex is concealed by the waters of Sidebriksfjord and by the glacier at its head. Gneiss areas on the eastern side of this fjord, and areas eastwards to Kong Oscar Gletscher, particularly on islands and peninsulas, have been derived from basic to intermediate rocks that on field criteria resemble rocks of unit **gr** of the Kap York meta-igneous complex (Dawes 1979). On this evidence, major components of the Melville Bugt orthogneiss complex (**gn**) are younger than the Kap York meta-igneous complex. Transitions between igneous-textured rock and orthogneiss are difficult to portray at reconnaissance level, but one relict area assigned to the Kap York meta-igneous complex (**gr**) is shown within orthogneiss east of

George Ø. To the north, the boundary between the Melville Bugt orthogneiss and Thule mixed-gneiss complexes is concealed by ice but defined rather arbitrarily by nunatak geology to trend north-east from the head of Sidebriksfjord. Rather than represent an abrupt break in geology, the general impression is that all gneiss outcrops to the west have a common complicated deformational history, while to the east the gneisses are bipartite being formed of (1) older, grey gneisses characterised by persistent amphibolite layers that are regionally concordant but preserve local discordancies and (2) younger orthogneisses lacking these amphibolites and that are presumably derived from a younger protolith coeval with the Kap York meta-igneous complex (Figs 15, 17).

4. **Melville Bugt orthogneiss complex / West Greenland**. The Melville Bugt orthogneisses (**gn**) are the equivalents of the Archaean tonalitic to granodioritic gneisses of the Red Head – Upernavik region that are designated **gn** on the Upernavik Isfjord map sheet (Escher 1985a) and that are continuous with the Umanak gneiss (Henderson & Pulvertaft 1987). These gneisses resemble the well-studied grey gneisses from the Fiskenæsset and Frederikshåb regions of West Greenland that were mainly generated around 3000–2600 Ma and reactivated in the Palaeoproterozoic (Escher & Stecher 1978). Such gneisses compose most of the Archaean craton of West Greenland (Henriksen *et al.* 2000).

5. **Lauge Koch Kyst supracrustal complex / Thule mixed-gneiss complex / Melville Bugt orthogneiss complex**. Rocks of the Lauge Koch Kyst supracrustal complex are folded and interleaved with gneisses of the Thule mixed-gneiss and the Melville Bugt orthogneiss complexes (see Figs 17, 18, 21). Thus generally, compositional layering in supracrustal rocks and regional foliation of the gneisses are concordant. However, in well-exposed sections where supracrustal rocks form thick successions in contact with gneisses – for example in De Dødes Fjord and Sidebriksfjord area and on nunataks east to Docker Smith Gletscher – structural comparisons suggest that some rocks referred to map units **ms, qt** and **a**$_1$ have not passed through the same deformational history as some gneiss components of the Thule mixed-gneiss and Melville Bugt orthogneiss complexes. Moreover in detail, discordancies have been preserved that strongly suggest basement–cover relationships. Thus, on steer nunatak cliffs – inaccessible but conducive for elucidating rock relationships – deformed amphibolite dykes clearly discordant to gneisses and older amphibolites, do not enter supracrustal packages, suggesting the younger age of the latter (Fig. 6). It is also significant that while many supracrustal tracts are magnetite-bearing, others are not, and this may reflect differing age. A field distinction was made between supracrustal units bearing iron-formation and those composed entirely of pelitic and semipelitic schists (Dawes & Frisch 1981). In contrast, no iron-formation has been reported south of the map sheet where supracrustal rocks are extremely common (Escher & Stecher 1978). As it happens, the nearest coastal outcrops south of the map sheet at Red Head, 35 km from Kap Seddon, are pelitic and semipelitic rocks overlying gneisses in what is regarded as a basement–cover relationship. These supracrustal rocks are referred to the Palaeoproterozoic Nûkavsak Formation of the Karrat Group (Escher 1985a, b). Thus, it seems probable that supracrustal rocks of two distinct ages occur in the Lauge Koch Kyst region: Archaean packages characterised by iron-formation and Palaeoproterozoic successions correlatable with the Karrat Group.

6. **The Prudhoe Land supracrustal complex / Thule mixed-gneiss complex**. The Prudhoe Land supracrustal complex overlies the Thule mixed-gneiss complex in a basement–cover relationship, in which strong deformation has obliterated all primary relationships (Dawes 1972). The contact is well seen on the northern side of Inglefield Bredning at Qattarsuit and on Josephine Peary Ø where it separates dark resistant orthogneiss from less resistant, brown-weathering supracrustal rocks. The contact, often seen as a scree-covered zone, is abrupt with a planar structure of the gneiss parallel to supracrustal layering but there are marked differences in thermo-tectonic history in the rocks either side of the contact (Fig. 7; Dawes 1976b, fig. 226; Thomassen *et al.* 2002a, fig. 3, 2002b, fig. 4). Where the older rocks are predominantly paragneisses, the contact is less distinct. Intense deformation including large-scale recumbent folding, such as the megastructure at Hubbard Gletscher (Hubbard isocline; Thomassen & Krebs 2004, fig. 1) has resulted in interleaving of the two complexes. The Qattarsuit supracrustal succession, preserved in the core of a broad E–W-trending synform that refolds a major recumbent isocline, is as shown on the map sheet, flanked both below and above by older gneisses. Several mountains are mesa-like being characterised by a resistant cap of older gneiss above moderate slopes etched

Fig. 7. Basement–cover relationship between the Archaean Thule mixed-gneiss complex (**og**) and the more recessive, rusty-weathering Palaeoproterozoic Prudhoe Land supracrustal complex (**ps**). **Arrow** marks a thin dark unit that may be a tectonic slice of gneiss**.** Northern side of Inglefield Bredning, east of Quinnisut, with summit Qattarsuit on the right *c.* 800 m a.s.l. Photo: Bjørn Thomassen.

from supracrustal rocks (Dawes 1979). Sugarloaf at the head of Bowdoin Fjord, aptly named and shown on the map, is one such example.

7. **Prudhoe Land granulite complex / Thule mixed-gneiss complex**. The boundary of the Prudhoe Land granulite complex with the Thule mixed-gneiss complex is arbitrarily placed west of Tuttu Gletscher. The relationship between the two sets of gneisses, Archaean and Palaeoproterozoic, is structurally complex since the rocks have been strongly deformed together in large-scale, refolded isoclinal structures so that they now are thoroughly interleaved. Very broadly speaking, the younger gneisses may be distinguished by their brownish, rather than greyish, weathering and by their more homogeneous nature. However, these characteristics are far from diagnostic and the reconnaissance style of the mapping did not allow such a distinction to be tested optimally. The conclusion is that the detailed differentiation of the two ages of crustal material will only be accomplished by a systematic isotopic dating programme. Rather than an abrupt change from map unit **og** (Archaean) to **grn** (Palaeoproterozoic) at Tuttu Gletscher – as the colour change on the map unavoidably infers – the interpretation is that a 'mixed' zone containing both Neoarchaean and Palaeoproterozoic gneisses occurs in Prudhoe Land. For example, a banded gneiss from Verhoeff Gletscher within map unit **grn** has given a Neoarchaean Sm-Nd model age of 2570 Ma (see earlier under *Isotopic ages*) while the stream-sediment geochemical data characterised by high Sr, Ba and P suggests that Palaeoproterozoic orthogneiss of intermediate composition is a component of map units **pg** and **og**, as far as Tracy Gletscher (Steenfelt *et al.* 2002).

8. **Prudhoe Land supracrustal complex / Prudhoe Land granulite complex.** Rocks of the Prudhoe Land supracrustal complex are intimately associated on all scales with orthogneisses of the Prudhoe Land granulite complex (**grn**). These relationships are seen in single outcrops as well as in large-scale isoclines (Dawes 1988a, fig. 8; 2004, fig. 7). The thickest supracrustal succession associated with the granulite complex is at Morris Jesup Gletscher where it is flanked above and below by orthogneiss suggesting location in the core of a recumbent fold. The smallest outcrops are discontinuous layers and rafts within orthogneiss. Field relationships are equivocal since primary relationships between the two complexes are not preserved. However, the presence of the inclusions within gneiss suggests that deposition of the supracrustal rocks preceded intrusion of the granulite protolith, a scenario that is supported by SHRIMP U-Pb ages, both within the map sheet region and beyond (see map unit descriptions and section 9 below; also Dawes 2004).

9. **Prudhoe Land supracrustal complex / Etah Group of Inglefield Land**. Inglefield Land, just beyond the map sheet to the north, is part of the Palaeoproterozoic *Inglefield Land mobile belt*, that

is dominated by bipartite geology: a thick supracrustal succession with prominent marble units (Etah Group) is intruded by a magmatic suite (Etah meta-igneous complex). The Etah Group accumulated between 1980 and 1950 Ma with igneous activity occurring between 1950 to 1915 Ma (Dawes 2004; Nutman *et al.* 2004). The recent discovery of marble within the Prudhoe Land supracrustal complex (see under *Map revision*, section 5), consolidated the view that these rocks are a correlative of the Etah Group (Frisch & Dawes 1982; Steenfelt *et al.* 2002; Thomassen *et al.* 2002a, b). Since both supracrustal successions are intruded by a suite of igneous rocks, contemporaneity of the two magmatic suites also seemed logical. However, SHRIMP U-Pb dating indicates that the relationship between Prudhoe Land and Inglefield Land is much more complicated. For example, the two supracrustal successions show contrasted detrital age populations indicating provenance from completely different sources. Quartzite of the Prudhoe Land supracrustal complex – as well as comparable quartzite in *southernmost* Inglefield Land – yield complex age spectra from *c.* 3250 to 2250 with 2600–2450 grains dominant whereas the paragneisses farther north have a much younger, almost unimodal population centred on 2000–1980 Ma (Nutman *et al.* 2004). Since orthogneiss of the Prudhoe Land granulite complex has a protolith age of *c.* 1980 (see map unit description), it is possible that these rocks are the source (partly or otherwise) of the Etah Group and derived paragneiss. Thus, evidence is emerging that indicates that the Prudhoe Land supracrustal complex and the Etah Group are not parts of a single Palaeoproterozoic sedimentary regime but that they accumulated in different depocentres from different sources and probably at different times (Dawes 2004). This difference is also exemplified by the overall lithological characteristics of the two successions: the Prudhoe Land supracrustals are quartzite-rich and marble-poor, the direct opposite of the Etah Group.

Archaean and ?Palaeoproterozoic

Five complexes and four other map units of magmatic rocks – ultramafic rocks (**u**), amphibolite (**a** and **a**$_1$) and tonalite (**tg**) – are referred to this province. The eight isotopic ages available fall between 3000 and 2500 Ma indicating major Neoarchaean crustal generation. However, the ages only pertain to three complexes and it remains an open question whether younger crustal material is present. It has been suggested above that metasediments correlatable with the Palaeoproterozoic Karrat Group of West Greenland may be present in the Lauge Koch Kyst supracrustal complex (see *Relationships of the complexes*, section 5). Also, the relatively lesser deformed intrusions **a**$_2$ and **tg**, as well as some of the minor felsic intrusions, might be of this age. These uncertainties explain the question mark in the *Archaean and ?Palaeoproterozoic* designation.

Thule mixed-gneiss complex

Age. The Sm-Nd model age of 2910 Ma given on the map pertains to a garnet-biotite gneiss from the inner part of Olrik Fjord studied by P.N. Taylor (personal communication 1990). The only other age determination deemed to be a protolith age is a U-Pb SHRIMP zircon age of 2600–2580 Ma on a greenish grey, hypersthene orthogneiss from the nunatak north of Bartlett Bjerg in Prudhoe Land, a sample that also indicates Palaeoproterozoic recrystallisation around 1900 Ma (Nutman *et al.* 2004). The Thule mixed-gneiss complex is cut by the Kap York meta-igneous complex dated at *c.* 2700 Ma (see under *Relationships of the complexes,* section 2). A K-Ar mineral age of 1750 ± 30 Ma on biotite from a ‘gray banded gneiss’ from the Carey Øer is the only other isotopic age from the complex (Ole Larsen, in Bendix-Almgreen *et al.* 1967).

Literature. Davies *et al.* (1963), Fernald & Horowitz (1964), Bendix-Almgreen *et al.* (1967), Dawes (1972, 1975, 1976a, b, 1979), Nutman (1979, 1984), Frisch & Dawes (1982), Garde *et al.* (1984), Steenfelt *et al.* (2002), Thomassen *et al.* (2002a, b), Krebs *et al.* (2003), Thomassen & Krebs (2004), Nutman *et al.* (2004).

Boundaries. Smithson Bjerge magmatic association, Kap York meta-igneous complex, Melville Bugt orthogneiss complex, Lauge Koch Kyst supracrustal complex, Prudhoe Land supracrustal complex and Prudhoe Land granulite complex (see under *Relationships of the complexes*, sections 1–3, 5–7).

Distribution, composition and metamorphism. This high-grade complex comprises interfolded multiphase ortho- and paragneisses underlying the central part of the Thule region including the Carey Øer. Earlier, it was referred to as the ‘Gneiss–schist–granite complex’ (Dawes 1975). The rocks have been passed through multi-event Archaean and Palaeoproterozoic diastrophism. Although two to three fold phases can be documented in outcrop-scale, and major refolded isoclines are common in fjord walls (see Fig. 41), the rocks have probably been subjected to many more deformation phases.

The rocks have been subjected to at least two, but probably more, high-grade metamorphic events, inclu-

Fig. 8. Multiphase orthogneiss of the Thule mixed-gneiss complex. Two-phase veined gneiss invaded by a late quartz-rich leucocratic phase that preserves thin layers and schlieren of amphibolite and ultramafic rocks. A tight isoclinal fold hinge is visible just to the right of the hammer. East side of the snout of Bowdoin Gletscher.

ding regional Palaeoproterozoic amphibolite- to granulite-facies metamorphism during which both para- and orthogneisses were completely recrystallised. The southern part of the complex between De Dødes Fjord and Inglefield Bredning is entirely in amphibolite facies while the rocks on Smithson Bjerge and in Prudhoe Land are in granulite facies. The granulite-facies gneisses on Smithson Bjerge represent peak pressures of 7.5 kbar with temperatures of *c.* 700°C (Garde *et al.* 1984). The gneisses around Qeqertat, Harvard Øer, and on Lille Matterhorn are in the amphibolite facies and although not all islands have been visited, the boundary between the two grades must be fairly abrupt trending up Heilprin Gletscher. The facies distinction is also reflected in the stream-sediment geochemical data, with lower values of Rb and K_2O characterising the granulites (Steenfelt *et al.* 2002). Whether the boundary represents a prograde or retrograde front is uncertain. As mentioned later, retrogression of granulite mineral assemblages has certainly taken place although the extent of this is uncertain; alternatively, the granulite-facies rocks in the north could have developed in the Palaeoproterozoic progressively from amphibolite-facies rocks, leading to their co-existence in different areas.

Orthogneisses (**og**) dominate and these are intimately associated on all scales with paragneiss (**pg**; Fig. 2). The rocks are structurally complex and the orthogneisses are clearly multiphase, the later phases of which cut paragneiss and associated amphibolite (Fig. 8, see Figs. 25B, 40). Apart from this, the geochronological relationship of the protoliths of the two gneiss units is obscure. The reconnaissance nature of the mapping dictated that little detailed differentiation between ortho- and paragneiss could be portrayed on the map. In contrast, the mapping of Smithson Bjerge at 1:25 000 scale allowed such differentation (see earlier under *Character of the Survey mapping*). Of the two belts of orthogneiss within paragneiss portrayed on Nutman's map (1984, plate 1), only one is wide enough to be shown on the Thule map sheet. Similar relationships between ortho- and paragneiss occur throughout the complex but poorly defined spatial relations allow portrayal only as intermixed units. Designation as **og** or **pg** is based on assessment of what is deemed to be the predominant gneiss type but this can be an arbitrary judgement, particularly in those areas where ground observations are scarce. Thus, the islands of the Harvard Øer, where garnet-biotite (± hornblende) paragneiss characterise some areas, might well have been designated **pg** rather than **og**. In hindsight, the helpful information that map units **og** and **pg** represent intermixed packages ought to have been made clear in the map legend.

Paragneisses within unit **og** include various outcrops of pelitic and semipelitic gneisses, mica-chlorite-talc and quartz-mica schists, quartzofeldspathic garnet gneisses and quartzitic rocks between Pituffik Gletscher and Prudhoe Land (Dawes 1972, 1975, 1976a, b) including the garnet-biotite schists in the North Star Bugt area (Davies *et al.* 1963) and the quartzitic, magnetite-bearing metasediments on Nunatarsuaq (Fernald & Horowitz 1964). The succession composing the nunataks and semi-nunataks at head of Inglefield Bredning (map unit **pg**) contains important intercalated orthogneiss units and, as has been mentioned above, the geology may be even more complicated by the presence of both Archaean and Palaeoproterozoic intrusive material (see under *Relationships of the complexes*, section 7).

Polygenetic garnet-bearing rocks

Characterisation of gneiss protolith is not everywhere straightforward. Apart from intense polyphase deformation and metamorphism, parentage can be obscured by feldspathisation often with intense porphyroblastesis, and widespread migmatitic veins and felsic sheets. Metasedimentary origin can be identified by pelitic and semipelitic composition, the presence of garnet and/or sillimanite and typical rusty-weathering character.

However, certain garnet-bearing quartzofeldspathic and quartz-rich rocks have questionable inheritance. In the Inglefield Bredning area, thin, pale leucocratic linear bodies produce a conspicuous layering or banding to the gneisses, as well seen on the north side of the fjord east of Quinnisut, on Harvard Øer and parts of Nunatarsuaq (see Thomassen *et al.* 2002a, fig. 6; 2002b, fig. 12). Although of similar appearance and composition, the pale layers are of two distinct types: (1) white to buff, foliated to gneissic, concordant psammitic units within paragneiss, and (2) younger, white, pink to reddish, concordant to subconcordant leucogranite sheets, that post-date the main schistosity of the paragneiss. The leucogranite varies from massive to gneissic, with the majority of rocks falling somewhere between with a weak to moderate foliation. Garnet is common but not ubiquitous, and it can be partially or fully replaced by chlorite and hornblende. Some leucogranites contain orthopyroxene suggesting formation during granulite-facies metamorphism as intrusive bodies during anatectic melting. In places, for example on the east side of Bowdoin Gletscher, such garnet-quartz-feldspar rocks form larger masses in which relict strips of paragneiss, amphibolite and ultramafic rock are preserved.

The leucogranites are too small to include on the map sheet, but prominent sheets, such as those on Harvard Øer and Lille Matterhorn, are shown on larger scale maps (Dawes 1988b). The sheets may well be correlatives of the acidic phases of the Smithson Bjerge magmatic association that likewise show a gradation from granite to platy gneiss with progressive deformation (see under map unit **gf**).

Orthogneiss (**og**)

Apart from interleaved paragneiss mentioned above, this map unit comprises a very wide variety of quartzofeldspathic lithologies ranging from strongly gneissic to homogeneous; most have a moderate to well-defined gneissosity. The range includes banded, veined, streaky and porphyroblastic gneisses, to more massive granitic gneiss, foliated and porphyroblastic granites, to *bona fide* migmatite and local agmatite. This variation is reflected to some extent in the terminology of some previous workers, for example 'gray banded gneiss', 'pink granitic gneiss', 'porphyroblastic gneiss' and 'migmatite' mapped by Davies *et al.* (1963) and Fernald & Horowitz (1964) in the Pituffik–Nunatarsuaq area, and 'red pegmatitic gneiss' and 'dark grey schistose gneiss' mentioned by Bendix-Almgreen *et al.* (1967) on Carey Øer. Grey, veined to banded gneisses dominate the amphibolite-facies part of the complex; the later phases are paler, generally more homogeneous and often weather reddish. The granulite-facies gneisses on Smithson Bjerge and in Prudhoe Land are brownish weathering and although of varied lithology, they seem to be dominated by massive to foliated rocks, with fewer orthogneiss phases. Gneiss with blebby textures both in the mafic and leucocratic components suggest retrogression but the extent of this has not been defined.

The bulk of the gneisses fall into the mafic tonalite to granodiorite compositional realm but there are gradations to mafic and felsic rocks. Thus, at one end of the range there are veined amphibolites and leuco-amphibolites, at the other end a suite of granitic rocks that are intersheeted with more intermediate phases or that form cross-cutting bodies. Mineral assemblages show wide variation with respect to biotite, orthopyroxene and hornblende; all three minerals may occur together. In the granulite-facies rocks of the north, orthopyroxene is the predominant mafic mineral, often with biotite, and in the lower-grade rocks biotite dominates, with hornblende present in the more mafic gneisses and leuco-amphibolites. K-feldspar is often present and predominates over plagioclase in some porphyroblastic gneisses and late felsic phases. Some of the latter phases also contain garnet (see above under *Polygenetic garnet-bearing rocks*). All but the late leucocratic phases contain Fe-Ti oxides normally in accessory amounts but in some magnetite is present in larger amounts (see later under *Economic geology*). Chemical analyses of orthogneisses are given in Fernald & Horowitz (1964, p. 15) and Nutman (1984, table 2); these two publications, and Davies *et al.* (1963) and Bendix-Almgreen *et al.* (1967), provide petrological descriptions.

Few outcrops are totally free from felsic veining of one type or another. Leucosome material ranges from pods, veins and layers of cm size derived by anatectic melting to larger sheets and masses, some of which are regarded as the products of high-level magmatism. Such material is often discordant to the regional gneiss foliation and the structure of associated rocks such as amphibolites (see Fig. 26B). Layering varies from fine compositional banding of mm- to cm-scale, best seen in more mafic components, to *bona fide* banded gneiss composed of discrete alternating layers of melanocratic (amphibolite/tonalite) and more leucocratic (granodiorite/granite) material (see Fernald & Horowitz 1964, figs 2, 10).

Feldspathisation is commonly seen in the form of elongate aggregates and augen that can form a well-developed foliation. Widespread development of pink feldspar augen up to 8 cm long occurs on the west side of Bowdoin Fjord, where there is a gradation from high-strain biotite gneiss with augen and aggregations elongated in the plane of schistosity to massive rapakivi-type granite (Fig. 9). Discrete units of porphyroblastic gneiss with augen up to 3 cm long, of both K-feldspar (Davies *et al.* 1963) and plagioclase augen (Fernald & Horowitz 1964, figs 6, 7, 9), have been mapped in the Pituffik–Nunatarsuaq area.

Paragneiss (**pg**)

Paragneiss occurrences *within* map unit **og** have been mentioned above. The rocks composing the areas marked **pg** on Smithson Bjerge and in eastern Prudhoe Land represent a supracrustal sequence of unknown but substantial thickness. The bulk of the succession comprises pelitic to quartzofeldspathic gneisses and schistose rocks that in some areas are interlayered with lighter coloured quartzitic and darker amphibolitic rocks. The paragneisses have a fairly monotonous appearance and an overall brown to rusty-weathering colour. Layering on 10 to 100 cm-scale in the quartzofeldspathic paragneisses on Smithson Bjerge provides useful markers in structural geology (Nutman 1984). Sections with intercalated quartzitic rocks can have a distinct layered character that is accentuated by late granite sheeting (see Fig. 10; also under *Polygenetic garnet-bearing rocks*). The rocks invariably contain a leucocratic component, either as segregations and lit-par-lit veining or later sheeting.

Fig. 9. Quartz-poor porphyroblastic granite showing a thin dislocated amphibolite dyke. Nearby outcrops show feldspar aggregates and porphyroblasts aligned in a distinct gneissosity. West coast of Bowdoin Fjord.

All paragneiss lithologies contain garnet and biotite with or without orthopyroxene and hornblende while sillimanite is present in some quartzofeldspathic and semipelitic rocks. Graphite occurs in pelitic schists. No obvious sedimentary features are preserved that can be directly related to primary depositional environment. The rocks are regarded as derived from a succession of feldspathic sandstones and mudstones; Fernald & Horowitz (1964, p. 20) mention a gneiss derived from “a low rank graywacke”. Ferruginous quartzites on Smithson Bjerge that contain both magnetite and iron sulphides are regarded by Nutman (1984) as chemical sediments with affinity to silicate-facies iron-formation (see under *Economic geology*).

Smithson Bjerge magmatic association

Age. The two main units of this magmatic association – the Qaqujârssuaq anorthosite (**an**) and meta-igneous rocks (**gf**) – are regarded as coeval but no isotopic ages of igneous protoliths are available. The rocks of **gf**, including the Heilprin Gletscher complex, may be of the same general age as the compositionally similar Kap York meta-igneous complex that was emplaced *c.* 2700 million years ago. The oldest of the metamorphosed basic dykes (**ad**) were emplaced during late stages of crystallisation of the anorthosite and meta-igneous rocks. K-Ar mineral ages on a garnet amphibolite dyke from Smithson Bjerge are cited under *Minor mafic intrusions*.

Literature. Dawes (1972, 1976b), Nutman (1979, 1984), Garde *et al.* (1984), Steenfelt *et al.* (2002).

Boundaries. Thule mixed-gneiss complex (see *Relationships of the complexes*, section 1).

Distribution, composition and metamorphism. The Qaqujârssuaq anorthosite and associated meta-igneous rocks were discovered in 1971 and mapped in detail with the other rocks of Smithson Bjerge in 1978 (Dawes 1972; Nutman 1979, 1984; see under *Character of the Survey mapping*). Field relationships, petrological details and main element chemistry of the main rock types can be found in Nutman (1984). As shown on the map sheet, the anorthosite body (**an**) is not in contact with unit **gf**, but both units intrude the Thule mixed-gneiss complex and both have been strongly deformed and affected by granulite-facies metamorphism. Also, both are cut by metamorphosed basic dykes (**ad**), the earlier phases of which show low ductility contact features within the anorthosite and granites indicating that the dykes were emplaced

Fig. 10. Thule mixed-gneiss complex in contact with the younger Qaqujârssuaq anorthosite (**an**) on Smithson Bjerge. Brown, rusty-weathered succession of the foreground cliffs is dominated by paragneisses (**pg**) with pale intercalated ferruginous quartzites. Other units are a granite sheet (**gf**) of the Heilprin Gletscher complex just above the talus cones and intercalated orthogneisses (**og**) at the contact zone with the anorthosite. View is west-north-west with ice-filled waters of Inglefield Bredning in the background. Contact is *c.* 300 m above the lake. Photo: Bjørn Thomassen.

before final crystallisation. In contrast, within gneisses of the Thule mixed-gneiss complex, the dykes are cross-cutting tabular bodies. These relationships also suggest that the anorthosite (**an**) and meta-igneous rocks (**gf**) were emplaced at about the same time and they are regarded as part of an anorthosite–ferrodiorite–granite association, named on the map sheet after Smithson Bjerge.

Anorthosite, leucogabbro (**an**)

The Qaqujârssuaq anorthosite – the largest single anorthosite mass in Greenland – covers the northern *c.* 100 km^2 of Smithson Bjerge and an unknown extent under the Inland Ice. It represents a *c.* 500 m thick succession exposed in an overturned antiform. The one contact exposed that is shown in Fig. 10 is essentially a sheeted zone with thin anorthosite units within paragneiss; the lower contact is at depth, and thus the true post-deformational thickness of the mass is unknown. The exposures are considered to represent the border of a body that was emplaced as a liquid-crystal mixture and composed of *c.* 90% anorthosite, with less than 10% leucogabbro and 1% gabbro (Nutman 1984). Ultramafic rocks or rocks rich in oxides such as chromite, that are characteristic features of the Fiskenæsset anorthosite complex of West Greenland (Myers 1985), have not been recorded.

The Qaqujârssuaq anorthosite body is strongly deformed and all internal structures, including mafic foliation, schlieren and banding are parallel to the exposed contact. Only within local low-strain areas are igneous features preserved and these include planar layering, plagioclase and pyroxene megacrysts, and sporadic graded bedding. Compositional layering on a cm-scale and upwards is interpreted as a tectonised igneous structure (Fig. 11).

There is appreciable lithological variation within the body due the very variable ratio of anorthosite to leucogabbro. Nutman (1984) was able to map three main E–W-trending zones on this basis. Large parts of the anorthosite contain little or no leucogabbro whereas elsewhere leucogabbro in 25–50 cm thick layers (and thicker), is commonly interspersed with anorthosite. Several lithological types of leucogabbro occur ranging from strongly banded to equigranular and megacrystic pyroxene leucogabbro, including ‘tennis ball’

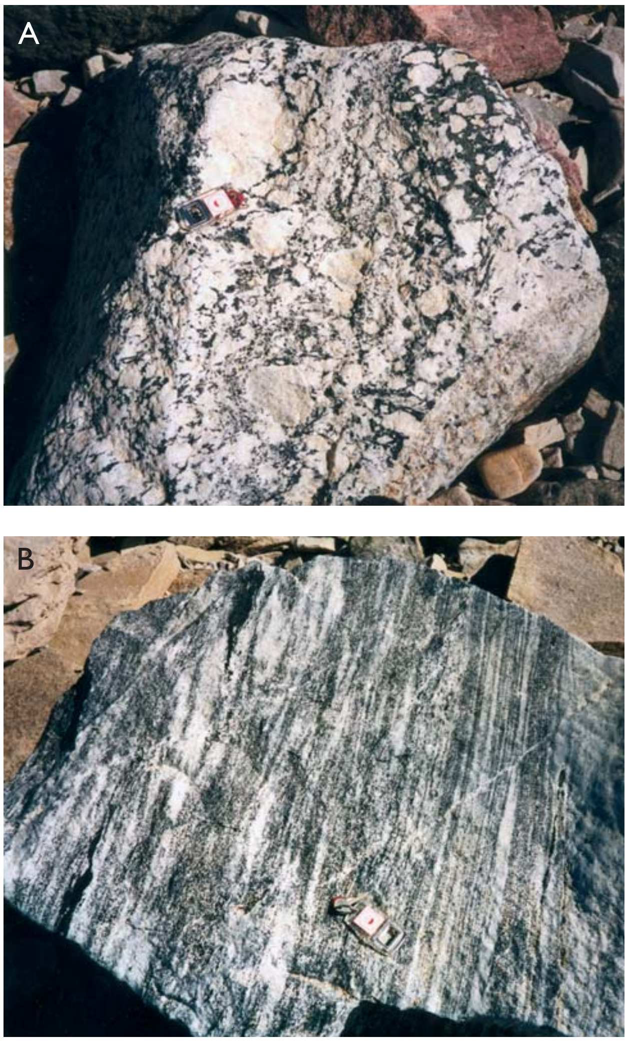


Fig. 11. Leucogabbro lithologies of the Qaqujârssuaq anorthosite. **A**: 'Tennis ball' leucogabbro. **B**: strongly deformed leucogabbro showing pronounced tectonic banding and streaked out anorthosite patches. Glacial erratic blocks from the coast, east of Qaanaaq; cf. outcrops in Nutman (1984, figs 5, 6). Scale is 10 cm long.

and brecciated types (Fig. 11). The plagioclase is calcic (~ 75% An), ferromagnesian minerals are predominantly hornblende + clinopyroxene ± orthopyroxene; garnet occurs locally and is involved in complex metamorphic coronas (Garde *et al.* 1984).

Granite, ferrodiorite, ferrogabbro (**gf**)

The south-western extremity of Smithson Bjerge is occupied by basic to acidic meta-igneous rocks to which Nutman (1979) gave the name *Heilprin Gletscher complex*. Several outcrops south of Heilprin Gletscher, both of metagabbro and granite, are placed in the map unit and interpreted as satellite intrusions of the main mass. The magmatic suite has been subjected to severe deformation, and some rocks are platy and schistose, even gneissic. Some of most deformed granites are very similar to, and thus correlated with, the pale flaggy rocks representing a late orthogneiss phase of the Thule mixed-gneiss complex (see earlier under *Polygenetic garnet-bearing rocks*).

In the type area of the Heilprin Gletscher complex, the map unit is characterised by intersheeting of granite and ferrodiorite in roughly equal amounts, with the diorite grading into subordinate ferrogabbro (Nutman 1984). Intermediate compositions make up less than 10% of the rocks. The ratio of the two main rock types varies, for example, in the west ferrodiorites predominate whereas in the east they are subordinate to granite. Granite sheets also penetrate the gneisses of the Thule mixed-gneiss complex adding to the often conspicuous layering of the paragneisses, which also contain anorthosite sheets (Fig. 10). In most areas, the initial relationships of the intersheeted rocks are obscured by intense deformation but elsewhere, for example at the south-western end of Smithson Bjerge, intrusive contacts are preserved. Relationships listed by Nutman (1984) lead to the conclusion that the ferrodiorites and granites represent contemporaneous intrusions, with ferrodioritic magmatism starting first, with the complete crystallisation of the granites post-dating that of the ferrodiorites.

With increased deformation, the granites vary from igneous-looking, rather massive pinkish rocks, locally with K-feldspar megacrysts up to 2 cm long, to rocks with a biotite foliation, to the platy, schistose and gneissic rocks mentioned above. Garnet is common, particularly in areas of contamination by country rock enclaves. No compositional layering is present but colour banding on a 25 cm-scale is preserved in the ferrodiorite. Hornblende is the main mafic mineral of the ferrodiorite and ferrogabbro but garnet, orthopyroxene and clinopyroxene also occur.

Amphibolite dykes (**ad**)

Smithson Bjerge is crossed by at least two ages of metamorphosed WNW–ESE-trending basic dykes subparallel to the contact of the Qaqujârssuaq anorthosite. These are the amphibolite and garnet amphibolite dykes of Nutman (1984, plate 1). On the Thule map, these are given the same colour and designated **ad**. The oldest dyke phase is regarded as an integral part of the Smithson Bjerge magmatic association; the less-deformed garnet amphibolite dykes are dealt with later under *Minor mafic intrusions*. It is noteworthy that the predominant structural direction of Smithson Bjerge followed by these dykes is also utilised by the much younger unmetamorphosed late Neoproterozoic dykes (see later under *Neoproterozoic dykes* (***d***$_2$)).

Metamorphosed basic dykes cut the anorthosite (**an**) and meta-igneous rocks (**gf**), as well as rocks of the Thule mixed-gneiss complex (**og**, **pg**). The dykes are up to 5 m thick but most are below 2 m. Individual dykes have not been continuously traced between map units but based on composition and dimension they are taken to be genetically related. Two types are recognised: dark amphibolite that grades to pyribolite depending on the ratio of pyroxene to amphibole, and paler diorite. The one cross-cutting relationship seen indicates diorite as the younger phase. As mentioned under *Distribution, composition and metamorphism* (pp. 28–29), dyke form varies according to the physical state of the host rock. Within the anorthosite and granite, dykes have a range of morphologies from irregularly bordered and sinuous to deformed and fragmented (Nutman 1984, fig. 10) whereas within the ferrodiorite and country rocks, they are tabular and linear. The dykes were emplaced in rocks that ranged from plastic to rigid.

Fig. 12. Pink foliated granite with enclaves of amphibolitic metagabbro cut by a thin metamafite dyke that is parallel to a tectonic fabric of the granite. Kap York meta-igneous complex, Niaqornaarsuk.

Kap York meta-igneous complex

Age. The Neoarchaean age of 2700 Ma given on the map remains the most refined isotopic age of this complex. It stems from Rb-Sr whole-rock analysis of nine samples from the south-eastern end of the Kap York peninsula, eight of which define an errorchron corresponding to an age of 2661 ± 168 Ma (Dawes *et al.* 1988). Coeval meta-igneous rocks may well be those of the Heilprin Gletscher complex of Smithson Bjerge (Nutman 1984). The igneous rocks have been deformed and metamorphosed and the disturbed Sr isotopic systems are considered to indicate Palaeoproterozoic orogenic activity.

Literature. Koch (1920), Davies *et al.* (1963), Dawes (1975, 1976a), Kalsbeek & Dawes (1980), Kalsbeek (1981), Dawes *et al.* (1988), Gowen & Kelly (1996).

Boundaries. Thule mixed-gneiss complex, Melville Bugt orthogneiss complex and Lauge Koch Kyst supracrustal complex (see *Relationships of the complexes*, sections 2, 3).

Distribution and composition. The existence of 'pre-Cambrian intrusive rocks' including granite, syenite and diorite around Parker Snow Bugt, emplaced into older gneisses, was mentioned by Koch (1920). Igneous rocks, described as predominantly quartz diorite, and partially deformed and feldspathised were found by Davies *et al.* (1963, p. 40, plate 1) to extend from this bay to Kap York. Unfortunately, technical difficulties during map production determined that the quartz diorite was not distinguished on the map as a 'basement rock' but it was given the same colour and legend identification (diabase) as the much younger post-tectonic dolerite dykes (W.E. Davies, written communication 1968).

The Kap York meta-igneous complex is composed of a basic (gabbro) to acidic (granite) plutonic suite with SiO_2 content varying from 46 to 77 per cent (21 analyses). Although few contact relationships between the different compositional phases have been studied, all evidence suggests that gabbroic rocks were emplaced first, followed by diorites and granites. For example, metabasite material occurs as enclaves within granite (Fig. 12). Feldspathisation of basic and intermediate rocks is common. Intermediate rocks are characterised by a variable alkali feldspar–plagioclase ratio. Relatively undeformed rocks of this map unit are generally medium-grained with textures varying from equigranular to those in which quartz grains are elongated and parallel to any mafic foliation. In hand sample, these rocks appear fairly homogeneous yet in outcrop most show a directional fabric of some sort. With varying degrees of deformation and migmatisation, there are gradations to weakly foliated rocks and to schistose and gneissic rocks with thoroughly penetrative fabrics. Hypersthene is regarded as a primary mineral but its recrystallisation and co-existence with clinopyroxene and hornblende indicates metamorphism under granulite-facies conditions. As explained earlier, large areas mapped as orthogneisses to the east in Melville Bugt are regarded as derivatives of the complex (see under *Relationships of the complexes*, section 3).

Metabasite dykes up to 5 m thick and of at least two generations occur within the granitoid rocks. At Niaqornaarsuk, dykes 30 cm to 2 m thick, composed of foliated amphibolite, have sinuous contacts with

Fig. 13. Pearys Mindevarde on the plateau at Kap York. This three-sided monument from 1932 is *c.* 30 m high. Apart from the marble forming the letter 'P', the column is built of rocks of the Kap York meta-igneous complex collected and quarried nearby. The mosaic is made up of blocks varying from dark grey (gabbro/amphibolite) to buff (granodiorite/granite), with the predominant rock being a grey, mesocratic tonalite/quartz diorite. Avatak Henson stands guard, 16 September 1974.

sheared margins and these bodies may have been emplaced before complete crystallisation of the host rock (Fig. 12). Younger, thicker tabular bodies have more regular contacts, in places have chilled contacts and post-date the tectonic fabric and migmatitic veins in the granitoids. At Niaqornaarsuk such bodies reach 5 m thick, strike NNE and dip 40–50° to the west and show some shearing and often epidotisation.

The two map units recognised represent a first-order subdivision of the complex into rocks of *generally* basic to intermediate composition (**gt**) and acidic (**gr**). Apart from one helicopter stop inland on a nunatak summit of Beverly Fjelde, the complex has only been sampled along the outer coast. Observations so far indicate that of the two map units, **gt** embraces the most variable suite of rocks with granite interleaved with the other lithologies given in the map legend. No basic to intermediate rocks are known within **gr**.

Gabbro, tonalite, granodiorite (**gt**)

Rocks on Conical Rock, Kap York peninsula and a single area to the east form this map unit that comprises a varied plutonic suite including as mentioned above granite, that in hindsight should have been named in the legend. Detailed mapping of the various magmatic phases has not been accomplished but sampling sites of rocks varying from gabbro to granite along the Kap York peninsula, and in the eastern outcrop, are given in Kalsbeek & Dawes (1980, fig. 8). A tripartite map division into basic, intermediate and acidic rocks is attempted on the 1:200 000 map of the Kap York peninsula (sheet 9 of Dawes 1988b). In broad terms, that map shows that melanocratic gabbroic rocks dominate in the area south of Parker Snow Bugt, younger mesocratic to leucocratic, variably deformed quartz diorites and granodiorites come in around Sukkat and to the east, while towards Niaqornaarsuk these rocks become distinctly gneissic and interleaved with granitoid and subordinate basic rocks.

Mesocratic rocks of intermediate composition predominate. A realistic illustration of the ratio between melanocratic, mesocratic and leucocratic rocks – broadly exemplified by gabbro/norite, tonalite/quartz diorite/monzonite and granodiorite/granite – can be seen in the mosaic of Pearys Mindevarde built of rocks collected locally and quarried on the shores of the bay to the north-west (Fig. 13). This bay is the sample centre for an isotopic dating study and is featured in Dawes *et al.* (1988, figs 2, 5).

Brown- to buff-weathered, metagabbro, metanorite with smaller areas of metadolerite, variously deformed and with major units characterised by pink feldspar porphyroblasts, characterise western exposures. These rocks are cut by dolerite sheets emplaced after the main deformation and metamorphism of the complex (see Fig. 42 in section *Palaeoproterozoic?, Mesoproterozoic and Neoproterozoic sills and sheets (**s**)*). Extremely deformed rocks occur at the head of Parker Snow Bugt, where basic rocks are distinctly foliated, sheared and in places mylonitised. One gradation seen is from dark grey, medium-grained porphyroblastic metadolerite, with coarser gabbroic parts, to black, fine-grained mylonite. Davies *et al.* (1963) mention black slickensided mylonite from the same area with the appearance of anthracite. The main mylonite zone,

Fig. 14. Rock association within map unit **gn** of the Melville Bugt orthogneiss complex: grey hornblende-biotite orthogneiss predominates with subordinate brownish paragneiss and amphibolite layers. Section is cut by a swarm of brown-weathered Palaeoproterozoic NW–SE-trending basic dykes ($\mathbf{d_1}$). Western side of Innaaqqissorsuq peninsula with plateau at *c.* 600 m a.s.l.

which has an easterly trend, may well mark the northern boundary of the meta-igneous complex in this area.

The intermediate rocks are grey to buff weathered, with a characteristic greenish tinge on fresh surfaces indicative of hypersthene; many contain biotite and/or hornblende. Granitoids rocks are either pink to reddish weathered with biotite as the dominant mafic mineral or pale-weathering leucogranites that have little or no mafic minerals. Quartz in both types can have a grey to blue colour. Some porphyroblastic varieties exist. At several places along the Sineriarsua coast, for example at the 60° dip symbol shown on the map (west of the moraine-dammed lake), garnet-bearing granite and granitic gneiss occur intercalated with amphibolite and rusty, sulphide-bearing schists. Such rocks are taken to represent enclaves of country rock paragneiss.

Granite (**gr**)

The granites composing this map unit are of two main types. Grey, medium-grained leucocratic granite, variably foliated by biotite, and in places gneissic, occurs on the northern side of Pituffik Gletscher. To the south of the glacier, bedrock is poorly exposed but much of the area designated **gr** on the map corresponds to the porphyroblastic gneiss of Davies *et al.* (1963). The rock is a biotite granite with pink feldspar augen that has undergone considerable deformation and in places migmatisation, so that it now has a marked gneissic structure. It is reminiscent of the reddish granitoids and granitic gneisses that occur within map unit **gt**.

Melville Bugt orthogneiss complex

Age. The Neoarchaean age of 2700 Ma cited in the map legend pertains to the Rb-Sr whole-rock isotopic age analyses on a sample suite from Kivioq Havn comprising orthogneisses and interleaved supracrustal rocks of the Lauge Koch Kyst supracrustal complex (*Kivioq Havn gneiss and supracrustal complex* of Dawes *et al.* 1988). An errochron of the ten samples processed yields an age of 2697 ± 168 Ma whereas the regression line based on the seven gneiss samples alone gives 2663 ± 274 Ma. The scatter of the data points is interpreted to be indicative of Palaeoproterozoic disturbance. As referenced earlier under *Isotopic ages*, the comparable age of 2620 Ma has been obtained on zircon from gneisses from Fisher Øer and Sabine Øer (Kalsbeek 1986). In particular, the tonalitic gneisses on Fisher Øer have been singled out on field relationships to be the end-product of a transition from homogeneous metabasite of igneous aspect (Dawes 1979, also below). The isotopic data thus support the thesis that large areas of orthogneisses have been derived from igneous protoliths coeval with rocks of the Kap York meta-igneous complex. However, field relationships show that many gneisses are structurally considerably more complex suggesting an older age. This is confirmed by the Sm/Nd model age of 2840 Ma from a grey gneiss from Innaaqqissorsuq, south of Gade Gletscher (see below and under *Relationships of the complexes*, section 3).

Literature. Koch (1920), Dawes (1976a, 1979), Dawes & Frisch (1981).

Boundaries. Thule mixed-gneiss complex, Kap York meta-igneous complex and Lauge Koch Kyst supracrustal complex (see *Relationships of the complexes*, sections 3–5).

Distribution and composition. The complex embraces all orthogneisses and granitoid rocks of the Lauge Koch Kyst, east of Sidebriksfjord. The reconnaissance nature and scale of the mapping, determined that only sizeable and conspicuous packets of associated rocks, for example paragneisses and associated mafic rocks, could be mapped separately as part of the Lauge Koch Kyst supracrustal complex (see under *Character of the Survey mapping*). Consequently, many areas within the main map unit **gn** contain lithologies that have not been derived from an igneous protolith and where intimately interfolded, these rocks can form an appreciable component. For example, many of the islands and peninsulas to the east of Nallortoq are characterised by units of brown- to rusty-weathering paragneisses and darker amphibolites, including Innaaqqissorsuq mentioned above as the site of isotopically dated orthogneiss (Fig. 14). The heterogeneous nature of the main map unit **gn** is illustrated more appropriately on the larger scale maps in Survey archives (Dawes 1988b). In contrast, the two other units, **gg** and **ag,** are considerably more restricted in lithology, with a distribution being recognised only east of longitude 60°W.

Since the orthogneisses have been derived from crustal material of *at least* two ages and the region has been affected by Palaeoproterozoic reactivation causing widespread recrystallisation (see under *Age* above), their thermo-tectonic history is complex. Detailed mapping, and geochemical and isoptoic work, are essential if this history is to be unravelled.

All rocks of the complex have a mineralogy indicative of amphibolite-facies metamorphism. Biotite and hornblende are the main mafic minerals and in many gneisses both are present. Hypersthene also occurs but is much less widespread being more common within basic rocks. The mineral ranges from fresh to being partially replaced by hornblende, or locally, chlorite. Granulite-facies metamorphism affected the Kap York meta-igneous complex in the west and thus the most likely scenario is that this also affected the entire Lauge Koch Kyst, followed by regional regression of Palaeoproterozoic age.

Gneiss (**gn**)

The two generations of orthogneisses (see above under *Age*) are termed here 'older' and 'younger' gneisses. They have been folded together during several phases of ductile deformation and subjected to feldspathisation, migmatisation and polyphase metamorphism. While the two groups can be identified over part of the region, for example in the west, their regional distribution is uncertain, particularly so since both gneiss groups contain variously veined and banded, grey gneisses of granodioritic to tonalitic composition.

'Older' gneisses

Included here are leucocratic to mesocratic, massive, veined and banded, quartzofeldspathic gneisses that are characterised by having intercalated amphibolites varying from cm-scale to several tens of metres thick. The proportion of amphibolite to quartzofeldspathic material varies but basic layers can form up to 50% of the rock (Fig. 15A). Between Savissuaq Gletscher and Docker Smith Gletscher, relationships between amphibolites and host rocks are well-illustrated in the steep, ice-polished faces of nunataks and semi-nunataks. For example, the exposure seen in Fig. 6 is particularly illustrative in that it reveals that at least two generations of metabasite material are present. The amphibolites range in form from continuous bodies to boudinaged and fragmented layers, with differing degrees of fragmentation occurring in different belts parallel to regional structure. A belt of strong fragmentation occurs in the area between Gade Gletscher and Morrel Gletscher where amphibolite occurs in agmatitic gneiss and scattered enclaves in leucocratic granitoid rocks. In many areas the pale quartzofeldspathic component of the gneiss is massive to foliated, often feldspar porphyroblastic, with the conspicuous layered and banded nature of the rocks being caused by the concordant amphibolites (Fig. 15B). There are gradations to grey veined and banded gneisses in which relatively few amphibolites occur (see Dawes & Frisch 1980, fig. 6).

Amphibolite is of two main types: (1) black to dark grey, massive to foliated rock, and (2) brown to dark grey, often compositionally banded, supracrustal rock, that can be magnetite-bearing and associated with pelitic schists (see under *Lauge Koch Kyst supracrustal complex*). Although highly deformed, type (1) amphibolites locally preserve discordant relationships

Fig. 15. Typical exposures of 'older' banded gneiss of the Melville Bugt orthogneiss complex showing varying proportions of amphibolitic to quartzo-feldspathic material. **A**: Polymictic amphibolites with some of the thicker layers representing metavolcanic rocks (**ms**). Eastern face of nunatak, northern Mohn Gletscher, with northern Meteorbugt in the background. Relief is *c.* 400 m. **B**: Thin amphibolite layers, many of which represent metamorphosed, highly deformed, basic dykes. Eastern face of nunatak east of Helland Gletscher, with relief *c.* 500 m.

to gneissic structure, thus establishing their identity as intrusions (Figs 6, 16). The persistence and wide distribution of these amphibolites throughout the map unit, define a major regional swarm of basic dykes (or sheets).

'Younger' gneisses

Transitions between basic to intermediate meta-igneous rocks and melanocratic to mesocratic gneiss are preserved in pockets of low deformation. Such meta-igneous rocks occur on islands and peninsulas between Sidebriksfjord and Kong Oscar Gletscher, for example George Ø, Nallortoq, Kap Edvard Holm, Heilprin Ø and Fisher Øer. One such area east of George Ø has been singled out from the gneisses and referred on the map to the Kap York meta-igneous complex (see under *Relationships of the complexes*, section 3). It is significant that the recognition of 'younger' gneisses has only been made in areas hosting little or no amphibolitic material of types 1 and 2 described above. On the eastern island of Fisher Øer, brown-weathering metadolerite and metagabbro, intrusive into highly-deformed grey gneiss, grade into foliated rocks and finally into hornblende-rich tonalitic gneiss. The transition takes place over *c.* 2 m, with leucocratic veins increasing in number from the metabasite into gneiss. Feldspar-rich pegmatites cut all rock types. Similar passages from massive dioritic rocks of igneous aspect to grey, hornblende-biotite veined gneisses occur at Kap Edvard Holm and on islands and peninsulas to the north-east.

In some areas, for example the Kap Melville – Sorte

Fig. 16. Banded 'older' gneiss of the Melville Bugt orthogneiss complex showing fragmented amphibolite dykes with consistent clockwise rotation of boudins, and with preserved discordancies (**arrow**). Southern coast of Bushnan Ø.

Fjeldvæg area, 'older' and 'younger' gneisses are recognisable as discrete units containing amphibolites that are interleaved with units that lack them (Fig. 17). However, identification on field characters alone is problematical, made so by the fact that discordant amphibolite bodies occur within the protolith of the 'younger' gneiss (Kap York meta-igneous complex, see Fig. 12) and late granitic sheets invade both gneiss groups. Consequently, knowledge about the regional distribution of the two ages of gneiss remains uncertain but it may be significant that all localities seen involving transitions between meta-igneous rocks and gneisses are located at the outer coast. This distribution simulates that of the Kap York meta-igneous complex, which to the north has a exposed boundary with gneisses of the Thule mixed-gneiss complex; in the south the boundary is under water. Projection of this boundary east from the Kap York peninsula would account for the location of 2.7 Ga plutonic rocks on islands and peninsulas, with submarine outcrops under the waters of the Melville Bugt, and backed by a hinterland of 'older' gneiss.

Granitic gneiss (**gg**)

This map unit occurs between Nansen Gletscher and Sverdrup Gletscher. It is composed of buff to pinkish, leucocratic granitic gneiss and massive granitoid rocks, in which compositional layering, leucosome veining and other gneissic structures are not prominent. Biotite is the main mafic mineral. Augen gneiss and granite occur, as for example, on Mylius-Erichsen Monument which is composed of a pink, biotite augen granite that varies to a granitic gneiss. Such rocks have K-feldspar porphyroblasts up to 3 cm in length that are often without preferred orientation but they may be weakly aligned parallel to any mafic foliation. The rocks have gradational relationships to the veined to banded gneisses of map unit **gn**. Gneiss and granit-

Fig. 17. Two generations of gneiss within the Melville Bugt orthogneiss complex: at the base mesocratic, tonalitic veined gneiss ('younger' gneiss) with a sharp contact (**dashed**) to paler gneiss characterised by concordant amphibolites ('older' gneiss). The quartzofeldspathic part of the 'older' gneiss is massive to foliated, with units characterised by porphyroblasts and elongated feldspar aggregates. Both gneiss units are cut by thin leucogranite veins that also in places have a gneissic aspect. **Arrow** points to amphibolite unit that contains banded iron-formation shown in Fig. 46. **d_1**, brown-weathering Palaeoproterozoic basic dykes. South face of Sorte Fjeldvæg, with summit at *c.* 500 m a.s.l.

Fig. 18. Contact between the Lauge Koch Kyst supracrustal complex (**ms**) and Thule mixed-gneiss complex (**og**). Magnetite-bearing metapelitic schist–amphibolite succession preserved in a synform, in gradational contact with grey, well-layered multiphase orthogneisses. Pale contact zone contains layers and schlieren of supracrustal rocks. Closer view of synformal succession is shown in Dawes (1976a, fig. 7) and Dawes & Schønwandt (1992, fig. 3). **d**, basic dyke of uncertain age. The view is of the western side of nunatak 620 m at the north-eastern end of Sidebriksfjord. **Note** that the photograph was taken in August 1975. Since then, the glacier in the foreground has disappeared and today the land is a semi-nunatak bordered by the sea (cf. map sheet).

oids of similar character occur throughout **gn** but in masses too small to be shown on the map sheet.

Granite (**ag**)

This map unit is only recognised on small islands south-east of Sabine Øer. The main rock has two main components: foliated, K-feldspar rich, pyroxene-biotite palaeosome invaded by pink granite veins mostly under 10 cm thick but that can reach 1 m. The veins are sub-parallel to the foliation in the palaeosome.

Lauge Koch Kyst supracrustal complex

Age. Samples of supracrustal rocks, including paragneiss and amphibolite, from Kivioq Havn are part of an Rb-Sr errorchron indicating an age of 2697 ± 168 Ma (Dawes *et al.* 1998). The supracrustal succession – referred to previously as the *Kivioq Havn gneiss and supracrustal complex* – contains magnetite-rich rocks that are regarded as an Archaean lithology. From the evidence discussed earlier, particularly the field recognition of the bipartite nature of supracrustal sequences based on the presence or not of magnetite, a Palaeoproterozoic age for some rocks cannot be discounted (see *Relationships of the complexes*, section 5).

Literature. Hovey (1918), Davies *et al.* (1963), Dawes (1975, 1976a, 1979), Dawes & Frisch (1981), Dawes *et al.* (1988).

Boundaries. Thule mixed-gneiss complex, Kap York meta-igneous complex and Melville Bugt orthogneiss complex (see *Relationships of the complexes*, sections 2, 5).

Distribution and composition. As implied by the name, this complex occurs throughout the Lauge Koch Kyst stretching from Kap Seddon in the south-east to Wolstenholme Fjord in the north-west. It comprises a diverse assemblage of metasedimentary rocks mainly pelitic, semipelitic and quartzitic, including oxide-facies iron-formation, and mafic to ultramafic rocks some of which represent metavolcanics. Some leuco-amphibolites may represent metatuffs. Having been severely deformed and metamorphosed together with the Thule mixed-gneiss and Melville Bugt orthogneiss complexes, the supracrustal rocks are intimately associated and structurally interleaved with gneisses. Contacts between supracrustal units and the predominant structure of the gneisses are concordant but small discordancies are preserved (Figs 6, 18, also Dawes *et al.* 1988, fig. 7). Late orthogneiss phases invade the rocks,

Fig. 19. Lauge Koch Kyst supracrustal complex overlying gneisses of the Thule mixed-gneiss complex (**og**). Pelitic schists, schistose gneisses with important units of magnetite-rich rocks (**ms**), pass into pale psammitic rocks of **qt** forming the summit. **Arrow** marks a thin unit of **qt** above the gneiss. The steep section above the rusty scree is featured in Schønwandt & Dawes (1993, fig. 3). Nunatak at the north-western end of De Dødes Fjord, with relief *c.* 350 m.

as do minor felsic intrusions including conspicuous late granite sheets.

The outcrop form of the supracrustal rocks is highly variable. It ranges from pods, rafts and discontinuous layers within gneiss that are usually of one lithology, to thicker and more intact sequences some of which preserve lithological diversity resembling initial stratigraphical order. For example, in the De Dødes Fjord area, supracrustal rocks structurally above the Thule mixed-gneiss complex, are composed of a thick unit of pelitic and mafic schists (**ms**) that passes upwards into a section dominated by pale psammitic metasediments (**qt**) (Fig. 19; see Dawes 1976a for description). This particular area preserves some of the largest exposures and thickest sections of the map unit and on one semi-nunatak, the **ms/qt** succession is at least 600 m thick. Seen as a whole, the supracrustal rocks are only fragmentarily preserved. Possibilities for tracing of individual supracrustal units over large areas, thereby providing meaningful structural correlation, is hindered by the nunatak physiography and abundant ice cover. Nevertheless, the supracrustal pile composed of metasedimentary and meta-igneous components represents a considerable post-tectonic thickness that must far exceed 1 km.

The rocks have amphibolite-facies mineral assemblages characterised by biotite, hornblende, garnet and sillimanite but like the 'older' gneisses that surround them, iron-formation and metabasites contain orthopyroxene that may well be indicative of earlier granulite-facies metamorphism (see under *Melville Bugt orthogneiss complex*).

Given the reconnaissance nature of the mapping, the subdivision of the complex into four map units (**pp**, **ms**, **qt**, **a$_1$**) is ambitious. Not only are the contacts between the main lithologies of **ms**, **qt**, and **a$_1$** gradational but map units are intercalated. Mapping was based on ground observations at selected localities extrapolated to other areas from vantage points and from the air, and thus rock colour and weathering characteristics played an important role. The pelitic and semipelitic metasediments (**ms**) tend to be brown to rusty weathered and semi-recessive, whereas amphibolites (**a$_1$**) tend to be darker and more resistant. However, magnetite and hematite occur in both, and the presence of iron-formation increases resistance, darkens colour and causes rusty weathering (Figs 18, 19). Consequently, designation as **ms** or **a$_1$** is often based on crude assessments, in some cases made quickly from the air. The synformal succession illustrated in Fig. 18 is one such example. Initially mapped as 'amphibolitic supracrustal rocks' (Dawes 1976a), it is referred on the map sheet to **ms** on account of the supposed predominance of metasedimentary rocks. Pale-weathered psammitic rocks of map unit **qt** are associated with both **ms** and **a$_1$** but at a distance, it is the dark rocks of the latter two units that are the most conspicuous while **qt** lithologies tend to blend in with the grey gneisses. Consequently, map unit **qt** may prove to be more widespread than indicated on the map.

In summary, for outcrops along the Lauge Koch Kyst that have only been studied from the air or at a distance, classification into map units **ms, qt** and **a$_1$** is commonly tenuous.

Paragneiss (**pp**)

This map unit is restricted to the south-eastern part of the map region, south of Duneira Bugt. It comprises units of rusty-weathering, semi-recessive pelitic schist

Fig. 20. Rusty-weathered biotite-garnet schists of map unit **pp** showing intense, small-folded anatectic veining cut by a discordant amphibolite body that contains a coarser set of leucocratic veins that in places invades the host rocks. A waterline, with stranded ice block on the left, marks the colour difference between upper rusty and lower darker rocks. Tuttulissuup Qeqertaa island, east of Kap Seddon. Hammer (**arrow**) is *c.* 50 cm long.

and semipelitic schistose gneiss with abundant anatectic veins (Fig. 20). The rocks are intercalated with grey orthogneiss (**gn**). The main rock type is a biotite-garnet (± sillimanite) schist characterised by an intense system of leucosome veins that in places composes up to 40% of the rock. The veins are of two ages: (1) early veins parallel to schistosity that show small-scale folds, with ptygmatic and pinch-and-swell structures, and (2) veins that cut these structures but that also are deformed. Subsidiary rock types are thin layers of biotite-muscovite schist and garnet gneiss, which is magnetite-rich in its more quartzitic parts.

A notable feature along the coast east of Kap Seddon and on the island of Tuttulissuup Qeqertaa, is the common presence of discordant amphibolite dykes that post-date the leucosome veins and small-scale folds in the paragneiss. Deformed and invaded by leucocratic material, the bodies are generally concordant to the regional structure of the host rock (Fig. 20). They range from less than 1 to 15 m in thickness. Some amphibolites are garnet-bearing and in places, particularly parallel to margins, the rock is schistose with in places elongated feldspar aggregates.

Pelitic and mafic schists (**ms**)

Pelitic schists characterised by garnet and biotite, and often rusty weathered, are common throughout the Lauge Koch Kyst supracrustal complex intercalated with other lithologies. Grouped together in this map unit are all substantial outcrops, except those of the previous map unit (**pp**) which are characterised by a high degree of anatexis. Two main associations are recognised: pelitic schists intimately associated with amphibolitic and magnetite-rich rocks (mafic schists) and those with few or no mafic schists. The former association, that forms the thickest sections, is more common occurring throughout the Lauge Koch Kyst, whereas the main exposures of the latter tend to be concentrated in the south-east. An attempt at differentiating these two associations on the map sheet was abandoned because of insufficient ground observations. Both associations are involved in complex structures so that they are interleaved with gneisses, and chronological relationships are unknown. Both show amphibolite-facies mineral assemblages and also varying degrees of anatectic veining and their identity as parts of the same supracrustal succession is a natural first assumption. However, it is also possible that some of the units lacking magnetite may be younger, and either Archaean or Palaeoproterozoic in age (see *Relationships of the complexes*, section 5).

The pelitic and mafic schists are brown to black, often show rusty weathering and they form rather semi-resistant sections exemplified by exposures shown in Figs 6, 18, 19, 21. Three main rock types occur: (1) biotite-rich schist with semipelitic paragneiss, with a variable degree of anatectic veining, (2) amphibolite ranging from foliated and semi-massive to schistose and occasionally associated with thinner ultramafic components, and (3) magnetite-rich rocks that show a wide variation from schists with biotite, hornblende and pyroxene, to magnetite-quartz rocks, including banded iron-formation and thin layers of almost pure magnetite rock (see under *Economic geology*, *Magnetite (**mg**)*). Quartzites and quartz-rich schistose gneiss are present in some sections.

Garnet is present in all rocks including the magnetite-rich rocks, sillimanite occurs in mica schists particularly in muscovite-rich varieties, orthopyroxene is common in iron-formation, as well as in the amphib-

Fig. 21. Unit of rusty-weathered metasedimentary schists and schistose gneiss of the Lauge Koch Kyst supracrustal complex (**ms**) within severely deformed grey orthogneisses of the Melville Bugt orthogneiss complex (**gn**). The unit is *c.* 50 m thick, regular in form and persistent around the south-western end of Tuttulissuup Tuttoqarfia, Duneira Bugt. The gneiss shows evidence of strong plastic deformation illustrated by trails of amphibolite fragments (**arrows**). Such supracrustal packages could be northern extensions of the Palaeoproterozoic Karrat Group of West Greenland, outcrops of which occur just south of the map sheet at Red Head. Dark outcrops upper right are metabasite intrusions of map unit **a**$_2$ (see Fig. 27). View is to the north-north-west across Sverdrup Gletscher to Tuttulipaluk.

olites, often in quantities that warrant the use of the rock name 'pyribolite'. The lithologies seem to be intergradational and concordant but the rocks have been highly deformed, as seen by the tight folds, even refolded structures that are conspicuous in banded iron-formation. Apart from the discrete banding of the iron-formation that presumably represents sedimentary layering, no primary features are preserved. The amphibolite units with associated ultramafic rocks occur mainly in rather persistent sill-like bodies but they may be boudinaged. Their origin as intrusions or extrusions, or a combination of both, remains an open question.

The supracrustal sections lacking magnetite-rich lithologies seem to be generally preserved in thinner successions than the pelitic–mafic schists and show less lithological diversity. They are recessive compared to the enveloping gneisses and they generally form moderate rusty-weathered slopes (Fig. 21). Rock types vary from schist to lit-par-lit paragneiss. A dominant rock is a garnet-mica-sillimanite schist that varies to a schistose gneiss and that may have biotite or muscovite as the dominant mica. Some schists contain graphite. Chlorite schists occur in some sections as do impure quartzites and these can have biotite and/or muscovite as the main impurities, sometimes with disseminated iron sulphides. The westernmost occurrence, at Parker Snow Bugt, contains appreciable semipelitic and quartzitic rocks including quartz-muscovite schist, quartz-chlorite schist and chlorite-muscovite-talc schist, as well as thin quartzites. These rocks are interleaved with grey quartzofeldspathic gneiss. This supracrustal package could also have been placed in map unit **qt**, particularly since similar lithologies characterise the **qt** succession on the nunataks to the east-north-east (west of Puisiluusarsuaq) that are on general strike with the outcrops at Parker Snow Bugt.

If Palaeoproterozoic metasediments exist within the Lauge Koch Kyst supracrustal complex, then the garnet-mica-sillimanite rocks in the south-eastern part of the region are prime candidates. Although generally recessive, relatively thin units are fairly consistent along strike, as for example the unit illustrated in Fig. 21. This unit is very regular in form and as shown on the map sheet it can be traced around the south-western end of Tuttulissuup Tuttoqarfia peninsula. In contrast, the gneiss shows evidence of strong plastic deformation illustrated by trails of amphibolite fragments – the relicts of once continuous layers. This suggests that the interleaved metasedimentary rocks have not passed through the complete structural history registered by the gneisses. Furthermore, the persistence of layers of comparable dimension within gneiss is not atypical of the disposition of Proterozoic supracrustal rocks within Archaean gneisses south of the map region in the Rinkian mobile belt (Escher 1985b; Henderson & Pulvertaft 1987, fig. 19).

Quartzite (**qt**)

Outcrops of this map unit occur in two areas of the Lauge Koch Kyst: in the west at the head of De Dødes Fjord and on a nunatak west of Puisiluusarsuaq – an area that preserves the thickest sections – and on a group of nunataks west-north-west of Haffner Bjerge.

Thin layers of psammitic rocks that tend to be lensoid are found within sequences mapped as **ms** in the two areas mentioned above, and more regionally between Savissuaq Gletscher and Docker Smith Gletscher, at Parker Snow Bugt, as well as sporadically within the gneisses (**gn**), for example in the Sidebriksfjord area (see below). In the De Dødes Fjord area, the map unit structurally overlies unit **ms** typically forming the summits of several nunataks but in some sections, a thin unit of psammitic rocks is present between the gneisses and unit **ms** (Fig. 19). Whether these 'basal quartzites' represent an original stratigraphical feature or a tectonic slice is unknown.

The rocks form pale-weathering successions in contrast to the darker colour of other supracrustal rocks and gneisses (Fig. 19) but some quartzite has a dark grey to greenish black colour that can be mistaken at a distance for a mafic rock. The general name 'quartzite' used to describe map unit **qt** refers to the main rock types composed of predominantly quartz; others include a variety of quartz-rich rocks, including siliceous schists, quartzofeldspathic schists and gneissic rocks that may contain magnetite in anomalous quantities, as well as iron-formation.

Most rocks are medium-grained and weakly to moderately laminated. All types fall into fine- to coarse-grained category except very sporadic, rubbly-weathered schist that may represent metaconglomerate (Fig. 22A). Primary sedimentary features have not been noted. While most of the above-mentioned rocks have been observed in intercalated packages (also with rocks of **ms** and **a$_1$**), the succession does seem to have a bipartite stratigraphy, with some sections dominated by quartzite and others by siliceous schist.

Quartzite is mostly white to pale grey, both on fresh and weathered surfaces, but some rocks are pinkish. Less commonly, quartzite is greenish, even greenish black (see above), and some thin, more friable brown to rusty-weathering quartzites contain very thin seams of biotite ± hematite ± iron sulphides. Sporadic, very fine-grained, dark quartzite may be a metachert. Most quartzites contain more than 75–90% completely recrystallised quartz, and there are gradations into rather massive, almost monomineralic coarse-grained quartz rock with minor impurities. These are garnet, biotite, muscovite, sillimanite, feldspar and magnetite, which increase in amount in the gradations to siliceous schists, and the pelitic and iron-formation lithologies of **ms.** The quartzites vary from largely structureless to foliated and banded. On the nunataks west of Haffner Bjerge, rather dark, banded quartzites contain appreciable biotite and garnet, interlayered with much paler biotite-sillimanite quartzite and garnet amphibolite.

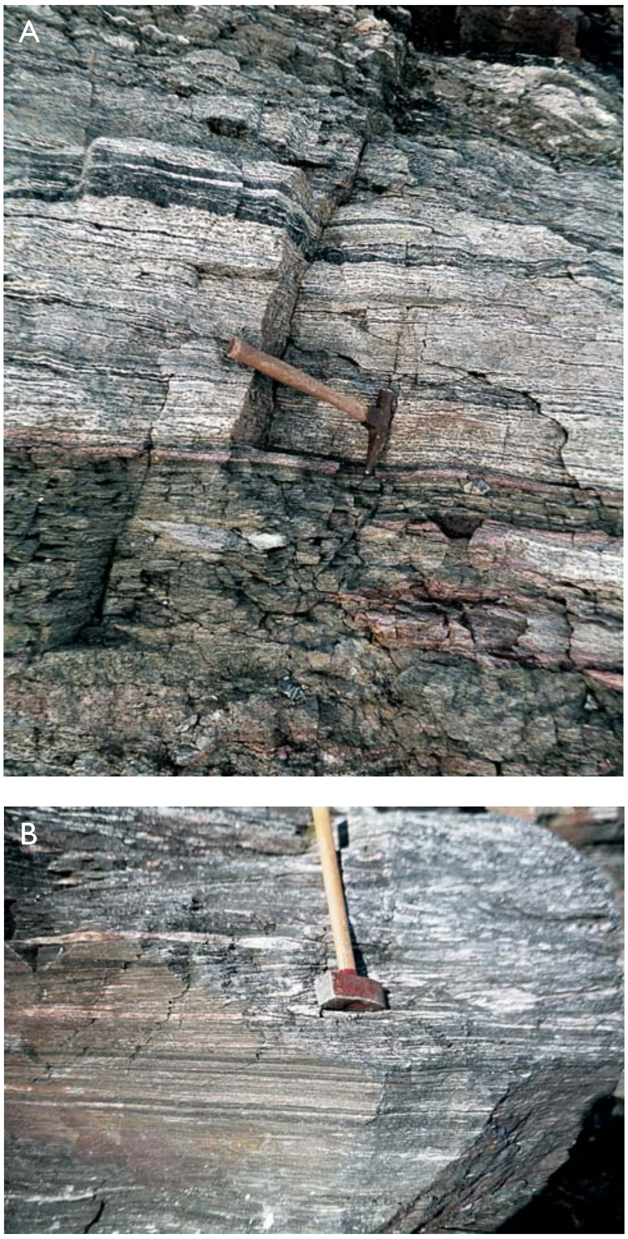


Fig. 22. Rocks of questionable origin. **A**: Rubbly rocks with quartz and quartzitic clasts (metaconglomerate?) in places with diopside and epidote, passing upwards into more feldspar-rich laminated rock (meta-arkose?). Associated leuco-amphibolites containing felsic clasts may represent metatuffs. Salve Ø. **B**: Severely deformed, isoclinally folded, laminated banded quartzite and leuco-amphibolite with stretched felsic clasts. A possible metatuff. Akuliarusersuaq, peninsula between De Dødes Fjord and Sidebriksfjord.

Siliceous schist packages have quartz-mica-feldspar schist and schistose gneiss as the main rock types in which quartz forms up to 75%. Both muscovite and biotite, and plagioclase and K-feldspar occur, as well as garnet, sillimanite, chlorite and hornblende. Many varieties occur, for example, quartz-muscovite (± chlorite) schist on nunataks east-north-east of Parker Snow Bugt (see also under **mg**), quartz-biotite-garnet schist, in places with abundant sphene, in the De Dødes Fjord area and quartz-sillimanite-mica schist west of Haff-

Fig. 23. Supracrustal amphibolites of map unit **a$_1$** showing alternating basaltic and leuco-amphibolite units with gradation on the left into a thicker felsic foliated granitoid. Coast east of Ulli, Wolstenholme Fjord, with thickness of section *c.* 100 m.

ner Bjerge. In the Sidebriksfjord area, for example on Salve Ø, outcrops of quartz-rich schist and quartzofeldspathic schistose gneiss are gradational with gneiss (**gn**). These outcrops are not large enough to be shown individually on the map but they are notable since they also display other uncommon lithologies. These include feldspar-rich units, rubbly quartz-rich schists, green to pinkish diopside-bearing calc-silicate rocks and grey schists that have a linear or rodded structure caused by concentrations of pale quartz-rich material. Two possibilities for the latter structure are quartz pebbles or volcanic clasts. Calc-silicate rocks are also known from several other localities, for example on Nuussuaq, as well as those within the metavolcanic sequence (see map unit **a$_1$**). Associated strata are leuco-amphibolite units that may represent intermediate to felsic metavolcanics (Fig. 22B).

The rocks of map unit **qt** are gradational with those of units **ms** and **gn**. Thus, in the De Dødes Fjord area where the main magnetite-bearing succession (**ms**) passes upwards into map unit **qt**, basal quartzites contain both disseminated iron oxide, as well as thin, lensoid, magnetite-rich layers. In parts of unit **qt,** iron-formation is thinly interlensed with quartzite and siliceous schist.

Amphibolite (**a$_1$**)

Outcrops of this map unit occur throughout the Lauge Koch Kyst from Duneira Bugt in the south-east to Wolstenholme Fjord in the north-west, being interfolded with other supracrustal rocks (**ms**, **qt**) and with gneiss. The main rock types are amphibolite *sensu lato* and magnetite-rich rocks including banded iron-formation. Subordinate ultramafic rocks are intergradational with the amphibolites. As described earlier, all these lithologies can also occur within map unit **ms**, just as biotite-rich metasedimentary schistose rocks can be intercalated in this map unit. Contacts with metasedimentary rocks are consistently conformable. Outcrop form varies from successions several hundred metres thick, as for example on the nunatak at Yngvar Nielsen Gletscher and in the fault-bounded block at Ulli, Wolstenholme Fjord, to thin layers, rafts and pods within gneisses. The rocks are variously migmatised and feldspathised with lit-par-lit veining, leucocratic sweats and K-feldspar porphyroblasts often producing gradation into veined and porphyroblastic tonalitic gneisses.

The majority of the metabasites are melanocratic hornblende-plagioclase rocks, often with biotite and garnet, although gradations into pyribolite occur. They vary from being dark grey and greenish grey to black; weathered surfaces are often stained rusty brown (see Fig. 46). There is a gradation into mesocratic leuco-amphibolites that vary from pale green to grey dioritic types and less frequently into more felsic rocks in which hornblende ± biotite form seams and thin layers. Successions range from dark and fairly homogeneous and composed mainly of mafic rock to distinctly banded when consisting of different mafic to felsic lithologies (Fig. 23).

The metabasites vary from equigranular, rather massive rocks to more common foliated and schistose varieties. Thicker units in many places preserve compositional layering on a mm- to cm-scale that is caused mainly by variation in the hornblende–plagioclase ratio, but also by the presence of other minerals, for example, epidote, diopside, calcite and actinolite. Such

Fig. 24. Metavolcanic succession of garnet amphibolites within map unit $\mathbf{a}_1$ of the Lauge Koch Kyst supracrustal complex. North-eastern end of peninsula, south-east of Rink Gletscher. Hammer is *c.* 50 cm long.

rocks may show banding in shades of green, yellow and grey. Some calc-silicate-bearing amphibolite shows banding that can be very irregular and distinctly lensoid; elongate ellipsoid structures with dark rims may well represent highly deformed pillow lava. The compositional layering and these rimmed structures suggest a metavolcanic origin (Fig. 24).

Some rather more massive rocks seen in the Sidebriksfjord area are characterised by having scattered plagioclase phenocrysts up to 1 cm that can create a crude layering simulating magmatic layering. If so, this provides evidence that intrusive material is also present. In addition to these rocks, leuco-amphibolite, often associated with quartzitic metasediments, contain what appear to be severely deformed felsic clasts. This rock may represent metatuff of intermediate to felsic composition (Fig. 22B).

Some amphibolites contain anomalous magnetite that may be disseminated, concentrated in layers up to 1 cm thick or in veinlets (Fig. 25). Only one locality has been seen where there appears to be a gradation from magnetite-bearing amphibolite into iron-formation. This is at Sorte Fjeldvæg where, in a sequence of garnet amphibolite, iron-formation and porphyroblastic granite, one 2 m-thick unit within granite is composed of garnet amphibolite that passes upwards into a magnetite-quartz rock that contains biotite-garnet pods and layers.

Otherwise, iron-formation within map unit *Amphibolite* (*$\mathbf{a}_1$*) occurs in two main settings: (1) as layers several metres thick, characterised by abrupt borders to amphibolite (see Fig. 46) and (2) as inclusions and rafts within granitoids, such as the porphyroblastic granite at Sorte Fjeldvæg, that has invaded the amphibolite and iron-formation.

Ultramafic rocks (**u**) and Amphibolite (**a**)

Age. Presumably Archaean.

Literature. Davies *et al.* (1963), Fernald & Horowitz (1954, 1964), Dawes (1975), Dawes & Frisch (1981).

Distribution and composition. The map units **u** and **a** are described here together for three main reasons: (1) there is often gradation within the same body between meta-ultramafic rocks and metabasite and thus map unit designation can be arbitrary, (2) amphibolite bodies and layers contain ultramafic rocks as pods, and (3) the rocks of both units have the same outcrop form occurring as severely deformed bodies, layers, pods and lenses within gneissic and granitoid rocks of the Thule mixed-gneiss and the Melville Bugt orthogneiss complexes. Rocks of both ultramafic and mafic composition vary from largely massive, homo-

Fig. 25. Banded garnet-rich, pyroxene-bearing amphibolite with magnetite concentrated in the darker bands. Loose block below Sorte Fjeldvæg.

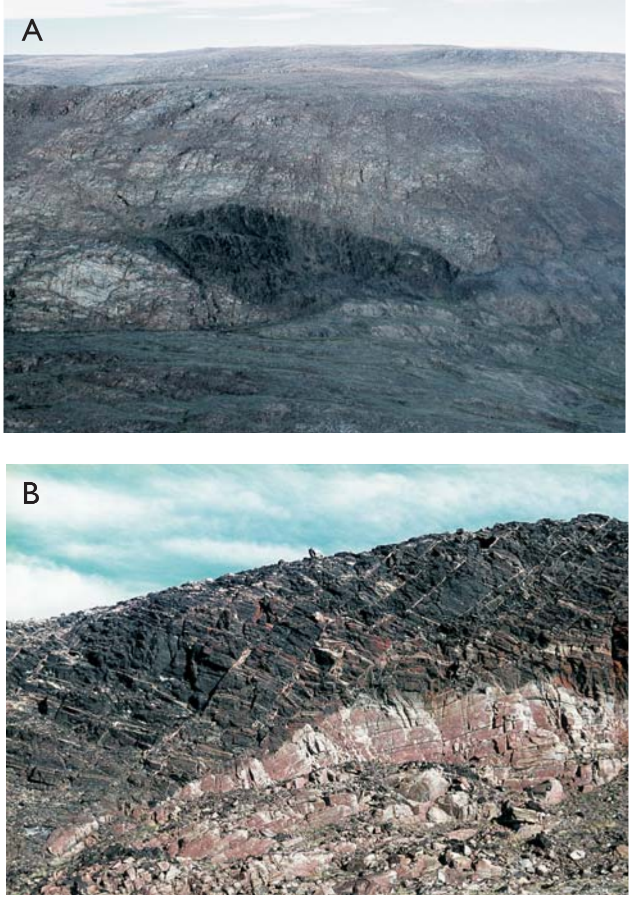


Fig. 26. Typical exposures of ultramafic and amphibolite rocks of map units **u** and **a** within the orthogneisses of the Thule mixed-gneiss complex. **A**: Ultramafic boudin estimated at 500 × 150 m, northern side of Academy Bugt at its head. Photo: Bjørn Thomassen. **B**: Amphibolite body (grades to hornblendite) showing well-developed schistosity cut by pale orthogneiss. Two generations of leucosome veining are present, the youngest of pinkish white pegmatite follows faults. Northern shore of Olrik Fjord, with height of section *c.* 30 m.

geneous rocks to foliated and schistose types; all are veined to varying degrees by leucocratic veins that penetrate the enveloping gneisses.

Rather than expand the legend of *both* the Thule mixed-gneiss and Melville Bugt orthogneiss complexes with two additional map colours to cover ultramafic and amphibolitic rocks, they are placed outside these complexes in the legend. Rocks of the same age almost certainly occur within the Lauge Koch Kyst supracrustal complex where the metavolcanic amphibolite-rich succession ($\mathbf{a}_1$) contains ultramafic components. The choice of placing rocks in map unit **a** and $\mathbf{a}_1$ is based on general aspect: those of metavolcanic aspect are placed in $\mathbf{a}_1$, other 'unspecified' types are placed in **a**.

Typical outcrops of ultramafic and amphibolite rocks are shown in Fig. 26. The large hornblendite boudin from Academy Bugt, the lower part of which is characterised by a anastomosing network of quartzofeldspathic veins, was discovered after the map compilation but two similar outcrops are shown just south of Olrik Fjord (Thomassen *et al.* 2002a, b; see under *Map revision*, section 1). The body featured in Fig. 26B with a strong schistose fabric and mapped as **a**, is also regarded as a large boudin. It shows subtle compositional layering, gradation from amphibolite to hornblendite and has two generations of quartzofeldspathic veins with preferred orientation.

Fresh rocks vary from dark grey to greenish grey and greenish black to black, often with dark brown weathering; amphibolites may show rusty weathering. Honeycomb weathering is common, and is seen, for example, in both bodies shown in Fig. 26. The rocks vary from very fine-grained to very coarse-grained; pegmatitic zones characterise some of the ultramafics. Amphibolite grades to pyribolite and both may contain biotite that occasionally is the main mafic mineral. Garnet occurs in both metamafites and ultramafites. The main ultramafites represent metamorphosed hornblendite, pyroxenite and peridotite, and varieties hereof.

The four examples given below serve to illustrate compositional range and replacement mineralogy. (1) Samples from the body south of Olrik Fjord (north of Tasersuaq lake) have equal amounts of black hornblende and brown hypersthene, with a lesser amount of olivine partially replaced by iddingsite, with pegmatitic aggregates of hornblende, augite, garnet and biotite; (2) olivine-bearing metapyroxenite is present is several bodies in the Nuussuaq area, Melville Bugt, (3) a peridotite body south-west of Rampen is composed mainly of actinolite, hornblende, olivine and hypersthene, and lesser amounts of iddingsite, tremolite and phlogopite (Fernald & Horowitz 1964) and (4) a variety of small altered hornblendite bodies between Parker Snow Bugt and Bylot Sund contain abundant penninite, anthophyllite, tremolite, actinolite and antigorite (Davies *et al.* 1963).

Many of the ultramafic rocks are serpentinised to varying degrees, with antigorite, chlorite, magnesite and talc as main replacement minerals. In the same region mentioned above in (4) and on Wolstenholme Ø, several occurrences of serpentine, described as "serpentinized dikes and plugs", are shown on the map of Davies *et al.* (1963, plate 1, p. 25). These are too small to be included on the Thule map sheet. One serpentine occurrence visited by the present author north-west of Freuchen Nunatak represents a sheared and altered ultramafic pod within gneiss, that contains talc-rich patches. Several serpentinised ultramafics have produced workable soapstone (see under *Handicraft and other raw materials*). The ultramafic rocks commonly contain abundant opaque minerals, of which magnetite is the most common, a mineral

Fig. 27. Discordant to subconcordant, metabasite bodies ($\mathbf{a}_2$) within pale orthogneisses of the Melville Bugt orthogneiss complex (**gn**). **d**, brownish-weathering post-$\mathbf{a}_2$ basic dyke of uncertain age. Western end of Tuttulissuup Tuttoqarfia, close to the front of Sverdrup Gletscher with recent lateral moraine flanking the shoreline. The snow-dusted peak with basic dyke is at *c*. 800 m a.s.l.

that also occurs in veinlet form. Chromite is reported by Fernald & Horowitz (1964) and Davies *et al.* (1963) in serpentinised rock.

Metadolerite, metagabbro, amphibolite ($\mathbf{a}_2$)

Age. The basic intrusions of this map unit cut the orthogneisses and related amphibolites of the Melville Bugt orthogneiss complex (‘older’ gneisses) and metasedimentary units of the Lauge Koch Kyst supracrustal complex. They have been correlated with the Kap York meta-igneous complex of Neoarchaean age (Dawes & Frisch 1981, table 1). This suggestion is based on the correlation of metabasites throughout the Lauge Koch Kyst linking them to the isotopically dated rocks of the Kap York peninsula (*c*. 2.7 Ga). Critical to this correlation are the metabasites on Fisher Øer that form the protolith of the ‘younger’ gneisses (see above under *Melville Bugt orthogneiss complex*). However, this long-range correlation (250 km) is far from proven and it is possible that the metabasites in the south-east around Duneira Bugt, that generally appear much less deformed than those farther west, are of younger age (?Palaeoproterozoic).

Literature. Dawes & Frisch (1981).

Distribution and composition. Metabasites placed in this map unit occur in two areas of the Lauge Koch Kyst more than 100 km apart: an isolated outcrop on Fisher Øer in the west (mentioned above) and in the south-east around Sverdrup Gletscher and Dietrichson Gletscher where the largest bodies occur. The outcrops represent dykes up to 10 m thick, concordant to subconcordant sheets tens of metres thick and laccolith-like masses that can be over l00 m thick (Fig. 27). Sharp intrusive contacts to the folded amphibolite-facies gneisses are preserved. The intrusions are themselves deformed and open folds produce curvilinear outcrops. Since the metabasites are generally more resistant than the host gneisses, a common outcrop form is as summit caps to mountains, such as on Fisher Øer and Tuttulipaluk.

Metamorphism has led to the varying replacement of pyroxene by hornblende producing a gradation from homogeneous and foliated metadolerite and metagabbro in which primary pyroxene can be preserved to hornblende-plagioclase rocks that may be massive, foliated or schistose. Biotite may be present in the amphibolites. Complete gradation from brownish, igneous-textured metadolerite to dark grey to black amphibolite and basic schists are preserved in the thicker bodies, often with the well-preserved textures in their centre. Where metagabbro forms hill summits as the central parts of eroded bodies, it may show weathering into a coarse gravel. Smaller bodies can be composed of amphibolite throughout, with any foliation or schistosity parallel to planar fabric of the enveloping gneiss.

Tonalite (tg)

Age. Previously classified as ‘?post-tectonic’ (Dawes 1976a), the rocks of this map unit post-date the regional foliation and banding of the gneisses of the Thule mixed-gneiss complex but have been subjected to some deformation. The rocks may be of similar age to the granitoids of the Heilprin Gletscher complex (**gf**), which also form small intrusions within the gneisses north of **tg** outcrops.

Literature. Fernald & Horowitz (1954, 1964), Dawes (1976a).

Distribution and composition. This map unit is represented by two outcrops flanking the Inland Ice in easternmost Steensby Land, an area with appreciable glacial debris and poor bedrock exposures. Typical frost-shattered, felsenmeer-dominated exposures, with well-jointed, spheroidal-weathered blocks are illustrated in Fernald & Horowitz (1954, plate 5). The exposures may represent the western parts of a larger intrusion, the main part of which is under the ice. Fernald & Horowitz (1964, p. 27) describe one outcrop on the largest nunatak in the glacier Rampen as a more or less circular stock "apparently surrounded by banded gneiss". On the Thule map, the entire nunatak is designated **tg**, the gneiss invaded by granite being regarded as xenoliths within a much more extensive body.

As mentioned under *Map revision* (section 3), the rock name 'tonalite' does not adequately cover the composition of the map unit. This identification of rather melanocratic hornblende-bearing rock pertains to a contaminated intrusive associated with xenoliths of gneiss with amphibolite bands. Grey- to pinkish-weathering, medium-grained granitoids seem to form the main part of the rock unit and these have textures varying from equigranular to directional with quartz being elongated parallel to any biotite foliation. Main types have both alkali feldspar and plagioclase and vary from granite and granodiorite. Some rocks are characterised by feldspar augen up to 2 cm long. Rocks described by Fernald & Horowitz (1964) from Rampen are leucocratic, composed of microcline and quartz with only minor amounts of oligoclase and biotite; hornblende and biotite characterise mesocratic rocks from more northern outcrops.

Minor mafic intrusions (including youngest **ad** dykes)

Age. Metamorphosed mafic intrusions or so-called 'discordant amphibolites', mostly too small to show on the map sheet, have been noted within five complexes: the Thule mixed-gneiss, Smithson Bjerge, Kap York meta-igneous, Melville Bugt orthogneiss and Prudhoe Land supracrustal complexes (Figs 2, 6, 9, 12, 16, 20; also Dawes 1976b, fig. 227; Dawes & Frisch 1981, fig. 6). The dykes relate to several chronological periods. Archaean complexes certainly contain Archaean metamafite bodies but some could represent much younger intrusions perhaps correlatable with the Palaeoproterozoic subconcordant garnet amphibolite/pyribolite sheets within the Prudhoe Land supracrustal complex. Many discordant amphibolites within the Thule mixed-gneiss complex, for example those between Bylot Sund and Parker Snow Bugt, cut the gneiss fabric and associated leucosome veins but are themselves invaded by felsic veins. Some are broken up and invaded by late orthogneiss phases. These bodies are Archaean in age and some are probably coeval with the dykes emplaced into partially crystallised rocks of the Smithson Bjerge magmatic association and Kap York meta-igneous complex (see earlier under *Amphibolite dykes (**ad**)*). Younger, less-deformed bodies may correlate with the intrusions known from the Lauge Koch Kyst, some of which are large enough to be shown on the map sheet (see under *Metadolerite, metagabbro, amphibolite (**a$_2$**)*). The widespread Archaean discordant amphibolites within the Melville Bugt orthogneiss complex are invaluable in determining the age relationships of rock units (Fig. 6; see under *Relationships of the complexes*, section 5).

The only isotopic ages available are K-Ar mineral dates of 1852 ± 48 and 1610 ± 46 Ma, respectively, on hornblende and biotite from a 30–40 m thick, garnet-biotite pyribolite dyke (designated **ad** on the map) cutting the Qaqujârssuaq anorthosite. These ages pertain to recrystallisation events in the Palaeoproterozoic reactivation and cooling of the region (Larsen & Dawes 1974).

Literature. Dawes (1975, 1976b), Nutman (1979, 1984), Dawes & Frisch (1981).

Character. Metamorphosed mafic dykes and sheets display a variety of forms depending on the nature of the country rocks at the time of emplacement and on the intensity of the ductile deformation imposed on them. Many dykes have been rotated so that they now appear concordant to the main foliation or planar fabric of the host rocks although local discordancies are preserved (Fig. 16). They vary from tabular to highly sinuous and folded bodies. Contacts are sharp to diffuse. Most are discontinuous and can only be traced over a few metres; transitions from coherent bodies into fragment chains are common (Fig. 21). The discordant nature of some layers can only be established in large rock exposures where the direction of fragment chains can be defined (Fig. 6). Depending on age and host rock, the bodies are variously invaded by leucocratic material. All are cut by the minor felsic intrusions described in the following section.

The rocks vary from melanocratic amphibolite and pyribolite to mesocratic diorite; both varieties may contain garnet. A chemical analysis of a garnet amphibolite from Smithson Bjerge is of iron-rich quartz tholeiitic affinity (Nutman 1984, table 4). Most dykes are composed of foliated rock but smaller dykes may be schistose; larger dykes such as the garnet amphibolite/pyribolite bodies on Smithson Bjerge, may have homogeneous centres but schistose borders (Nutman 1984, fig. 14).

Dykes are generally less than 5 m thick and most are in the range 1–3 m. In the Kap Seddon area several reach 10–15 m thick and notably thicker discordant amphibolites occur on Smithson Bjerge with individual dykes up to 40 m thick. One of these dykes, traceable for 12 km from the central ice cap to the coast and shown on the map, represents the most persistent discordant amphibolite of the region. This and other dykes of the swarm are grouped together with older dykes and designated **ad.** Another persistent body is a deformed sheet within paragneisses and associated rocks on the nunatak north of Tracy Gletscher. This sheet has not been examined but from the air it appears deformed (?variable thickness) and cut by pale sheets and pegmatites. It may be a correlative of the garnet-amphibolite/pyribolite **ad** dykes on Smithson Bjerge and the sheets of similar composition within the Prudhoe Land supracrustal rocks mentioned above under *Age*.

Minor felsic intrusions (not shown on the map)

Age. All seven complexes composing the shield contain minor granitic intrusions emplaced into the host rocks after ductile deformation. Within the Thule mixed-gneiss complex and the younger Prudhoe Land supracrustal complex – two complexes involved in a basement–cover relationship – felsic intrusions vary in form and intensity and demonstrate that felsic intrusions can be referred at least to two chonological periods: Neoarchaean and Palaeoproterozoic (see under *Relationships of the complexes*, section 6).

Literature. Davies (1954), Fernald & Horowitz (1964), Dawes (1975, 1976b), Nutman (1979, 1984).

Character. Minor granitic intrusions vary from irregular masses to tabular bodies, the latter varying from veins just centimetres wide to sheets and dykes several metres thick. Dykes of 'granitic pegmatite' up to 6 m thick are present on Nunatarsuaq (Fernald & Horowitz 1964). Irregular bodies of pale granite and pegmatite can be several hundred metres across, for example the pegmatite recorded by Davies (1954) on the west side of Pingorsuit. Since the region has been subjected to Palaeoproterozoic orogenesis, the intrusions as a whole show a range of deformational and recrystallisation features. Archaean intrusions are variously deformed – sinuous to folded and pinch-and-swell to fragmented – whereas the intrusions that post-date the late Palaeoproterozoic ductile deformation are undeformed linear veins, dykes and sheets. These cut all rock lithologies including the *Minor mafic intrusions* described above. Locally, undeformed dykes show preferred strike directions: for example, on Smithson Bjerge many microgranite and pegmatite dykes have a N–S trend (Nutman 1984).

Fig. 28. Minor granitic intrusions are common in the Thule mixed-gneiss complex (see Fig. 2). Xenoliths of grey veined gneiss within a homogeneous, more leucocratic grey granite, cut by an irregular pegmatite and a younger dilatational aplitic sheet. The aplitic sheet, *c.* 25 cm thick, has pegmatitic borders. South coast of Hvalsund.

Granitic rocks range in grain size from aplites, to medium-grained granite and to pegmatites. The Thule mixed-gneiss complex commonly hosts a variety of veins and sheets varying from subconcordant to distinctly cross-cutting (Fig. 2). Present also in these well-exposed rocks along Hvalsund are irregular masses of granite that pre-date the more tabular pegmatite/aplite sheets; aplites can have pegmatitic margins (Fig. 28). Most pegmatites are homogeneous, some dykes and sheets are composite with aplitic or quartz-rich cores (Fernald & Horowitz 1964, figs 8–10). Most felsic intrusions are white to buff in colour but in the Inglefield Bredning area, undeformed late aplitic sheets and dykes that post-date some pegmatites, are distinctly pinkish. Similar pink granitic rocks are known from Bushnan Ø. Apart from quartz, plagioclase and K-feldspar, the main accessories are biotite, muscovite, magnetite, allanite, tourmaline, sphene and apatite. Biotite often forms a thin sheath lining margins of pegmatite dykes. Veins and dykes of essentially quartz also occur and these reach a width of 2 m on Smithson Bjerge (Nutman 1984). Muscovite is conspicuous in some quartz veins so that the rocks are essentially esmeraldites (Fernald & Horowitz 1964).

Palaeoproterozoic

The northernmost shield outcrops are of Palaeoproterozoic age belonging to two complexes: a supracrustal succession that forms a cover to the Thule mixed-gneiss complex and a supposed younger orthogneiss suite (see *Relationships of the complexes*, section 8). Both complexes extend beyond the map sheet to the north and are named after Prudhoe Land, their outcrop area. As explained in the Introduction, the term Palaeoproterozoic replaces the *Early–Middle Proterozoic (Aphebian)* heading of the map legend.

Prudhoe Land supracrustal complex

Age. SHRIMP U-Pb zircon dating has been carried out on two metasedimentary samples from northern Morris Jesup Gletscher (Nutman *et al.* 2004). A pale, mature quartzite contains Mesoarchaean, Neoarchaean and Palaeoproterozoic detrital zircons with an age spectrum of 3200–2250 Ma whereas an intercalated garnet-mica-sillimanite schist that lacks datable detrital zircons has yielded an age of 1923 ± 8 Ma. This latter age is interpreted as dating zircon growth during high-grade metamorphism. Deposition of the sediments thus occurred between *c.* 2250 and 1920 Ma. The most reliable K-Ar mineral age from the succession at Qattarsuit, Inglefield Bredning is 1881 ± 84 Ma on hornblende from garnet amphibolite while the ages on muscovite and biotite from garnet-mica-sillimanite schists are some 200 million years younger (Larsen & Dawes 1974). The hornblende age corresponds well with the SHRIMP age for a main recrystallisation event (see under *Prudhoe Land granulite complex*).

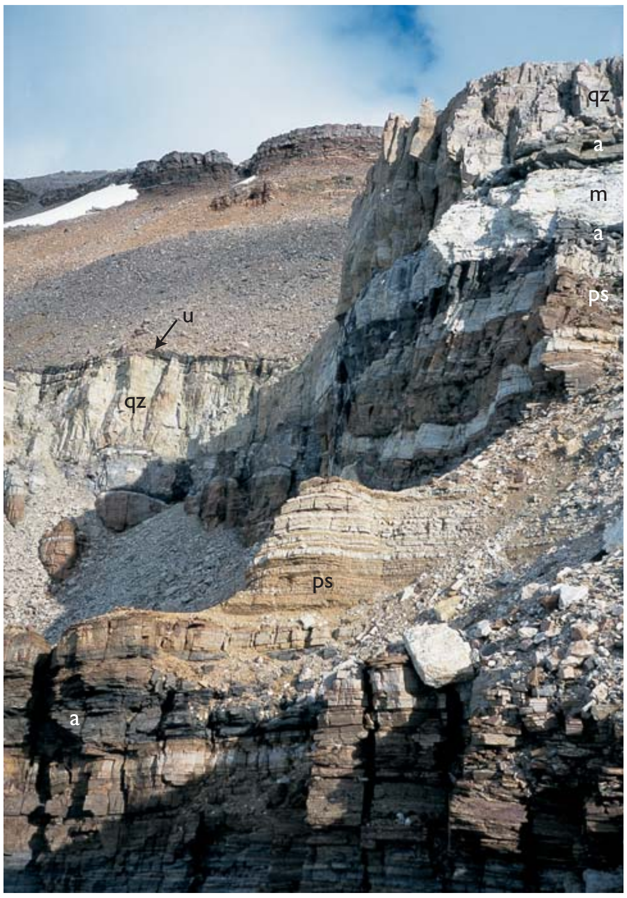


Fig. 29. Section showing main lithologies of the Prudhoe Land supracrustal complex north of Morris Jesup Gletscher. **a**, amphibolite/pyribolite; **m**, marble; **ps**, rusty paragneiss and schist with intercalated pale quartzitic layers; **qz**, quartzite; **u**, ultramafic rock. Height of the section on the right is *c.* 50 m. Photo: Bjørn Thomassen.

Literature. Dawes (1972, 1976b, 1979, 2004), Steenfelt *et al.* (2002), Thomassen *et al.* (2002a, b), Nutman *et al.* (2004).

Boundaries. Thule mixed-gneiss complex and Prudhoe Land granulite complex (see *Relationships of the complexes*, sections 6, 8)

Distribution, composition and metamorphism. Outcrops are shown on the map in two areas of Prudhoe Land: in the west on the northern side of Morris Jesup Gletscher and in the east between Bowdoin Fjord and Josephine Peary Ø. The western occurrences were previously referred to as the *Morris Jesup Gletscher supracrustals* (Dawes 1979). As explained under *Map revision* (section 4), other outcrops large enough to be shown on the map are now known, including tightly folded packages on the southern side of Morris Jesup Gletscher (Thomassen *et al.* 2002a, fig. 1). In reality, supracrustal rocks occur throughout Prudhoe Land interfolded with gneisses of the Thule mixed-gneiss complex and Prudhoe Land granulite complex. The thickest succession – at least 800 m, and possibly over 1000 m thick – is preserved in the east at Qattarsuit. This is the post-tectonic thickness that certainly represents a repeated sequence due to isoclinal folding and one undoubtedly thinned by extension. Outcrops vary from the coherent successions in the two main outcrop areas, to isolated thinner packages and to discontinuous layers and inclusions within orthogneisses.

The succession consists of schistose to gneissic pelitic, semipelitic and quartzitic rocks, with intercalated mafic rocks (Fig. 29). Marble and ultramafic rocks are subordinate (see under *Map revision*, section 5). The supracrustal rocks are readily identified by their brown- to rusty-weathering, recessive nature although the quartzitic and mafic rocks tend to form resistant benches. Rusty colour can be intense and parts of the succession in the east are characterised by a deep orange to reddish brown colour derived from iron sulphides (Thomassen *et al.* 2002b, fig. 13). Hypersthene, common in mafic rocks but less abundant in the metasedimentary rocks, indicates that the supracrustal succession has been metamorphosed under granulite-facies conditions, probably around 1900 Ma (see above under *Age*). There are clear signs of retrogression under amphibolite facies with partial to complete replacement of hypersthene, hornblende and garnet, the timing of which is unknown.

The sediment precursors represent a varied shallow-water sequence formed of detritus eroded from continental crust. The quartzites (**qz**) represent mature sediments deposited in a near-shore environment, the pelitic rocks (**ps**) might well be littoral to deltaic sediments while the subordinate marbles are indicative of sporadic carbonate deposition typical of the inner part of a shallow continental shelf. The geochemical characteristics of the pelitic rocks – enrichment in Hf, Th, U, REE, TiO_2 and Cr – suggest that they contain appreciable heavy minerals, as would be expected from erosion of acidic to mafic rocks, such as compose the Thule mixed-gneiss complex (Steenfelt *et al.* 2002).

Mafic rocks (**a, p**)

As indicated on the map, mafic rocks form discrete layers within the metasedimentary succession. These are concordant to the host rocks and vary from tabular bodies to interfingering layers within other rocks, to discontinuous and boudinaged layers and lenses. Most contain both hypersthene and amphibole (± biotite) but in varying ratios thus leading to the two units shown: amphibolite (**a**) in which hornblende is the predominant mafic mineral and pyribolite (**p**) that contains both in roughly equal amounts. Also present are pyriclasites, in which hornblende is a subordinate mineral, and enderbitic rocks in which quartz is an important constituent (Dawes 1979).

Garnet is often present and occasionally forms over 50% of the rock. Such is the case in rather massive amphibolites in the succession at Qattarsuit which are peppered with garnets approaching 1 cm in diameter. Although some discrete units are characterised by massive rocks, most show a fabric that varies from a mineral foliation to lamination and fine layering. Mafic schists occur and in these garnets may be flattened in the schistosity. Intense leucocratic veining has locally produced gneissic varieties. A malachite-stained amphibolite-dominated succession is illustrated in Thomassen & Krebs (2004, frontispiece).

Quartzite (**qz**)

Pale-weathering, buff, pink to brownish quartzitic rocks, including grey, white and often bluish, massive quartz rock, form a substantial part of the succession. Siliceous mica schists also occur. Most commonly, the quartzitic rocks occur as thin layers intercalated with pelitic and semipelitic rocks (**ps**) but individual units may be over a hundred metres thick. At the other end of the outcrop scale, quartzitic and quartz rocks form discontinuous layers and inclusions within orthogneiss. Depending on location the quartzites show varying internal appearance. In pockets of low strain, primary sedimentary features such as lenticular bedding is preserved, often with thin, interfingering layers and seams of siliceous sillimanite-mica schists (Fig. 30A). Elsewhere contorted folds conspicuously visible in pelitic seams leave no doubt about the intensity of deformation that has affected the rocks (Fig. 30B; Thomassen *et al.* 2002b, fig. 17). Such rocks are rather massive with extensive recrystallisation of quartz, often with secondary muscovite.

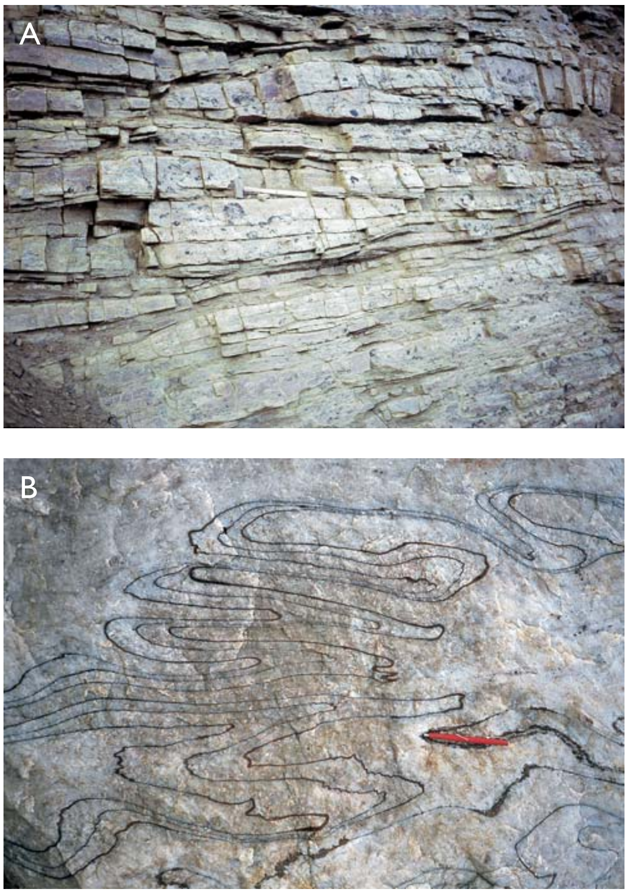


Fig. 30. Varying deformational state of quartz-rich rocks of the Prudhoe Land supracrustal complex. **A**: Lenticular-bedded garnet quartzites intercalated with thin siliceous sillimanite schist layers. Qattarsuit, Inglefield Bredning. Hammer *c.* 45 cm long. **B**: Bluish grey, impure quartz rocks showing highly distorted pelitic seams. North-west of Morris Jesup Gletscher. Pen is 12 cm long. Photo: Bjørn Thomassen.

The quartzites commonly contain garnet that may be crudely aligned parallel to a weak schistosity formed by muscovite and biotite. Apart from these minerals and quartz, other constituents are sillimanite, orthopyroxene, magnetite and feldspar.

Quartz rocks, similar to those shown in Fig. 30B, are known beyond Prudhoe Land in south central Inglefield Land where they are associated with paragneiss and ultramafic rocks (Dawes 2004, p. 18).

Fig. 31. Biotite-graphite-garnet schist with highly distorted, quartzofeldspathic leucosome veins. Prudhoe Land supracrustal complex, east coast of Bowdoin Fjord.

Pelitic and semipelitic schists (**ps**)

The prominent rocks of this map unit are rusty-weathering pelitic schists and schistose gneisses and semipelitic paragneisses. There is a gradation through subordinate, paler quartzofeldspathic paragneiss to the quartz-rich rocks of unit **qz**. The thickest units, several hundred metres thick, occur in the exposures east of Bowdoin Fjord, but more commonly the rocks form units tens of metres thick intercalated with other supracrustal lithologies (Fig. 29). The rocks show compositional banding on a cm- to 10 cm-scale seen as changes in brownish yellow and grey colours, mainly due to variable quartz content. Dark pelitic schists containing little or no quartz but flecked by feldspar are common in the succession at Bowdoin Gletscher. Most contain a leucosome component varying from isolated veins and stringers to rocks composed of more than 50% vein material (Fig. 31; cf. with Thomassen *et al.* 2002b, fig. 14). This takes the form of sinuous veins, frequently with pinch-and-swell structure, that are commonly folded and highly disrupted. Quartz veins and pods also occur.

All lithologies are garnet-bearing and many contain sillimanite. Pelitic rocks are biotite-rich, and particularly in eastern outcrops, they are pyritic and graphitic (see Fig. 34). Many sulphidic schists are friable and difficult to sample. Schists can contain up to 20% disseminated graphite and 15% pyrite in the form of mm-thick layers and veins. Pyrite also occurs in leucosome indicating remobilisation during a hydrothermal overprint (Thomassen *et al.* 2002b, figs 15, 16).

The characteristic rusty-weathering nature of the map unit, with vivid red, orange and yellow colours, is apparently due to a combination of oxidation of iron suphides and argillite alteration.

Marble (not in map legend)

Layers of marble and calc-silicate rocks occur in the succession at Morris Jesup Gletscher (Fig. 29) but only one other outcrop has been sampled. This is a poorly exposed steeply dipping, northerly trending layer within pelitic schists to the east of Bowdoin Fjord just east of an outlier of Thule strata. Other small, pale-weathering outcrops seen from the air within the poorly exposed supracrustral succession in the same area and northwards towards Sugarloaf, may also be marble (see under *Map revision*, section 5).

The main rock type seen is a white, calcite-rich, medium-grained marble, often with green diopside-rich streaks, which locally grades into buff to greenish, finely banded calc-silicate rocks.

Prudhoe Land granulite complex (**grn, grg**)

Age. The *c.* 2000 Ma age cited on the map sheet for this complex has been refined by SHRIMP U-Pb zircon dating of three hypersthene orthogneisses: one within the map sheet from Morris Jesup Gletscher and two just north of the map at Sonntag Bugt (Fig.1; Nutman *et al.* 2004). At least two ages of igneous zircons – *c.* 2400 and 2250 Ma – are present in the sample from Morris Jesup Gletscher which is a grey gneiss with thin pyribolite bands. The gneiss is clearly polyphase and it is tempting to correlate the ages with the macroscopic components of the gneiss. It is noteworthy that a similar ‘grey banded granulite gneiss’ from Verhoeff Gletscher has given a Sm-Nd model age of 2570 Ma (see under *Isotopic ages* and *Relationships of the complexes*, section 7). The two Sonntag Bugt samples are rather massive foliated granulites and repre-

Fig. 32. Typical cliff exposures of the Prudhoe Land granulite complex, showing interleaved packages of gneisses of varying composition, including massive granulites forming the highest summit, and more melanocratic units with amphibolitic/pyribolitic rocks. Eastern side of Sun Gletscher, with relief *c.* 600 m.

sentative of much of the complex (for terminology, see below). An age of 1984 ± 8 Ma is taken to be close to the age of the igneous protolith with a younger age of 1886 ± 25 Ma marking a main recrystallisation event (Dawes 2004; Nutman *et al.* 2004). From this it can be concluded that within the areas marked **grn** and **grg** on the map, there exist several Palaeoproterozoic igneous components, as well as possible Neoarchaean material. These mixed orthogneisses could have formed the basement on which the Prudhoe Land supracrustal rocks were deposited, after which the main protolith to the Prudhoe Land granulite complex was emplaced around 1980 Ma. However, since the precise age of the supracrustal succcession is unknown being bracketed by SHRIMP ages *c.* 2250 and 1920 Ma, all the granulite gneisses may have formed the basement.

Literature. Dawes (1979, 1988a, 2004), Steenfelt *et al.* (2002), Nutman *et al.* (2004).

Boundaries. Thule mixed-gneiss complex and Prudhoe Land supracrustal complex (see *Relationships of the complexes*, sections 7, 8)

Distribution, composition and metamorphism. The Prudhoe Land granulite complex stretches beyond the map region to north of Sonntag Bugt where it is lost beneath the Inland Ice (Dawes & Garde 2004). The term 'granulite' is used in a metamorphic and lithological sense. It covers the main rock types that have granulite-facies mineralogy with ubiquitous hypersthene and a rather massive appearance, being characterised by a granular texture and a foliated to weak gneissic fabric. The gneissosity is mainly due to foliation of mafic minerals and the parallel alignment of elongated concentrations of quartz and feldspar. Quartz typically has a bluish colour and some rocks contain garnet. Characteristic granulites of this complex were first seen by the present author at Sonntag Bugt where the rocks form a flat-lying to shallow-dipping succession of brown-weathering, homogeneous to strongly foliated orthogneisses that on fresh surfaces are typically grey to greenish grey or mauve.

The rocks are cliff-forming and intercalated with packages of rusty paragneisses of the Prudhoe Land supracrustal complex (Dawes 2004, fig. 7). Similar rocks and structures characterise the shield in the area between Morris Jesup Gletscher and Tuttu Gletscher where the gneisses are composed of units of varying composition including mafic rocks (Fig. 32). This is seen both as cm-scale banding due to mafic components (mainly pyribolite), as well thick packages of gneisses of varying lithology. All these rocks are included in map unit **grn** while an area of hypersthene granite, homogeneous to weakly foliated, on nunataks to the north of Verhoeff Gletscher, is separated out as **grg**. From isotopic age determinations, it is now known that at least some of the banded orthogneisses at Morris Jesup Gletscher and Verhoeff Gletscher are older than the massive granulites.

The protolith to the massive granulites emplaced around 1980 Ma is thought to have been a suite of intermediate to felsic igneous rocks. Stream-sediment geochemistry over map unit **grn** shows high Sr, Ba and P suggesting quartz dioritic, monzonitic and syenitic compositions comparable with those of the Etah meta-igneous complex of Inglefield Land (Steenfelt *et al.* 2002).

Mesoproterozoic–?Neoproterozoic Thule Basin

The Thule Basin overlies the eroded Canadian-Greenland shield and straddles northern Baffin Bay and Smith Sound (Fig. 1). The basin is defined by an unmetamorphosed sedimentary-volcanic succession – the Thule Supergroup – that is at least 6 km thick. The Thule map sheet covers the eastern and south-eastern parts of the basin, with the central part being predominantly offshore but represented in Greenland by the thick section on Northumberland Ø (see Dawes 1997, figs 12, 119). The northern margin is defined by outcrops on both sides of Smith Sound and the western and south-western margins of the basin are in coastal Ellesmere Island. These outcrops are featured on the maps of Frisch (1983, 1984a, b) and Dawes & Garde (2004).

As mentioned in the *Introduction*, the reader is referred to a monograph for a full treatment of Thule Basin lithostratigraphy (Dawes 1997). This contains 20 geological maps showing the distribution of the stratal units, 12 of which feature areas within the map region.

Age of the Thule Supergroup

In the map legend the Thule Supergroup is designated a *Late Proterozoic (Neohelikian–Hadrynian)* age, or in present terminology, *middle Mesoproterozoic – late Neoproterozoic*. This is based on both radiometric dating of basic sills and dykes, and on biostratigraphic ages of microfossils (acritarchs) from the upper part of the succession that inferred a latest Proterozoic (Vendian) age (Vidal & Dawes 1980; Dawes & Vidal 1985). Regional unconformities have not been recognised although, as discussed below, the boundary between the upper groups (Dundas and Narssârssuk Groups) is unexposed. Nevertheless, despite the somewhat problematic scenario of having an exceptionally long period of sedimentation – 500 million years from the middle Mesoproterozoic to late Neoproterozoic – the age was anchored in what were considered diagnostic Vendian (Sinian) acritarch identifications from the Dundas and Narssârssuk Groups.

The age of the microfossil assemblage is now regarded to be of *late Mesoproterozoic and/or early Neoproterozoic* age (Fig. 4; Samuelsson *et al.* 1999). The correlation between the Thule succession and those of other Proterozoic basins in Canada – specifically the Mesoproterozoic Bylot Supergroup of the Borden Basin of Baffin Island – suggests that the entire Thule Supergroup could have been deposited in Mesoproterozoic (Ectasian) time, *c.* 1300 to 1200 Ma (Knight & Jackson 1994; Jackson 2000). Since there is nothing in the make-up of the Thule Basin that conclusively militates against this restricted evolution, it is certainly one possibility. However, a *categorical* Mesoproterozoic age is not adopted for two reasons: (1) the microfossil assemblage is not specifically age-diagnostic, i.e. Mesoproterozoic *or* Neoproterozoic (Strother *et al.* 1983; Hofmann & Jackson 1996; Samuelsson *et al.* 1999) and (2) Mesoproterozoic *and* Neoproterozoic successions do occur in Greenland farther east in the Kronprins Christian Land region (Fig. 1; Henriksen *et al.* 2000).

The *Mesoproterozoic–?Neoproterozoic* age is based on the following relationships. Stratigraphically, the Thule Supergroup is bracketed by the Palaeoproterozoic shield and Lower Cambrian (Atdabanian) strata of the Franklinian Basin that crop out just beyond the map region (Fig. 1; see Dawes 1997, figs 8, 14; Dawes 2004, figs 11, 13). Tighter constraints are provided by two periods of basic dykes that date sedimentation to between *c.* 1300 and 730 Ma. The oldest dykes (designated $\mathbf{d}_1$) cut the shield but not the Thule Basin whereas the younger dykes (designated $\mathbf{d}_2$) cut the entire Thule succession. The $\mathbf{d}_1$ and $\mathbf{d}_2$ dykes have yielded K-Ar whole-rock ages between *c.* 1670–1310 Ma and *c.* 730–630 Ma, respectively (see under *Palaeo-, Meso- and Neoproterozoic basic intrusions,* Table 1; Dawes *et al.* 1982b; Dawes & Rex 1986).

The youngest pre-Thule Basin age has a large error (1313 ± 39 Ma) and the most reliable isotopic age of relevance to the onset of sedimentation history is an U-Pb age of *c.* 1270 Ma on a sill indicating that the lowermost Thule strata are at least middle Mesoproterozoic (Ectasian; LeCheminant & Heaman 1991; see below under *Nares Strait Group*). However, the age of the upper strata (Baffin Bay, Dundas and Narssârssuk Groups) is poorly constrained radiometrically, viz. the strata pre-date the late Neoproterozoic $\mathbf{d}_2$ dykes, and the acritarchs of these groups, as mentioned above, suggest a late Mesoproterozoic *and/or* early Neoproterozoic age.

Structure and metamorphism

The Thule Basin is a intracratonic fracture basin characterised by block faulting and basin sagging, the product of a divergent plate regime. Its central fill is defined by the lower Thule Supergroup (Nares Strait Group) that thins to the north, east and south-east

Fig. 33. Severe bleaching of ferruginous sandstone showing relict redbeds. **Arrows** point to a late generation of reduction spots. Northumberland Formation, *c.* 10 m above the crystalline shield. East of Parish Gletscher, Northumberland Ø. A slab from similar bleached redbeds is shown in Fig. 51.

from Northumberland Ø. The limit of the basin is defined by the Baffin Bay Group that oversteps the Nares Strait Group to overlie the shield in the east and south. The margin on the map stretches from De Dødes Fjord in the south to the semi-nunatak Nunatarsuaq at the head of Inglefield Bredning, across Inglefield Bredning and Hubbard Gletscher, and north to the nunatak terrain in Prudhoe Land at the heads of McCormick and Robertson Fjords. Outliers beyond this – too small to show on the map – range from a coherent sandstone and conglomerate veneer into diffuse areas of rubble with concentrations of quartz pebbles.

Thule strata form predominantly homoclinal, shallow-dipping sections, with anomalous inclinations caused by block faulting, tilting, drag folding and regional flexuring. The rocks have not been regionally metamorphosed but they are indurated and locally altered. Quartz impregnation has taken place at certain levels and such rocks appear as sugary quartzites. Apart from crushing along faults with gouge formation, the main types of alteration seen in the sediments are contact metamorphic effects and chemical changes, for example baking of argillaceous lithologies and bleaching of redbeds, occur adjacent to basic intrusions. Bleaching along basic dykes is well illustrated in the Imilik Formation just south of Pituffik (see Fig. 39) while contact metamorphic effects are common in the Steensby Land sill complex (see under *Neoproterozoic sills* (***s***$_1$)). Shales adjacent to sills can be slaty, greenish and chloritised, with a slight waxy sheen and in which mica is sericitised. Pyritisation also occurs (see under *Economic geology*, section *Iron-sulphide mineralisation* (***py***)).

Chemical action by solutions has been widespread and is seen by ferruginous banding and colour alteration in redbeds. Ferruginous banding in sandstone occurs on all scales from fine lamination parallel and sub-parallel to bedding, to discordant liesegang rings of several generations. Where just of one generation and regular in form, liesegang rings can readily be mistaken for bedding; where two generations occur at a low angle to each other, the pattern resembles cross-bedding (see Fig. 52; Fernald & Horowitz 1964, figs 13, 14). Swirl-forms occur, some of which can simulate folding. Dark brown, highly ferruginous veins up to 1 cm thick are associated with liesegang rings. The most intense ferruginous banding occurs in red to purple quartz arenites in strata not far removed from shield outcrops suggesting that the unconformity, as well as faults, have aided the diffusion of iron-rich solutions. Kurtz & Wales (1951) mention diffusion banding in sandstone associated with solutions derived from a basic dyke, as well as alteration of a 1 m thick dolomite bed with pyrite adjacent to a basic sill.

Bleaching and reduction phenomena in redbeds are common, with the effects well seen along bedding planes, joints and fissures. At bed scale, effects vary from fish-eye spots and irregular bleach patterns, to pale, almost fully transformed beds identified by relict patches of initial red colour (Fig. 33, see also Fig. 51). On a larger scale, such as in the sea cliffs on the northern side of Hakluyt Ø, purple sandstone tens of metres thick may pass along strike into an interfingering network of dark and pale beds, and finally into pale, sandstones in which purple colour has been eliminated. Strong reduction patterns have been recorded particularly in basal strata, both in the central basin (e.g. Northumberland Ø) and in basin margins (e.g. Wolstenholme Ø), suggesting that the unconformity acted as a passageway for the reducing solutions.

Nature of the unconformity

The shield below the Thule Basin forms a regional peneplain (see *Erosion surfaces* under *Physiography*). The actual unconformity is invariably a recessive zone and often scree-covered but where examined, it is generally well preserved. Locally, the contact may be tectonised with minor faults, shearing and cataclastic effects in strata both above and below the hiatus. The palaeosurface is planar to slightly undulating with relief generally below 2 m. Palaeovalleys and topographic highs have not been unequivocally identified although several areas with locally dipping beds that do not seem to be related to faulting, may represent drapes over more pronounced relief.

A regionally consistent regolith cover has not been identified and in some localities the underlying crystalline rocks appear remarkably fresh. However, in most areas the rocks on either side of the unconformity show alteration and anomalous colour, often due to hematite impregnation. Gneiss and granitic rocks may be reddened, slightly to moderately weathered, with hematite as seams along joint surfaces and as veins up to 3 cm as joint infillings. With a high intensity of joints, red staining may be over a metre deep. 'Softer' supracrustal rocks, such as pelitic schists of the Prudhoe Land supracrustal complex, are typically more severely weathered, and often there is a paler zone of variably friable and sericitised rocks (Fig. 34).

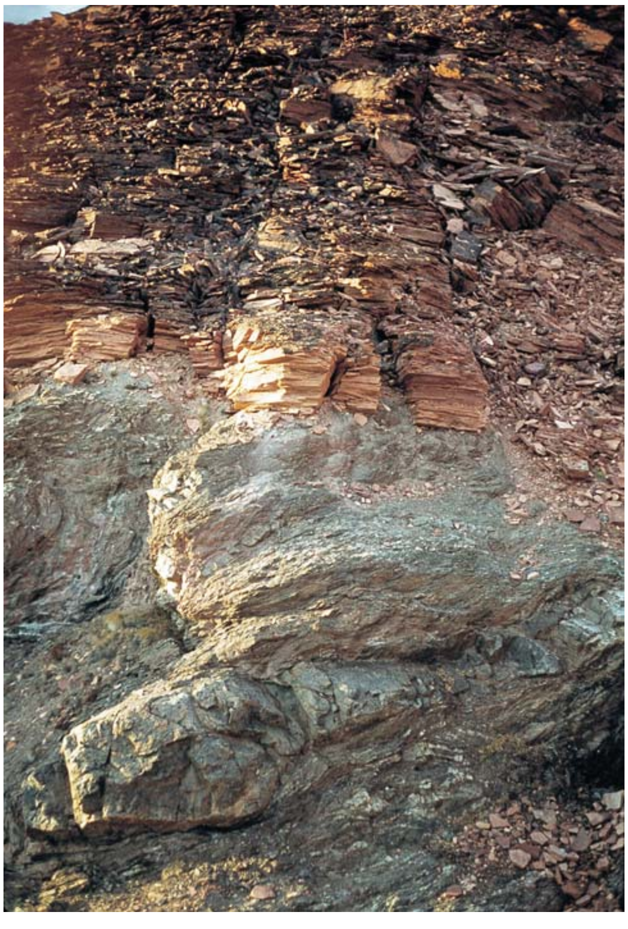


Fig. 34. The unconformity below the Thule Basin at Bowdoin Fjord. Pale orange sandstone of the Northumberland Formation (Nares Strait Group) overlying highly folded, graphitic schists of the Prudhoe Land supracrustal complex. Note the bleaching of the basal sandstone beds and the pale regolithic zone up to *c.* 2 m thick.

In several localities, basal beds show signs of silicification and platy siltstone or shale can be enriched in kaolinite, sericite, chlorite and secondary quartz. Such beds at Magnetitbugt have been considered to be reworked residual soils with scattered pebbles of crystalline rock (Kurtz & Wales 1951). On Wolstenholme Ø, the rock package spanning the unconformity comprises red platy hematite gneiss passing upwards into similarly platy, fine-grained hematite-rich sandstone. The hematite gneiss contains large quantities of green to yellowish, angular to rounded quartz set in a sericitic matrix, for which Davies *et al.* (1963, p. 28) suggested a possible fault gouge origin. However, this quartz-sericite deposit resembles regolithic material, for example that underlying the Borden Basin on northern Baffin Island (Jackson 1986).

Thule half-graben system

The outcrop pattern of Thule strata is strongly controlled by faults, mainly WNW–ESE- to NW–SE-trending, that split the region into tilted blocks of varying stature. These fault blocks make up the Thule half-graben system, that is so named here (Fig. 35). Six major half-grabens dominate, each with the same fundamental structure: on the north-eastern side, the shield is overlain by a normal, south-westerly dipping section that is bounded in the south-west by a steeply inclined master fault that juxtaposes the upper Thule Supergroup against the shield of the adjoining block. Movements along the bounding faults are measurable in kilometres, with the greatest displacements commonly in the west, i.e. in the deepest part of the Thule Basin. Within the half-grabens, smaller fault blocks occur, including both graben and horst structures, and these represent small to moderate displacements, which repeat stratal levels within the same formation or group, as well as larger displacements affecting the map outcrop pattern. Five of the six half-grabens contain successions that top in the Dundas Group; the Pituffik half-graben preserves the Narssârssuk Group.

The Thule half-graben system is schematically shown in Fig. 35 (see also front cover illustration). Many small, often closely-spaced intragraben faults, that do not radically affect the regional map pattern, have been omitted from the map sheet (see Fig. 37;

Dawes 1997, figs 90, 91) and for a more detailed fault representation the reader is referred to 1:100 000 maps in Survey archives (Dawes 1988b). For mineralisation of the faults, see under *Economic geology*, section *Fault-related mineralisation*. The main characteristics of the six half-grabens are described below, starting in the north.

Prudhoe half-graben

This half-graben bounded by the Murchison Fault forms the north-eastern margin of the Thule Basin stretching from Prudhoe Land to south of Inglefield Bredning. The overall structure is a series of tilted fault blocks with downthrow to the south-west, with sedimentary contacts to the shield preserved in all but northernmost exposures. North of Diebitsch Gletscher, and on the adjoining map sheet, a major fault – the Dodge Gletscher Fault – limits the Thule strata on the north-east (Dawes 1997, fig. 111). Apart from this fault, two other master faults have been named, viz. the Morris Jesup and Diebitsch Gletscher Faults, both with downthrow on their coastal side (see Dawes 1997, figs 1, 5B, 90, 111; Dawes 2004, fig. 12). However, some faults within the half-graben have reversed displacement, such as the Scarlet Heart Fault described earlier (see under *Map revision*, section 8; Dawes 1997, fig. 91). Local horst and graben structures occur (Figs 5, 37). Spacing of faults varies markedly from dense fault systems to isolated faults.

The Thule strata above the shield are shallow dipping, commonly a few degrees to the south-west, as for example on both sides of Bowdoin Fjord, but within fault blocks stratal dips reach up to *c.* 25°, locally even steeper (see Dawes 1997, figs 53, 74, 85). A noteworthy feature is the presence of large-wavelength, WNW–ESE-trending folds that are well seen in the Dundas strata on the peninsulas between Morris Jesup Gletscher and McCormick Fjord, where dips of limbs up to 10° are shown on the map.

The Murchison Fault intersects the south coast of Inglefield Bredning east of Tikeraasaq and strikes east along the northern side of a local ice cap. Steep dips due to drag characterise the Dundas strata adjacent to the main fault plane. The master fault is crossed by dislocations of other directions and this complicates the outcrop pattern of Thule strata and the shield. The master fault has not been mapped to the south-east of Kangerdlugssuaq but a number of WNW–ESE-trending faults strike towards the head of Academy Bugt. To the west, it is projected offshore along Murchison Sund parallel to the outer coast of Piulip Nunaa. The linear form of this coast west of Kap Ackland reflects the presence of the Kap Cleveland Fault, that passes onland west of the snout of Fan Gletscher separating Kap Cleveland off as an uplifted block. This block forms one side of a graben preserving the Dundas Group that is bordered to the north-east by the Fan Gletscher Fault.

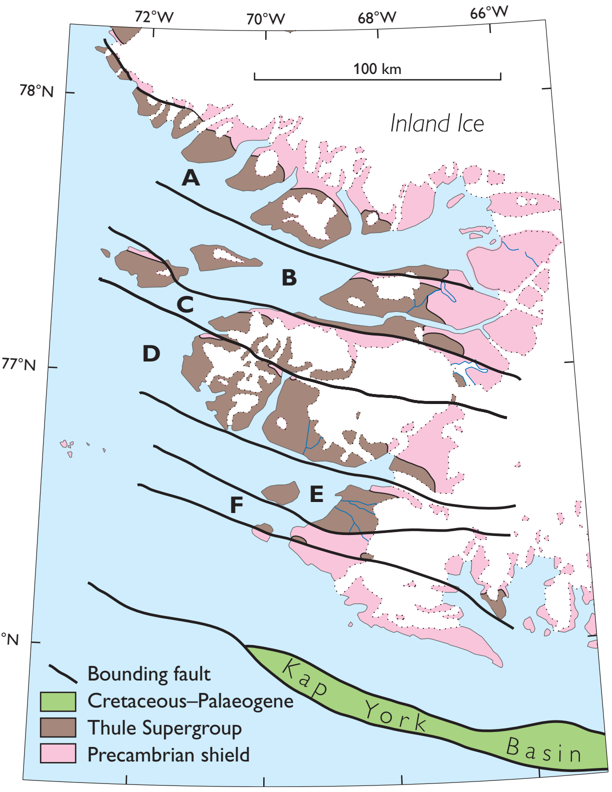


Fig. 35. The Thule half-graben system composed of six half-grabens each with its bounding fault on the southern side along which Thule Supergroup is downdropped against the shield. Intragraben faults are not shown. From north to south: **A**, Prudhoe half-graben / Murchison Fault; **B**, Olrik half-graben / Itilleq Fault; **C**, Itillersuaq half-graben / Granville Fault; **D**, Moriusaq half-graben / Moltke Fault; **E**, Pituffik half-graben / Narssarssuk Fault; **F**, Qeqertarsuaq half-graben / Magnetitbugt Fault. The Kap York Basin, an offshore half-graben of similar polarity, is taken from Whittaker *et al.* (1997).

Olrik half-graben

Olrik Fjord is illustrated in the literature as an example of a fault-controlled fjord and the type of graben tectonics that affect the Thule Basin (e.g. Dawes 1976b, fig. 231; 1997, fig. 109). The steep to vertical southern bounding fault – the Itilleq Fault – separates a 5-km wide coastal strip of Dundas strata (Olrik Fjord Formation) from an inland shield escarpment (see Fig. 48). In detail, the fault is composed of several splays and at places, tectonic slivers of pale sandstone referred to the Baffin Bay Group are caught up in the fault zone. The strata adjacent to the Itilleq Fault may

Fig. 36. Qaqqarsuaq fault block within the Olrik half-graben showing downdrop to the south-west. The mountain is located at the pronounced bend in Olrik Fjord marked on the map by symbol Bq. **Ps**, Precambrian shield; **Bw**, Wolstenhome Formation; **Bq**, Qaanaaq Formation, **D**, Dundas Group. As shown on the map sheet, there are also downdropped strata on the north-eastern side of the shield outcrop and the structure is interpreted as a horst. The Dundas Group, seen in the distance, may have been draped over an early manifestation of the horst prior to renewed faulting. View is towards the east; height of summit is *c.* 700 m a.s.l.

be highly contorted, sheared and crushed, with drag folding and steeply dipping sections, as well as the presence in some places of fine-grained fault gouge. Iron-sulphide mineralisation has been recorded along the fault (Gowen & Sheppard 1994; see under *Fault-related mineralisation*).

The eastern part of the Itilleq Fault is not depicted on the map but, as described earlier, this strikes towards lake Tasersuaq (see under *Map revision*, section 12). To the west of Itilleq, the steep linear sea cliffs are a reflection of the master fault concealed by morainic deposits forming a narrow coastal strip. The fault strikes into Hvalsund and towards Northumberland Ø where its continuation is the Kiatak Fault. This juxtaposes the Dundas Group with basic sills against the Nares Strait Group, and farther west, the Baffin Bay Group against the shield (Dawes 1997, fig. 48).

A number of faults with downthrow to the south-west dissect the strata within the half-graben. For example, the Narsaq Fault that reaches the coast north of Kangeq and repeats the south-westerly dipping stratigraphy of the Baffin Bay Group (Dawes 1997, fig. 95) and farther east, the Gyrfalco Fault limiting Dundas strata against the shield (Dawes 1997, fig. 103). Westerly projection of the faults cutting the mountain Qaqqarsuaq at the distinct bend in Olrik Fjord (Fig. 36; marked Bq on the map) along the northern side of the fjord led to an earlier assumption that the western part of Olrik Fjord was a full graben. However, the shield at Qaqqarsuaq is downfaulted on its northern and southern sides and is now interpreted as a local horst. There is evidence of syn-depositional faulting and it is possible that the Dundas Group may have been draped over an early manifestation of the horst prior to fault rejuvenation.

Itillersuaq half-graben

This half-graben occupies the northern part of Steensby Land. It is named after the Greenlandic name for Politiken Bræ that transects the fault block from Itilleq to its southern boundary, the Granville Fault. This fault is traceable from Barden Bugt in the west through heavily ice-covered terrain to the head of Granville Fjord where it juxtaposes the Dundas Group and the shield (Dawes 1997, figs 70, 87; see also front cover illustration). However, there is also downthrow to the south-west along parallel dislocations to the north, so that in effect the Dundas Group lies in a narrow graben that manifests itself as a low, glacier-filled depression. This continues to the east from the head of Granville Fjord under a large, unnamed, advancing glacier which has overrun several outcrops of the Dundas Group that were exposed in the early 1970s (see under *Recent glacial history*). However, the fault remains exposed, with Dundas strata juxtaposed against the Nares Strait and Baffin Bay Groups. Several fault planes make up the contact zone, which is characterised by drag folds, anomalously steep stratal dips, sheared and crushed rocks, and local fault gouge.

To the east, the fault is concealed by the large ice cap but it strikes towards the Rødstenbæk Fault of Gregory (1956) and Fernald & Horowitz (1964), just south of Dryasbjerg. This fault juxtaposes the lower strata of the Baffin Bay Group (Wolstenholme Formation) against the shield and represents a displacement of *c.* 100 m that is considerably less than that documented at Granville Fjord. To the west, the Granville Fault is surmised to strike south-west of Northumberland Ø (Fig. 35).

On the mainland, the Itillersuaq half-graben exposes a more or less uninterrupted sequence from the shield through the Nares Strait, Baffin Bay and the Dundas Groups, with the gradational passage into the latter group well seen in the small outlier at Kap Powlett. However, as described above, it is possible that much of the Dundas strata to the east of this locality has a fault relationship to the underlying Baffin Bay Group. Most of the faults seen within the half-graben are parallel to the boundary faults with downdropping to both the north-east and south-west, for example, two faults of opposing polarity shown on the map cross southern Northumberland Ø and form a small graben (see Dawes 1997, fig. 48). The northern part of this island is characterised by a series of fault blocks downdropped to the north and a similar fault pattern characterises the south coast east of Isussik. The fault blocks of the latter location are not shown on the map since stratal repetitions are small, but the structures are persistent along strike and probably correlate with a series of faults on the mainland north-east of Kap Powlett that have been utilised by basic dykes ($\mathbf{d}_2$).

Moriusaq half-graben

This half-graben, named after the village of Moriusaq, has the Moltke Fault of Davies *et al.* (1963, fig. 6) as its southern bounding fault. This fault is inferred beneath Harald Moltke Bræ and Wolstenholme Fjord separating the south-westerly dipping strata (Baffin Bay Group) north of the glacier from the shield rocks east from Ulli. The precise position of the fault is unknown. There is, however, a marked contrast in topography between the two sides of the glacier valley, and the steep cliffs of the south side compared to the more gentle slopes of the northern side, suggests a proximal position of the fault just off the cliffs. Stratal thickness considerations and extrapolation of the geology from southern Steensby Land, west of Knud Rasmussen Gletscher, suggest that the Baffin Bay and Dundas Groups continue under Wolstenholme Fjord and thus in fault contact with the shield along the Uvdle Fault.

The Moriusaq half-graben is 30 km across and thus the widest of the six half-grabens of the region. Unlike the three northern half-grabens, it is relatively uncomplicated by intragraben faults and it preserves a more or less uninterrupted section from the shield through the Nares Strait, Baffin Bay and Dundas Groups. Contacts between the Thule strata and the shield are well preserved and mainly shallow dipping up to 15° (Dawes 1997, fig. 97). The faults recorded are mainly parallel to the boundary faults, for example, the one shown on the map striking across Granville Bugt to reach the outer coast in the bay north of Kap Leiningen (Dawes 1997, fig. 70). Small faults may have downdrop to the north-east (e.g. Dawes 1997, fig. 88). Several cross-faults are known, including the Ohio Fjeld Fault of Fernald & Horowitz (1964), north of Harald Moltke Bræ, that delimits the main outcrop of Thule strata to the east.

Pituffik half-graben

The Pituffik half-graben preserves the youngest part of the Thule Supergroup – the Narssârssuk Group – downfaulted against the shield along the Narssarssuk Fault. Unlike the other half-grabens, its north-eastern boundary to the shield is not a sedimentary contact but a steep fault – the Uvdle Fault of Davies *et al.* (1963, fig. 6). This shield outcrop represents a horst, being bounded on the south by this fault along which strata of the Baffin Bay Group (Qaanaaq Formation) have been displaced at least 500 m, and on the north by the Moltke Fault that, assuming a normal stratigraphy below the ice, represents a much larger displacement (see *Moriusaq half-graben* above).

The southern bounding fault of the half-graben is the Narssarssuk Fault. Although the actual fault plane is poorly exposed, the fault line can traced from the coast south of Narsaarsuk, through the poorly exposed ground north of Pinorsuit, to the Inland Ice. Projecting the fault offshore suggests a position west of Saunders Ø and the straight south-western coast of the island may well express fault proximity. This position was favoured by Kurtz & Wales (1951, fig. 1) but it is at variance with Davies *et al.* (1963, fig. 6), who advocate a change in strike direction offshore to more or less E–W so as to link up with a fracture of much lesser magnitude in northern Wolstenholme Ø. This latter island is considered by the present author to be an integral part of the adjoining half-graben (Fig. 35).

The mainland between the Uvdle and Narssarssuk Faults is not crossed by visible faults although the broad topographic depression in which the Pituffik air base is situated is most probably fault controlled. Several faults cross Saunders Ø, including the Agpat and Kulukupaluk Faults shown on the map sheet (see Dawes 1997, figs 113, 114). The general structure is thus a broad WNW–ESE-trending asymmetrical syncline, with dips on the northern limb generally less than 15° and on the southern limb as much as 30°. The northern limb is formed of the Dundas Group (Steensby Land Formation) interspersed by basic sills and the lower part of the Narssârssuk Group (Imilik and Aorfêrneq Formations) while the trough of the syncline and its southern limb is formed of upper Narssârssuk Group (Bylot Sund Formation). This large-scale syncline also occurs on Saunders Ø but limbs are shallower as shown by the dips on the map.

On the mainland, the southern limb of the syncline is truncated by the Narssarssuk Fault, which indicates a major displacement zone. Assuming that the Narssârssuk Group wholly post-dates the Dundas Group, the displacement may well be 5 km or more. Moderate to steep dips occur in connection with contortions, folds and tilted blocks up to 2 km away from the fault. Davies *et al.* (1963) suggested that a series of local anticlines and synclines with dips as steep as 45° occur north of the fault. These, as well as the north-easterly regional inclination of the strata, might well be due to a massive drag effect along this major movement zone, rather than a regional compressional event.

Qeqertarsuaq half-graben

This half-graben, named after the Greenlandic name for Wolstenholme Ø, is the southernmost and smallest of the six half-grabens. The southern bounding fault is the Magnetitbugt Fault that on the mainland juxtaposes outliers of the Baffin Bay Group against the shield (Davies *et al.* 1963, fig. 6, plate 2; see under *Map revision* section 13). To the west on southern Wolstenholme Ø, the Baffin Bay and Dundas Groups are downdropped against the shield.

To the east, the Magnetitbugt Fault has not been traced far inland but it lines up with observed faults near the Inland Ice, west of Freuchen Nunatak, where the Baffin Bay Group occupies the northern part of a semi-nunatak. However, this area has heavy surficial cover, relief is low and the nature of the southern contact between Thule strata and the shield was not determined by the present author during a helicopter stop. Thus on the map, the boundary is shown as 'inferred or arbitrary' while a fault borders the outcrop in the west. This outlier of Thule strata appears on maps in Davies *et al.* (1963) but information about its relationship to the shield is contradictory. On their geological map (op. cit. plate 1), profuse Quaternary cover is shown at the outcrop in question but a contact between gneiss and Thule strata is shown as a solid line corresponding to a normal contact. However, on a sketch map (op. cit. fig. 6), a bold fault line trending WNW–ESE with downdrop to the north limits the Thule strata. W.E. Davies (personal communication 1980) confirms he did not locate the unconformity at this locality and that an 'inferred or concealed fault' ought to have been shown on plate 1. This interpretation is supported by a Landsat 'Crosta image' of the Freuchen Nunatak area shown in Krebs *et al.* (2003, fig. 2; Fig. 35).

The most complete section in this half-graben occurs on Wolstenholme Ø, with the Baffin Bay and Dundas Groups preserved. The standard tilted sequence characteristic of all the half-grabens is exposed on the Bylot Sund coast, where south-westerly dips exceed 20° (Dawes 1997, fig. 93). A second, narrow half-graben forms the northern part of the island with the Baffin Bay Group downdropped against shield, and with a normal contact preserved at the northern cape (the shield outcrop is just large enough to be portrayed on the map). Deformation of this fault block has produced moderate dips of opposing directions. Normal faults with northerly directions affect the outcrop pattern of Thule strata in the central part of the island.

Age of the faulting

The age of the Thule half-graben system is not tightly constrained. The main faults are considered to have been initiated in the Proterozoic but their rejuvenation is only bracketed by Quaternary deposits. The youngest movements may well be part of the late Phanerozoic tectonism that affected the Baffin Bay region (see below under *Correlation with the offshore*). The main period of extensional faulting is placed within the Franklin magmatic episode in the mid-Neoproterozoic (Cryogenian) being bracketed by the emplacement of a suite of basaltic sills ($\mathbf{s}_1$) – that are consistently tilted within the fault blocks – and a regional swarm of basic dykes ($\mathbf{d}_2$) that cuts the sills (see Table 1; Dawes 1997, fig. 106). Since the sills do not cross the main faults and there is no trace of magma splays along the faults, their pre-faulting age is certain.

In contrast, the relationship of the $\mathbf{d}_2$ dykes to the *main* fault movements is less certain, made so by the facts that dykes and faults are regionally parallel (WNW–ESE-trending) and both are steeply dipping features. Moreover, deciphering age relationships is complicated by the fact that at least some faults (probably all main structures) register more than a single movement episode. A particularly dense part of the $\mathbf{d}_2$ dyke swarm crosses the Itillersuaq and Moriusaq half-grabens where dykes can be seen to have exploited faults, for example east of Kap Powlett and south of Olrik Fjord. Other exposures providing cross-cutting information also indicate that the dykes post-date faulting (see Fig. 37). However, some dykes show features of brittle deformation, such as brecciation and crushing, indicative of fault reactivation.

At Asungaaq, south-eastern Northumberland Ø, a cross-cutting relationship is shown on the map between a $\mathbf{d}_2$ dyke and the southern branch of the Kiatak Fault that at the outer coast juxtaposes redbeds of the Baffin Bay Group against the Clarence Head Formation of the Nares Strait Group (Dawes 1997, fig. 48; see under *Map revision*, section 7). This fault zone is also known for a stream-sediment gold-barium anomaly, as well as quartz-baryte-pyrite mineralisation in clastic rocks adjacent to the basic dyke (Thomassen & Krebs 2004, figs 15, 16; see also under *Economic geology*, section *Fault-related mineralisation*). The scenario favoured to explain the mineral occurrence is that initial faulting resulted in brittle deformation of the clastic rocks, after which the emplacement of the basic dyke caused the contact mineralisation that is thus regarded as Neoproterozoic in age. The dyke shows colour variations and crushing that are referred to fault reactivation of unknown (?Cenozoic) age.

Correlation with the offshore

The structural characterisation, limits and development of the Thule Basin as a regional depocentre on the northern margin of the North Atlantic craton have been summarised in Dawes (1997). Exposures in both Greenland and Canada disappear seawards in down-faulted blocks and they represent the outermost fragments of a large sedimentary and volcanic province preserved under northern Baffin Bay. Gravity, magnetic and seismic reflection data collected since the 1970s indicate that the offshore is composed of a faulted sedimentary section, at least 10 km thick but in places possibly considerably thicker. Recent seismic data indicate that the section is composed of at least two sedimentary packages, a late Phanerozoic section and an underlying succession that includes Proterozoic strata of the Thule Basin (e.g. Jackson *et al.* 1992; Reid & Jackson 1997; Whittaker *et al.* 1997; F. Tessensohn, personal communication 2003). Although not yet mapped in detail, there is clear correlation between onland geology and the offshore, for example, the Steensby Basin of Newman (1982, fig. 7) trends north-west from the Bylot Sund area and is directly online with the Pituffik half-graben.

An integral element of regional tectonic models is that the coastal regions of Baffin Bay have been affected by late Phanerozoic rifting and the faults of the Thule region have been regarded as of similar age (e.g. Koch 1926; Fernald & Horowitz 1964; Monahan & Johnson 1982). A system of extensional faults has been mapped offshore within the south-western quadrant of the map sheet (Whittaker *et al.* 1997). The straight, cliffed coastline west-north-west of Kap York suggests fault control and it is parallel to the main offshore structure, the Kap York Basin (Fig. 35). This is a half-graben with the same polarity as the onland half-grabens with a bounding fault on its south-western side and with the sedimentary fill onlapping a 'basement' to the north-east. The early-rift sediments are of Early to mid-Cretaceous (Barremian–Cenomanian) age and the basin – like the other offshore structures to the south-east in Melville Bugt – is regarded as late Mesozoic to Cenozoic in age. It seems likely that the tectonic regime that produced these offshore features also affected the coastal region, as exemplified by the linearity of the Kap York coastline. Thus, some of the onland faults, as well as the rejuvenation of the Thule half-graben system, are probably related to regional, late Phanerozoic tectonic processes.

Thule Supergroup

The published lithostratigraphic subdivision of the Thule Supergroup of Greenland and Canada into five groups has been mentioned in the *Introduction*. In that publication (Dawes 1997), the tripartite subdivision of the two youngest groups that are restricted to Greenland – the Dundas and Narssârssuk Groups – was not formalised. Four of these formations – the Olrik Fjord Formation of the Dundas Group and the Imilik, Aorfêrneq and Bylot Sund Formations of the Narssârssuk Group – are named units on the map sheet. This, as well as the fact that the Smith Sound Group, that represents the northern basin margin, crops out beyond the map region, determine that the Thule Supergroup *in the map region* comprises four groups, 15 formations and nine members.

Nares Strait Group

Name. Dawes (1991, 1997).

Other literature. Jackson (1986), Steenfelt *et al.* (2002), Thomassen *et al.* (2002a, b), Dawes (2004).

Distribution and age. This group represents the oldest Thule strata overlying the shield in the central basin. It is conformably overlain by the Baffin Bay Group. Basal strata are at least 1268 Ma old (middle Mesoproterozoic or Ectasian). This is based on the most reliable isotopic age available: a ^{207}Pb/^{206}Pb baddeleyite age of a basic sill within the Cape Combermere Formation from Ellesmere Island, a sequence of tholeiitic basalt extrusive and intrusive rocks coeval with the Mackenzie magmatism well known from elsewhere in northern Greenland and Arctic Canada (LeCheminant & Heaman 1991; Henriksen *et al.* 2000). This refines the K-Ar age range of 1220–1205 Ma cited on the map sheet taken from Dawes & Rex (1986).

Composition. The group comprises five formations – Northumberland, Cape Combermere, Josephine Headland, Barden Bugt and Clarence Head Formations – in which eight formal members have been

Fig. 37. Faulted margin of the Thule Basin at head of McCormick Fjord, Prudhoe Land. Blocks of Mesoproterozoic strata and a Neoproterozoic(?) basic sill (**s**) cut by a late Neoproterozoic basic dyke of the Thule dyke swarm (**d**$_2$). **Ps**, Precambrian shield; **No**, Northumberland Formation; **CC**, Cape Combermere Formation; **BB**, Barden Bugt Formation; **CH**, Clarence Head Formation; **RF**, Robertson Fjord Formation. **d** (top right), basic dyke of uncertain age. The basic sill (**s**) is within the Kap Trautwine Formation, the basal strata of the Baffin Bay Group (see Dawes 1997, fig. 74 for comparative, undisturbed section at Robertson Fjord). Lower and upper basaltic members separated by semi-recessive volcaniclastic redbeds characterises **CC**, a tripartite subdivision that is developed regionally (see Fig. 2). View is to the north-west with plateau surface at *c.* 700 m a.s.l.

defined, two of which are restricted to Canada (see Dawes 1997, fig. 49). Other members are not formally defined, for example the tripartite subdivision of the Cape Combermere Formation recognisable in many parts of the Thule Basin in Greenland and Canada (Figs 2, 37). The Nares Strait Group has a composite thickness of up to 1200 m and the thickest section in the map region is *c.* 950 m on Northumberland Ø. As explained earlier under *Map revision*, the group has a wider distribution than shown on the map since it is now known to be present at the base of the succession throughout Prudhoe Land and at Tikeraasaq on the south side of Inglefield Bredning.

The products of the intracratonic Thule Basin volcanism are discussed later in the section on basic intrusions, particularly under *Chemical characteristics and magmatic types*. Both effusive and intrusive rocks of the Nares Strait Group are included in the TiO_2/mg# plot (see Fig. 40) while seven representative chemical analyses of lavas and sills are given in Table 2 (analyses 6–12).

Nares Strait Group, undivided (**N**)

Composition. This map unit corresponds to all formations of the group except the Clarence Head Formation, the strata of which are included in the map unit *Baffin Bay Group undivided.* The circumstances surrounding this have been explained earlier under *Map revision,* sections 6–10.

Lithology. The map unit comprises, in ascending stratigraphic order, sandstone with subordinate siltstone and shale, with occasional basic sills (Northumberland Formation), a volcanic/redbed sequence of tholeiitic lavas with coeval sills, agglomerates, tuffaceous strata (lithic tuffs, tuff breccias and ash flows) and interflow clastic sandstone-siltstone-shale packages (Cape Combermere Formation), and stromatolitic carbonates, sandstone and shale with tuffaceous elements (Josephine Headland and Barden Bugt Formations). The unit represents shallow-water deposition in mainly alluvial plain and littoral environments, with one main interval of terrestrial volcanism including plateau basalts. The thickest section of map unit **N** on Northumberland Ø, *c.* 700 m, thins towards the mainland (Figs 4, 37), pinching out somewhere in the inner part of Inglefield Bredning and eastern Steensby Land where the overlying Baffin Bay Group (Wolstenholme Formation) oversteps onto the shield (Fig. 36).

Baffin Bay Group

Name. Dawes (1991, 1997).
Other literature. Hofmann & Jackson (1996), Samuelsson *et al.* (1999), Steenfelt *et al.* (2002), Thomassen *et al.* (2002a, b), Dawes (2004).
Distribution and age. Microfossils suggest a late Mesoproterozoic (Ectasian/Stenian) and/or early Neoproterozoic (Tonian) age. The group represents the most widespread strata of the Thule Basin present in the central part of the basin, as well as on the eastern and south-eastern margins. It overlies the Nares Strait Group in the central basin along an abrupt contact that represents a change to redbed sedimentation (Dawes 1997; figs, 77, 78) while to the east and south-east it overlaps onto the shield (op. cit., figs 93, 103). Its upper contact is conformable and gradational with the Dundas Group.
Composition. The group comprises five formations, four of which are present in Greenland – the Kap Trautwine, Robertson Fjord, Wolstenholme and Qaanaaq Formations (Figs 4, 36, 37). Three members have been formally defined. The group ranges in thickness from at least 1300 m in the central basin to less than 300 m in basin margin sections. Thinner sections characterise the eastern exposures at the head of Inglefield Bredning and around lake Tasersuaq, but such sections are cut by the present erosion surface.

Baffin Bay Group, undivided (**B**)

Composition. This map unit corresponds to the Clarence Head Formation (now formalised as the uppermost strata of the Nares Strait Group, see under *Map revision,* section 7) overlain by the lowermost strata of the Baffin Bay Group within the central part of the basin, i.e. the Kap Trautwine and Robertson Fjord Formations. The statement in the map legend that “at Bowdoin Fjord” the basal part of this unit includes “strata of the Nares Strait Group” actually refers to strata below the Clarence Head Formation, in other words, the Northumberland, Cape Combermere, Barden Bugt and Josephine Headland Formations (Fig. 5). However, rather than applying specifically to Bowdoin Fjord, this statement is now known to apply to all exposures of the map unit between McCormick Fjord and the Hubbard Gletscher (see under *Map revision,* sections 6, 8, 9).
Lithology. The unit comprises multicoloured, shallow-water to terrestrial siliciclastic strata. Pale, clean sandstone with conglomerate at the base (Clarence Head Formation) indicative of deposition in the tidal zone, are overlain by a redbed succession composed of highly ferruginous sandstone and conglomerate, with siltstone and shale (Kap Trautwine Formation) and interbedded sandstone, siltstone and shale (Kap Robertson Formation). The redbed succession, with regolith deposits at the base, marks the incoming of a strongly oxidising environment; as a whole the succession represents mixed continental to marine shoreline environments.

Wolstenholme Formation (**Bw**)

Name. Kurtz & Wales (1951), Davies *et al.* (1963); redefinition with drastic reduction of stratigraphic range and distribution by Dawes (1991, 1997).
Composition. This map unit crops out on the eastern and south-eastern margins of the basin directly overlying the shield (Fig. 36). It is conformably overlain by the Qaanaaq Formation and varies in thickness from less than 100 to *c.* 250 m. Easternmost outcrops are thinner but limited by the present erosion surface. These cap the plateau surface of the seminunataks at the head of Inglefield Bredning, for example south of the Kinginneq, and they vary from low-relief outliers to veneer and rubble deposits on the shield. The outcrops south and south-east of Tikeraasaq, on the southern side of Inglefield Bredning, illustrated in Dawes (1997, fig. 95), are now referred to the Nares Strait Group while the upper part of the De Dødes Fjord outlier is known to include strata of the Qaanaaq Formation (see under *Map revision*, sections 10, 11).
Lithology. The map unit comprises redbeds dominated by ferruginous sandstone and conglomerate with minor siltstone and shale interbeds. It is interpreted as a fluvial deposit laid down in an overall oxidising environment.

Qaanaaq Formation (**Bq**)

Name. Dawes (1991, 1997).
Composition. This map unit is the thickest and most widely distributed formation of the Thule Supergroup being present both in the central basin and on the eastern and south-eastern margins. Apart from the outcrops shown on the map, it is now known to be preserved in the southernmost outcrops in the De

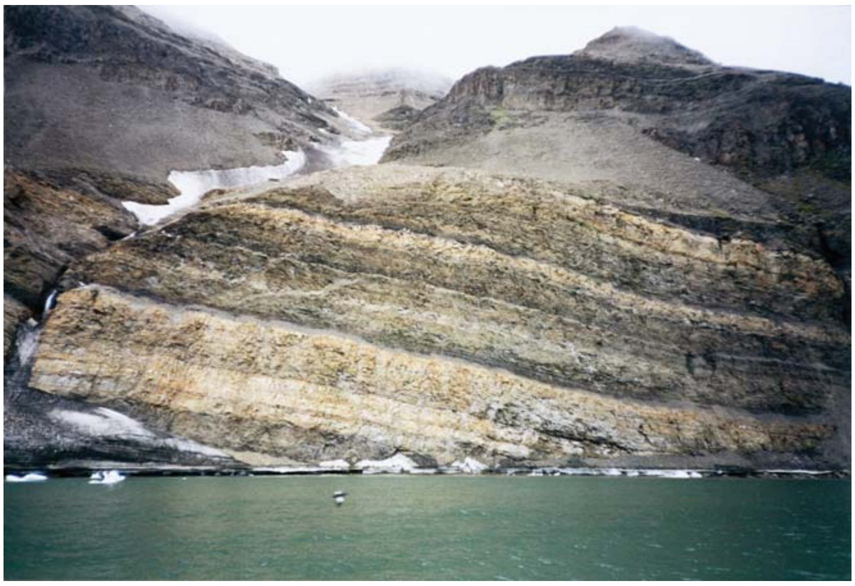


Fig. 38. Typical lithology of the Prudhoe Land Formation, Dundas Group: coarsening-upwards cycles with dark shale-rich bases and pale sandstone tops. North of Kap Chalon, Prudhoe Land, with height of the foreground cliff *c.* 150 m.

Dødes Fjord outlier (Dawes 1997, fig. 13; see under *Map revision*, section 11). It ranges in thickness from 200 m in the interior of Olrik Fjord to perhaps as much a 1000 m in Prudhoe Land.

Lithology. A rather monotonous succession of pale-weathering sandstone with conglomerate beds, and minor shale and siltstone that is regarded as an alluvial plain to marine shoreline deposit. Some redbeds are present in the upper strata in northernmost exposures. Argillaceous strata increase in abundance upwards producing a transitional contact into the Dundas Group that is taken to represent a regional regression of the shoreline (see Dawes 1997, fig. 102).

Dundas Group

Name. Davies *et al.* (1963); raised to group status by Dawes (1991, 1997).

Other literature. Munck (1941), Kurtz & Wales (1951), Vidal & Dawes (1980), Jackson (1986), Dawes & Vidal (1985), Dawes (1989, 2004), Hofmann & Jackson (1996), Samuelsson *et al.* (1999), Steenfelt (2002), Steenfelt *et al.* (2002), Thomassen *et al.* (2002a, b).

Distribution and age. Microfossils suggest a late Mesoproterozoic (Ectasian/Stenian) and/or early Neoproterozoic (Tonian) age. The group encompasses thick basinal clastic strata with a wide distribution from northern Prudhoe Land (also to Sonntag Bugt just beyond the map sheet) to the head of Olrik Fjord and south to Wolstenholme Ø. Regionally, it conformably overlies the Baffin Bay Group along a gradational boundary (see under *Qaanaaq Formation*) but locally, as in the Olrik Fjord area, Dundas strata overlap nonconformably fault blocks of the Baffin Bay Group. The upper limit of the group is unknown and its position in the map legend below the Narssârssuk Group is based on lithological and structural inferences suggesting an older age (see under *Narssârssuk Group*). The group forms the uppermost strata in five of the six half-grabens that dissect the Thule Basin and the strata are characteristically downdropped against the shield on the north-eastern side of regional NW–SE and WNW–ESE-trending faults (Fig. 35; see *Thule half-graben system*).

Composition. The group has a somewhat monotonous lithology without regional markers and correlation of sections is not obvious. It is estimated to be at least 2 km, possibly as much as 3 km, thick. The three formations recognised – the Steensby Land, Kap Powell and Olrik Fjord Formations are based on lateral lithological facies and are essentially geographically defined (Fig. 4). The first two formations conformably overlie the Qaanaaq Formation of the Baffin Bay Group; the Olrik Fjord Formation is only recognised in a downfaulted block and its stratal limits are unknown. However, this formation may well represent the youngest strata as its position in the map legend implies (see below under *Narssârssuk Group*).

Dundas Group, undivided (**D**)

Composition. This map unit covers the majority of exposures shown on the map sheet comprising the Kap Powell and Steensby Land Formations that crop out in two NW–SE-trending belts. In the north within the Prudhoe half-graben, the Kap Powell Formation stretches from Kap Chalon throughout coastal Prudhoe Land to the Inglefield Bredning area, while the Steensby Land Formation, characterised by basic sills (**s_1**), forms a broader belt from Northumberland Ø and

Herbert Ø through Steensby Land to the type area around Dundas and to the southernmost exposures on Wolstenholme Ø.

Lithology. The map unit is composed of sandstone, siltstone and shale with lesser amounts of carbonate (dolomite, limestone, arenaceous dolomite), chert and evaporitic beds. Regionally, the unit shows wide lateral variation in the ratio of sandstone to siltstone-shale. The Kap Powell Formation contains more sandstone than the Steensby Land Formation, which is thin bedded and dominated by black shale in which carbonate beds with stromatolitic reefs occur (Dawes 1997, figs 105, 112; Thomassen *et al.* 2002a, fig. 7). The common upwards-coarsening units suggest deposition in an overall deltaic to offshore environment (Fig. 38). The thick cycles of the Kap Powell Formation might represent progradation delta front sequences, the thinner lower energy cycles with some pyrite development of the Steensby Land Formation possible delta plain deposition. Characteristic lithologies are illustrated in Dawes (1997, fig. 110).

Olrik Fjord Formation (**Do**)

Name. Dawes (1991, 1997).

Other literature. Samuelsson *et al.* (1999), Thomassen *et al.* (2002b).

Composition. This formation crops out on the south coast of Olrik Fjord restricted to the central part of the Olrik half-graben (Dawes 1997, fig. 109; Thomassen *et al.* 2002b, fig. 19; see under *Thule half-graben system*). Contacts to other map units are tectonic and the stratal limits of the formation are unknown. On the south, the strata are juxtaposed against the shield and slivers of Baffin Bay Group along the Itilleq Fault; to the east the formation is faulted against the Baffin Bay Group (see Fig. 48). Over the main outcrops, stratal dips are gentle, but adjacent to the Itilleq Fault, contortions and drag folding produce steeply dipping sections. The thickness of the unit is estimated to be at least 400 m.

Lithology. A dark-weathering, thin-bedded, clastic sequence characterised by lithological cycles with multicoloured shale units that are variously intercalated with laminated siltstone, sandstone, thin carbonate beds and (?)evaporitic beds. An overall deltaic or coastal plain environment is favoured for the Dundas Group but the characteristic features of this formation with redbeds, may be indicative of progradation of the shoreline. The well-layered, dominantly fine-grained lithologies, resembles in gross character some parts of the Narssârssuk Group and similarity in depositional environment is suggested by siliciclastic redbeds topping cyclic sequences with carbonate rocks.

Narssârssuk Group

Name. Davies *et al.* (1963); raised to group status by Dawes (1991, 1997).

Other literature. Munck (1941), Kurtz & Wales (1951), Dawes (1979), Vidal & Dawes (1980), Strother *et al.* (1983), Dawes & Vidal (1985), Jackson (1986), Hofmann & Jackson (1996), Samuelsson *et al.* (1999).

Distribution and age. Microfossils suggest a late Mesoproterozoic (Ectasian/Stenian) and/or early Neoproterozoic (Tonian) age. The group is restricted to the Pituffik half-graben on the south-eastern margin of the basin. It composes Saunders Ø and a mainland belt limited to the south by the Narssarssuk Fault (see under *Thule half-graben system*). The relationship to the Dundas Group in the north, which is the nearest unit both geographically and stratigraphically, is hidden by surficial deposits filling Pituffik valley (Frontispiece). Regional structure suggests that the Narssârssuk Group is likely to be all, or in part, younger than the Dundas Group (Steensby Land Formation). The group is limited upwards by the present erosion surface.

Similarities to Narssârssuk Group lithologies in the Dundas Group suggest depositional affinity and implies a similar biostratigraphic age that is supported by the acritarch taxa (Samuelsson *et al.* 1999; see under *Age of the Thule Supergroup*). For instance, the uppermost beds of the Steensby Land Formation on Dundas Fjeld contain thin carbonate beds with stromatolites, chert and evaporite, while the Olrik Fjord Formation has multicoloured cycles including red siliciclastic rocks and carbonates. The present consensus is that the Narssârssuk and Dundas Groups are *not* separated by a substantial age gap or a major unconformity.

Composition. The group has an unknown but substantial thickness estimated at between 1.5 and 2.5 km. The strata represent subtidal to supratidal deposition in very shallow water and in a low-energy, arid or semi-arid environment, in conditions perhaps analogous to modern coastal sabkhas. Characteristic lithologies are illustrated in Dawes (1997, fig. 117); chemical composition of various carbonate rocks are given in Munck (1941) and Davies *et al.* (1963).

Tripartite division into the Imilik, Aorfêrneq and Bylot Sund Formations is established in the sea cliffs south of Pituffik, where strata are undisturbed by faulting (Fig. 39). In contast, faults cut Saunders Ø and have displacements in excess of the island's relief (see Dawes 1997, fig. 114). This, and lateral facies and thickness changes, make stratigraphic correlation between the mainland and the island problematic. However, rather than classify Saunders Ø as a fourth map unit (i.e. Narssârssuk Group undivided), formational correlation between the mainland and Saunders Ø has been attempted.

Fig. 39. Imilik (**Ni**) and Aorfêrneq (**Na**) Formations of the Narssârssuk Group. Multicoloured progradational cycles with basal grey carbonates topped by red siltstone–sandstone forms the lower strata (Imilik) overlain by abortive carbonate-dominated cycles lacking redbeds (Aorfêrneq). **d_2**, basic dyke of the Thule dyke swarm, which has caused bleaching in a zone several metres wide. Coast south of Pituffik, Bylot Sund, with cliff height *c.* 150 m a.s.l.

Imilik Formation (**Ni**)

Name. Dawes (1991, 1997).

Composition. This formation comprises the lowermost strata of the group. On the mainland the base of section is covered by surficial deposits; on the south side of Saunders Ø it is below sea level.

Lithology. The succession has a well-layered, colourful appearance, due to alternating clastic redbeds and paler carbonates arranged in lithological cycles (Fig. 39; Davies *et al.* 1963, fig. 9; Dawes 1976b, fig. 234). A typical cycle has pale limestone and/or dolomite at the base grading into mixed carbonate-siliciclastic lithologies, in places with chert and evaporite, and finally into red siltstone and sandstone. The cycles are taken to indicate regular fluctuations of shallow, quiet water indicating repeated progradation from intertidal carbonates to supratidal siliciclastics. An 8 m-thick bed of "white, light gray or translucent orange gypsum" occurs in drill core from just south of Pituffik air base (Davies *et al.* 1963, p. 30). Such thick homogeneous evaporite beds have not been recorded in outcrop.

Aorfêrneq Formation (**Na**)

Name. Davies *et al.* (1963) raised to formation status by Dawes (1991, 1997).

Compositon. This unit composes the middle strata in the mainland succession reaching the coast north of Aafeerneq and it forms the western end of Saunders Ø. In contrast to formations below and above, it is not characterised by redbeds. It gradationally overlies the previous unit within a cyclic sequence in which individual cycles are aborted and lack red siliciclastic tops (Fig. 39).

Lithology. A carbonate-dominated (mainly dolomite) cyclic sequence that in many sections is characterised by evaporite in varying forms, from thin beds, veins and nodules to the matrix of thick breccia beds. Stromatolites and algal mat associations, with chertified microbiota, are common in the dolomites indicating deposition on broad tidal flats with the persistence of warm hypersaline conditions. Siliciclastic rocks are restricted on the mainland to very sporadic thin beds, some of which are red, although on Saunders Ø pale sandstone, commonly calcareous, and arenaceous dolomite, come in.

Bylot Sund Formation (**Nb**)

Name. Dawes (1991, 1997).

Composition. This formation represents the youngest strata of the group conformably overlying the previous unit. On the mainland, it crops out north of Narsaarsuk in a broad syncline the southern limb of which is truncated by the Narssarssuk Fault (Fig. 35) while on Saunders Ø it forms much of the eastern and northern parts of the island.

Lithology. The map unit has a similar appearance and lithology to the Imilik Formation with siliciclastic redbeds topping cycles. However, generally there is lesser siliciclastic material and dolomite, variably arenaceous, predominates. Some transgressive cycles exist in which multicoloured siliciclastic rocks grade upwards into dolomites that are variably arenaceous.

Palaeo-, Meso- and Neoproterozoic basic intrusions

Minor basic intrusions occur throughout the map region from the land bordering Steenstrup Gletscher in the south to Kap Chalon in the north. They form conspicuous features of the landscape, as they do on parts of the map. Kap Chalon itself, is a bold buttress etched from a basic dyke while the celebrated landmark of North-West Greenland – table mountain Dundas Fjeld, known internationally as 'Thule mountain' at the site of Thule (Ummannaaq) – is capped by a subhorizontal sill (Frontispiece; Dawes & Rex 1986, fig. 3; Dawes 1997, fig. 105). Several islands in Melville Bugt owe their existence to master dykes.

The bodies are undeformed and unmetamorphosed being composed of rocks of grossly similar appearance, termed in the map legend 'dolerite', and in earlier literature 'diabase' (e.g. Koch 1920; Munck 1941; Kurtz & Wales 1951; Davies *et al.* 1963; Fernald & Horowitz 1964). They are predominantly sills and dykes, with occasional sheets, characterised by sharp chilled contacts. Two volcanic necks have been identified although these are not shown on the map. In areas where numerous sills are cut by a dense dyke swarm, as in southern Steensby Land, dolerite forms more than a minor rock type representing appreciable vertical and horizontal crustal extension. Only a selection of intrusions mapped is shown on the map sheet and for a more complete representation the reader is referred to larger scale maps (Dawes 1988b).

Map categories and their age

The basic intrusions fall into three age groups with respect to their relationship to the Thule Basin: pre-, syn- and post-sedimentation (Fig. 4; Table 1). These ages are confirmed by radiometric dating to be late Palaeoproterozoic to early Mesoproterozoic (Statherian–Calymmian), Mesoproterozoic (Ectasian–Stenian) and Neoproterozoic (Tonian–Cryogenian, possibly Sinian) or in map terminology, Palaeohelikian, Neohelikian and Hadrynian (see *Introduction*). The three age groups have distinctive geochemistry (see Fig. 40; Table 2). Based on field and laboratory data available at the time of map compilation, an ambitious attempt was made to distinguish the three intrusion ages on the map. However, for many intrusions within the Precambrian shield beyond the limits of the Thule Basin, assignment to a precise map category proved problematical. Fifteen years later, this statement is still true, with the degree of uncertainty ranging from those intrusions mapped solely from the air or on photographs, to those only cursorily studied in the field and to those for which petrological, chemical and isotopic data are available.

Five categories are depicted on the map, three of dykes (**d**, **d**$_1$ and **d**$_2$) and two of sills and sheets (**s** and **s**$_1$). The two most obvious regional dyke swarms, viz. pre- and post-Thule Basin sedimentation, are designated **d**$_1$ and **d**$_2$, while a sill complex that cuts the youngest Thule strata but pre-dates regional faulting is designated **s**$_1$. All other intrusions were placed in the less specific units **d** and **s**. Although at map compilation it was known that several other ages of sills and sheets existed, for example Mesoproterozoic (syn-Thule sedimentation and part of the Cape Combermere Formation) and Neoproterozoic (post-**s**$_1$ and post-faulting), the establishment of a more sophisticated classification with additional map units to cover the few bodies of these ages that are shown on the map was not editorially recommended.

Chronology

Cross-cutting relationships between intrusions and tectonic features such as faults, supported by comparative geochemistry, indicate that each of the five map units contains more than a single intrusive episode. Available field and chemical data have been synthesised into the chronology presented in Table 1 that shows that map unit assignment of some dykes has been revised since compilation (see earlier under *Map revision*, section 14). While it is fully acknowledged that the definition of magmatic episodes on the basis of K-Ar isotopic ages is problematical, the twelve events of Table 1 are positioned on the basis of supplementary field and/or chemical information, details of which are given in the descriptions of the five map units.

For example, two of the most conspicuous Neoproterozoic basic intrusions of the map sheet – **s**$_1$ sills and **d**$_2$ dykes – have K-Ar ages that overlap within error and thus on this basis they cannot be separated as distinct magmatic episodes. However, where such sills and dykes dominate the landscape and have comparable chemistry, as in Steensby Land, dykes of the main swarm (WNW–ESE-trending) consistently cut the sill complex thus determining their relative positions in Table 1 (Dawes 1997, fig. 106; see also under *Age of the faulting*). Furthermore, several intrusions mapped as **s**$_1$ and **d**$_2$ elsewhere show chemical variation and since the youngest K-Ar ages (610 and 530 Ma)

Table 1. Chronological summary of Palaeo-, Meso- and Neoproterozoic basic intrusions in the Thule region

Map unit*	Chemical group†	Thule Basin‡	Type of intrusion§	Isotopic age, Ma
s_1	4	post	Sills	610–530[d]
d_2	4	post	ENE–WSW dykes	n.d.
d_2 (+ d)	3	post	WNW–ESE dykes, varying NW–SE to E–W, Thule dyke swarm (TDS), with local NNW–SSE and NE–SW dykes	725–630[d]
s	n.d.	post	Sheets, post-Thule half-graben system	n.d.
s_1	3	post	Sills, pre-Thule half-graben system, includes Steensby Land sill complex (SLSC)	705–660[d]
s	n.d.	post	Sills and sheets	765–730[d]
d[a]	n.d	syn or post	WNW–ESE dykes	1015[d]
s	2	syn	Sills, coeval with plateau basalts of the Nares Strait Group (Cape Combermere Formation)	1220–1205[d] 1268[e]
(d_2 + d)[b]	2	syn	WNW–ESE dykes	n.d.
d_1 (+ d)	1	pre	NE–SW dykes	1315[d]
d_1	1	pre	NW–SE dykes, varying to WNW–ESE, Melville Bugt dyke swarm (MBDS)	1540–1450[d] 1629[f], 1628[g]
d[c]	n.d.	pre	NNE–SSW dykes, varying to NE–SW	1670[d]

n.d. not determined.
* parentheses indicate map unit designation revised in these explanatory notes.
† refers to the four geochemical groups outlined in Fig. 40.
‡ relationship to Thule Basin sedimentation.
§ only those intrusions having field and/or laboratory data constraints are included.
a specific dyke from Kivioq Havn, Melville Bugt, with a K-Ar age of *c.* 1015 Ma is not depicted on the map sheet but in Dawes (1988b).
b position is based on probability that these dykes are feeders to Thule Basin volcanicity (Cape Combermere Formation).
c specific dykes known on field relations to pre-date MBDS are not depicted on the map sheet but in Dawes (1988b).
d K-Ar whole-rock ages from Dawes *et al.* (1973) and Dawes & Rex (1986).
e U-Pb baddeleyite age from LeCheminant & Heaman (1991) on a sill from Ellesmere Island, Canada, within the Cape Combermere Formation.
f U-Pb baddeleyite age from Hamilton *et al.* (2004) on a NW–SE-trending dyke south of the Thule region.
g U-Pb baddeleyite age from Denyszyn *et al.* (2005) on a NW–SE-trending dyke, Semiarsupaluk, Olrik Fjord.

derive from such sills (the dykes are undated), these intrusions are placed in Table 1 as concluding the Proterozoic basaltic magmatism.

Given the nature of the Cretaceous–Paleogene tectonism the Baffin Bay region, mafic intrusions of Cenozoic age might be expected to occur (A.V. Okulitch, personal communication 2005). Since there are hundreds of undeformed mafic intrusions in the map region, few of which have been isotopically dated (see below), the possibility of onland late Phanerozoic magmatic rocks cannot be excluded. In summary, the chronology put forward in Table 1 is a model to be tested by new field work and more refined chemical identification.

Isotopic age determinations

K-Ar whole-rock isotopic work was carried out concurrently with the regional mapping. Thirty samples were dated: 24 within the map sheet and 6 to the north in northernmost Prudhoe Land and western Inglefield Land (Fig. 1). The samples stem from 29 intrusions: 14 sills, 11 dykes, 3 flows and 1 sheet, with the ages ranging from 1670 to 430 Ma. The 430 Ma (Silurian) age from an olivine sill within the Cape Combermere Formation has been discounted as an expression of a fundamental disturbance of the K-Ar isotope system (Dawes & Rex 1986). However, other 'young' ages, 610 Ma and 530 Ma, may be indicative of the waning activity of the Franklin magmatism that extends in parts of neighbouring Canada into the Cambrian (see Okulitch 1988, fig. 13; also below under *Neoproterozoic sills* (s_1)). It can also be assumed that in general the ages are 'younger' than the age of intrusion. For example, Christie & Fahrig (1983), dealing with Neoproterozoic dykes in adjacent Canada, suggested a discrepancy of 10–15%.

Nevertheless, even with these limitations, the K-Ar ages fall into the three age groups mentioned above – Palaeoproterozoic, Mesoproterozoic and Neoproterozoic (Dawes *et al.* 1973, 1982b; Dawes & Rex 1986). Since map compilation, more precise isotopic dates are available using the U-Pb method on baddeleyite and three ages are relevant to the geology of the map region. These are 1629 Ma (Hamilton *et al.* 2004), 1628 Ma (Denyszyn *et al.* 2005) and 1268 Ma (LeCheminant & Heaman 1991) that confirm the K-Ar ages of the main Palaeoproterozoic and Mesoproterozoic magmatism (Table 1; see earlier under *Nares Strait Group* and below under *Palaeoproterozoic–Mesoproterozoic dykes (*$\boldsymbol{d_1}$*))*.

General characteristics

Field, petrological and chemical aspects of basic intrusions from the map region are found in Callisen (1929), Munck (1941), Davies *et al.* (1963), Fernald & Horowitz (1964), Dawes *et al.* (1973, 1982b), Dawes (1975, 1976a, 1989, 1997), Nutman (1979, 1984), Dawes & Frisch (1981), Dawes & Rex (1986), Nielsen (1987, 1990) and Steenfelt (2002). Survey data are based on regional field observations and *c.* 150 rock samples, with major element chemistry available for about two thirds of these (see below). Since dolerite of all ages is of quite uniform aspect, general comments on field and mineralogical features of the intrusions as a whole are given here, thus avoiding repetition in the map unit descriptions.

The rocks vary from black, dark grey to greenish grey; severely-weathered dykes can have a reddish-brown hue. A few of the oldest dykes are distinctly green, altered and veined. Some $\mathbf{d_2}$ dykes are characterised by greenish margins with a reddish core (Fig. 2). Chilled margins are present but in some intrusions, mainly sills, they are not particularly conspicuous. Depending on intrusion size, dolerite is fine-, medium- or coarse-grained. Black aphanitic rock characterises chilled margins and thin dykes and dykelets but the bodies shown on the map are medium- to coarse-grained dolerite and gabbro. Medium-grained intrusions above *c.* 50 m thick generally have a coarser central part. Bodies above 100 m thick are gabbroic except for a marginal zone and such rocks display the typical speckled appearance of ophitic-textured gabbro. Apart from chilled margins, gabbroic centres and pegmatitic patches, textures are essentially uniform. Only a faint suggestion of igneous layering in some sills has been seen; xenoliths are rare.

All intrusions are pyroxene-plagioclase rocks with a varying amount of opaque minerals, generally in accessory amounts although Neoproterozoic intrusions are characterised by essential amounts of ilmenite, which may reach over 15% vol. Some dolerites are quartz-bearing, others olivine-bearing, and in some cases olivine is completely replaced. The main accessories are biotite, hornblende, zircon, sphene and apatite; garnet, associated with chlorite, is mentioned by Davies *et al.* 1963). Rocks of all ages may show alteration features and the degree of alteration, both of feldspar and mafic minerals, varies locally. The most severely altered are often greenish, typically with chlorite, uralitisation of pyroxene, and sericitisation and/or saussuritisation of feldspar. Some rocks, although fresh-looking in hand sample, may show intense alteration of the feldspar with no fresh laths preserved. The mineral alteration is considered to be deuteric.

The basaltic intrusions are post-tectonic in a regional sense so that they appear as undeformed linear, tabular bodies; a few dykes have sinuous forms. Most bodies show some degree of jointing and fracturing: many show dark green discoloration zones and chlorite films, while epidote and calcite are the most common vein fillings. Joints can be closely spaced and sills are characterised by vertical joints, and in places by columnar jointing (e.g. Munck 1941, figs 9, 12; Dawes 1997, figs 59B, 71).

Chemical characteristics and magmatic types

Major element chemistry for *c.* 100 samples of Proterozoic basaltic rocks from North-West Greenland is available in Survey archives. The majority of analyses are from intrusions and effusive rocks within the Thule map region, with eight (7 sills and 1 dyke) from Ingle-

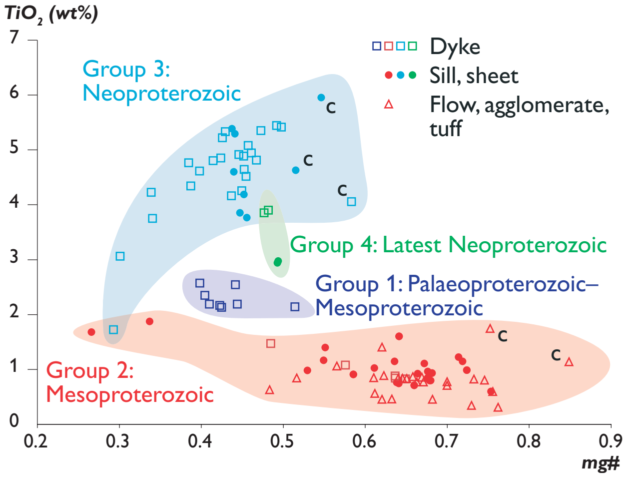


Fig. 40. TiO_2/mg# plot of 98 basalt samples showing four magmatic groups. All samples are from the map region except five Mesoproterozoic sills from Inglefield Land to the north. The plot includes the four analyses from the Palaeoproterozoic Melville Bugt dyke swarm and two from the Neoproterozoic Thule dyke swarm given in Nielsen (1990, table 1) and Nielsen (1987, table II), respectively. **Group 1**, continental dyke magmatism; **group 2**, intracratonic basin volcanism; **groups 3 and 4**, rift-related magmatism. **c**, cumulative sample. Representative analyses of the four groups are given in Table 2.

Table 2. Representative chemical analyses of Palaeo-, Meso- and Neoproterozoic basaltic rocks

Analysis no.*	1	2	3	4	5	6	7	8	9	10	11
GGU no.†	165818	141023	212497	212489	243210	212653	212610	166197	212570	212519	166621
Type	dyke	dyke	dyke	dyke	dyke	lava	lava	lava	sill	sill	sill
Group‡	1	1	1	2	2	2	2	2	2	2	2
SiO_2	48.29	49.20	48.44	51.68	50.65	48.87	53.91	51.61	49.52	48.25	52.52
TiO_2	2.04	2.30	2.47	0.86	1.44	1.01	0.73	0.81	0.80	0.98	0.89
Al_2O_3	18.32	14.60	13.28	14.22	13.06	13.97	13.03	13.85	13.96	14.81	14.01
Fe_2O_3	4.84	3.71	4.84	1.61	4.14	9.28	5.25	6.95	6.41	8.31	2.39
FeO	5.25	10.69	10.74	7.62	9.36	4.33	2.73	2.74	2.85	3.72	6.43
MnO	0.26	0.16	0.17	0.12	0.17	0.08	0.12	0.10	0.10	0.13	0.11
MgO	5.03	4.71	5.91	7.85	6.09	8.15	7.51	7.91	8.91	8.71	8.39
CaO	5.31	7.23	9.08	11.72	9.76	8.04	6.05	7.08	8.31	6.71	9.03
Na_2O	3.43	2.98	1.84	1.69	2.42	1.23	4.09	2.97	2.23	2.22	1.94
K_2O	2.62	2.26	0.54	0.48	0.85	0.69	1.76	2.96	1.92	2.48	1.02
P_2O_5	0.42	0.41	0.22	0.07	0.11	0.09	0.08	0.09	0.10	0.08	0.12
LOI	3.18	1.36	2.38	1.66	2.24	3.63	3.05	2.32	3.85	3.05	2.86
Sum	98.99	99.61	99.91	99.58	100.29	99.37	98.31	99.39	98.96	99.45	99.71
FeO′	9.61	14.03	15.01	9.07	13.09	12.68	7.45	8.99	8.62	11.20	8.58
mg#	0.51	0.40	0.44	0.64	0.48	0.57	0.67	0.64	0.68	0.61	0.66

mg# calculated after correction of Fe_2O_3/Fe_2O_3 + FeO = 0.15.

* analyses are arranged from 1 to 22 in general younging order to correspond with the chronology of Table 1.

† six digit numbers refer to samples in the collections of the Geological Survey of Denmark and Greenland (GEUS), Copenhagen. All samples are from the Thule map sheet region except 140811 that is from Inglefield Land to the north.

‡ numbers 1 to 4 refer to the geochemical groups outlined in Fig. 40.

Continental dyke magmatism. Group 1: Palaeoproterozoic–Mesoproterozoic

1 Trachybasalt dyke of uncertain direction (?NW–SE) cutting Thule mixed-gneiss complex, eroded at the Thule Basin unconformity, eastern Wolstenholme Ø, Bylot Sund.
2 Trachybasalt dyke, NW–SE-trending, cutting Prudhoe Land supracrustal complex, Josephine Peary Ø, Inglefield Bredning.
3 Tholeiitic basalt dyke, NE–SW-trending, cutting Thule mixed-gneiss complex, Sermiarsupaluk glacier, eastern Olrik Fjord.

Intracratonic basin volcanism. Group 2: Mesoproterozoic

4 TiO_2 and P_2O_5-poor tholeiitic basalt dyke, WNW–ESE-trending, cutting Lauge Koch Kyst supracrustal complex, west of Savissuaq Gletscher, Sidebriksfjord.
5 Tholeiitic basalt dyke, WNW–ESE-trending, cutting Melville Bugt orthogneiss complex, east of Helland Gletscher, Lauge Koch Kyst.
6 TiO_2 and P_2O_5-poor tholeiitic basalt flow, Cape Combermere Formation, north-east of Siorapaluk, Robertson Fjord, Prudhoe Land.
7 Potassic, TiO_2 and P_2O_5-poor basalt flow; Cape Combermere Formation, Kissel Gletscher, Northumberland Ø.
8 Potassic, TiO_2 and P_2O_5-poor basalt flow; Cape Combermere Formation, Robins Gletscher, Northumberland Ø.
9 Potassic, TiO_2 and P_2O_5-poor basalt sill cutting Northumberland Formation, Robins Gletscher, Northumberland Ø.
10 Potassic, TiO_2 and P_2O_5-poor basalt sill, Cape Combermere Formation, Robins Gletscher, Northumberland Ø.
11 TiO_2 and P_2O_5-poor contaminated tholeiitic basalt sill, Cape Combermere Formation, west of Kap Trautwine, Hvalsund.
12 Potassic, TiO_2 and P_2O_5-poor basalt sill within Smith Sound Group, Hartstene Bugt, south-western Inglefield Land.
13 Potassic, TiO_2 and P_2O_5-poor basalt sheet cutting foliated metagabbro of Kap York meta-igneous complex, south-east of Parker Snow Bugt.

Rift-related magmatism. Groups 3 and 4: Neoproterozoic

14 High-TiO_2 and P_2O_5 tholeiitic basalt sill within Dundas Group, Booth Sund, Steensby Land.
15 High-TiO_2 and P_2O_5 tholeiitic basalt sill within Dundas Group forming cap of Dundas Fjeld, Ummannaaq.
16 High-TiO_2 and P_2O_5 tholeiitic basalt sill within Dundas Group, Asungaaq, Northumberland Ø.
17 High-TiO_2 and P_2O_5 tholeiitic basalt dyke, E–W-trending, cutting Qaqujârssuaq anorthosite, Smithson Bjerge.
18 High-TiO_2 and P_2O_5 tholeiitic basalt dyke, NE–SW-trending, cutting Dundas Group, Nuulliit, Steensby Land.
19 High-TiO_2 and P_2O_5 tholeiitic basalt dyke, WNW–ESE-trending, cutting Narssârssuk Group, Nunngarutipaluk, Narsaarsuk, Bylot Sund.
20 High-TiO_2 and P_2O_5 trachybasalt dyke, WNW–ESE-trending, cutting Nares Strait Group, Robin Gletscher, Northumberland Ø.
21 High-TiO_2 K_2O and P_2O_5 tholeiitic basalt dyke, ENE–WSW-trending, cutting Baffin Bay Group, Morris Jesup Gletscher, Prudhoe Land.
22 Tholeiitic basalt sill, within Dundas Group, road-cut north-east of the site of Dundas village.

field Land to the north (Fig. 1). Samples show varying degrees of alteration and *c.* 18% of the analyses contain more than 4 wt% (H_2O + CO_2). However, rather than undertake a screening, 98 samples are shown in the TiO_2/mg# plot that defines four compositional age-related groups (Fig. 40). Distinguishing between sill rock and lava in the field can be difficult and even in thin section the rocks are very similar; thus the rock identifications relating to group 2 – indicated by symbols in Fig. 40 – are not definite. Twenty-two chemical analyses representing these four groups, all with a LOI values below 4, are given in Table 2. The dividing line between the fields of alkaline and tholeiitic basalt mentioned below derives from the alkali/silica diagram of Irvine & Baragar (1971).

Group 1: continental dyke magmatism (Palaeoproterozoic–Mesoproterozoic)

All but one of the eight dykes fall above the line separating alkaline and tholeiitic basalts in the alkali/silica diagram, and by this definition the rocks are alkaline. As mentioned later under *Palaeoproterozoic–Mesoproterozoic dykes (**d**$_1$)*, the NW–SE-trending dykes of the map region are part of the regional Melville Bugt dyke swarm regarded as Si-saturated to undersaturated trachybasalts and trachyandesites (Nielsen 1990). The chemical analyses given here (Table 2, analyses 1–3) are supplemented in the literature by five other analyses from the map region – four in Nielsen (1990, table 1) and one in Fernald & Horowitz (1964, p. 39).

12	13	14	15	16	17	18	19	20	21	22	[*]Analysis no.
140811[†]	165845	166630	243559	166163	141012	166643	165809	212556	140954	141038	[†]GGU no.
sill	sheet	sill	sill	sill	dyke	dyke	dyke	dyke	dyke	sill	Type
2	2	3	3	3	3	3	3	3	4	4	[‡]Group
51.30	59.42	47.52	49.52	48.88	49.16	47.91	48.12	49.24	49.90	48.78	SiO_2
0.74	0.96	5.25	4.51	3.68	4.66	4.94	5.21	4.48	3.73	2.89	TiO_2
14.09	14.39	12.31	12.57	12.36	12.15	12.27	12.06	12.45	13.08	12.46	Al_2O_3
1.86	0.66	2.70	3.56	3.08	3.37	2.80	3.48	3.49	3.22	1.43	Fe_2O_3
6.89	6.70	11.33	9.73	11.31	11.53	10.51	10.95	10.78	9.96	12.31	FeO
0.11	0.09	0.19	0.15	0.15	0.13	0.19	0.14	0.16	0.16	0.22	MnO
7.48	4.06	5.29	5.02	5.83	4.50	5.43	5.24	4.55	5.79	6.54	MgO
8.85	6.35	9.31	8.60	9.04	8.38	9.20	8.13	6.82	5.37	10.46	CaO
2.43	2.19	2.68	2.79	2.51	2.57	2.91	2.61	2.89	2.64	2.50	Na_2O
3.61	2.93	0.56	1.46	0.78	1.06	0.66	1.42	1.94	2.54	0.40	K_2O
0.08	0.11	0.48	0.40	0.30	0.49	0.50	0.50	0.49	0.64	0.27	P_2O_5
2.59	1.45	1.78	1.21	1.80	1.45	2.25	1.65	2.14	2.63	1.79	LOI
100.03	99.31	99.39	99.52	99.72	99.45	99.58	99.51	99.43	99.66	100.05	Sum
8.56	7.29	13.76	12.93	14.08	14.56	13.03	14.08	13.92	12.86	13.60	FeO´
0.64	0.53	0.44	0.44	0.46	0.38	0.46	0.43	0.40	0.48	0.49	mg#

Group 2: intracratonic basin magmatism (Mesoproterozoic)

The dykes, and the majority of the sills and volcanics, fall within the tholeiitic field in the alkali/silica diagram, and thus match the classification of the Mesoproterozoic basalts from the western part of the Thule Basin in Ellesmere Island (Frisch & Christie 1982). The wide scatter of points in an alkali/silica diagram, particularly of the effusive rocks, bears witness to the high mobility of alkalis. The rocks are characterised by being relatively poor in TiO_2 and P_2O_5 (Table 2, analyses 4–13). The ten chemical analyses given here are supplemented in the literature by eleven from Ellesmere Island given in Frisch & Christie (1982, table 1, appendix p. 13).

Groups 3 and 4: rift-related magmatism (Neoproterozoic)

Most intrusions of this group are quartz tholeiites having both hypersthene and quartz in the norm, but some are alkaline basalts (e.g. Table 2, analysis 20). All sills fall below the line dividing tholeiitic and alkaline fields in the alkali/silica plot, while the majority of dykes also fall within the tholeiitic field. The rocks are characterised by relatively high TiO_2 and P_2O_5 (Table 2, analyses 14–20); for example, the mean TiO_2 contents of four sills and eight dykes from southern Steensby Land quoted in Dawes (1989) are 5.3 and 4.9 wt%, respectively. Two dykes from the map region, classified as a Fe- and Ti-rich tholeiite (GGU 212407) and a trachybasalt with 1.76 K_2O (GGU 166161), are cited in Nielsen (1987, table II; note that the latter sample is incorrectly given as 116161). Four dykes and five sills of comparable chemistry are included in the mean of nine samples given in Steenfelt (2002, table 3). Dykes with matching composition – both the high ratio of tholeiitic to alkaline dykes, and major element chemistry – occur in Ellesmere, Coburg and Devon Islands in Canada; for example, the eight analyses given in Frisch (1988, table VIII) have a mean TiO_2 of 4.7 wt%. The few sills and dykes separated out as group 4 have lower TiO_2 and very variable K_2O and CaO (Table 2, analyses 21, 22).

Dolerite dykes

Dykes show a very wide range of direction and frequency. Some are traceable throughout the map sheet and are part of regional swarms that extend into Canada (Fig. 1, inset), others represent more local swarms, while clusters of dykes with no preferential orientation are presumably controlled by local structural conditions. Main swarms strike WNW–ESE, NW–SE and NE–SW; subsidiary directions are northerly, varying between NNW–SSE, N–S and NNE–SSW. Other directions can be found on the map, for example E–W-trending dykes at the head of Inglefield Bredning described by Nutman (1984). An interesting structural condition is that the NW–SE to WNE–ESE sector, in particular, has been favoured by dykes during all three periods of basic magmatism (Palaeo-, Meso- and Neoproterozoic) and cases are known where a Palaeoproterozoic master dyke has been utilised by a Neoproterozoic dyke, as for example on Thom Ø in Melville Bugt.

The majority of dykes range from a metre-wide to

Fig. 41. Two $\mathbf{d_1}$ basic dykes (pre-Thule Basin) cutting polydeformed, multiphase orthogneisses of the Thule mixed-gneiss complex. The NW–SE-trending dyke parallel to the glacier and the southern branch of Olrik Fjord is *c.* 150 m thick and has an age of 1628 Ma being part of the latest Palaeoproterozoic Melville Bugt dyke swarm (Table 1). The thinner dyke cutting it is NE–SW-trending and of Mesoproterozoic age. **Dashed line** accentuates a refolded isoclinal hinge. Note the well-developed plateau surface that coincides with the Mesoproterozoic (Calymmian) peneplain. North-eastern side of Sermiarsupaluk glacier with height of plateau above glacier *c.* 700 m a.s.l.

c. 75 m thick; the thickest dykes, some exceeding 200 m occur along the Lauge Koch Kyst. Portrayal of dykes on the map is diagrammatic with representation aided by two line thicknesses that broadly correspond to widths, below and above 50 m. Dykes below *c.* 10 m thick are not shown unless closely spaced in a swarm.

Most dykes are composed of homogeneous dolerit. Porphyritic varieties have normally randomly orientated plagioclase laths, occasionally with preferred 'flow' orientation parallel to contacts. Some dykes in Melville Bugt have feldspars up to 6 cm long within a central core. Several dykes that at first sight appear composite show strong differential weathering, often with a reddish centre (Fig. 2).

The oldest dykes ($\mathbf{d_1}$) have a grey colour on the map. All other dykes are black but not all have been given a qualifying symbol. This is due to two things: (1) it is impractical in areas of map detail, for example in southern Steensby Land, where incessant use of $\mathbf{d_2}$ would clutter and where it is also superfluous in such a dense swarm where dykes are interrelated and coeval, and (2) in shield exposures, it signifies areas where many dykes have been plotted from aerial observations and photo-interpretation, and where age assignment would amount to guesswork.

This cautious approach has proved its worth. For example, on Nunatarsuaq, north of Harald Moltke Bræ, where more than two dozen WNW–ESW- to NW–SE-trending dykes are plotted within the shield mainly from aerial photographs and a published map (Fernald & Horowitz 1964, plate 1). On face value, these dykes might be taken for a single swarm. On the map, age symbols are only given to four dykes: two marked **d** and two $\mathbf{d_2}$. This indicates to the map user that the dykes are thought to be of more than one age but that the age of individual bodies is uncertain. Some dykes clearly are part of the Neoproterozoic $\mathbf{d_2}$ swarm conspicuous through Steensby Land cutting the Thule Supergroup, and comparative geochemistry shows that Palaeoproterozoic–Mesoproterozoic ($\mathbf{d_1}$) dykes (pre-Thule Basin) also occur. Moreover, Mesoproterozoic dykes might also be represented since such dykes in western Melville Bugt strike towards this area (see below, under map units).

Where the relationship to the Thule Basin strata is unknown, dyke direction played an important role in the map unit classification. However, data refinement has led to reclassification, for example, several dykes marked $\mathbf{d_2}$ on the map are now thought to be older (Table 1).

Palaeoproterozoic–Mesoproterozoic dykes (d_1)

Name, direction and distribution. This map unit is composed of dykes of two main directions, viz. NW–SE (varying to WNW–ESE) and NE–SW (varying to NNE–SSW) (Table 1). The former dykes represent the northern part of the *Melville Bugt dyke swarm* (MBDS) of Nielsen (1987), that is traceable for at least 1300 km along the western coast of Greenland (Fig. 1, inset). The distribution of MBDS shown in Nielsen (1990, fig. 1) can be extended north into Inglefield Land, thus increasing the width of the swarm by about 75 km (Dawes 2004, fig. 13).

Age: The K-Ar age range of 1670–1450 Ma given on the map straddling the Palaeoproterozoic–Mesoproterozoic boundary is based on four dykes: three NW–SE-trending dykes and one trending NE–SW. The former dykes are from inner Olrik Fjord, on the north-east side of Sermiarsupaluk (1667 ± 50 Ma; Fig. 41), from Josephine Peary Ø at the head of Inglefield Bredning (1563 ± 60 Ma) and on Thom Ø, an island in Melville Bugt (1450 ± 44 Ma); the NE–SW-trending dyke is from Balgoni Øer, Melville Bugt (1538 ± 46 Ma) (Dawes *et al.* 1973; Dawes & Rex 1986). The latest Palaeoproterozoic (Statherian) age of the MBDS is established by a U-Pb baddeleyite age of 1628 ± 3 Ma on the Sermiarsupaluk dyke (Denyszyn *et al.* 2005) and 1629 ± 1 Ma obtained from a dyke south of the map region (Hamilton *et al. 2004*) (Table 1). The presence of dykes older and younger than the MBDS is based on field relationships. For example at Kivioq Havn, Melville Bugt, a slightly sheared, greenish-weathered NNE–SSW-trending dyke is cut by a MBDS dyke (P. Hyldegaard Jensen, personal communication 1980, cited in Dawes & Frisch 1981, p. 23) while at Sermiarsupaluk, Olrik Fjord, a NE–SW-trending dyke cutting a MBDS dyke has a K-Ar whole-rock age of 1313 ± 39 Ma (Fig. 41; Dawes & Rex 1986).

The pre-Thule Basin age is confirmed by field relationships, for example, the sea cliffs of north-eastern Wolstenholme Ø, where a vertical, greenish and somewhat altered dyke – of unknown direction and too small to show on the map sheet – is seen to be truncated by the unconformity below the Wolstenholme Formation (Dawes 1975; Table 2, analysis 1).

Characteristics. *NW–SE-trending dykes* (and related trends) occur throughout the Lauge Koch Kyst and shield areas in the central part of the region, to Prudhoe Land in the north. The northernmost dykes marked as $\mathbf{d_1}$ are at the head of Inglefield Bredning, on Josephine Peary Ø and west of Hubbard Gletscher but some dykes in Prudhoe Land (some marked **d)**, for example the dyke west of Verhoeff Gletscher, are part of this swarm. Dyke rock is characteristically dark weathering, somewhat greenish, and fairly resistant compared to younger dykes. This is exemplified in Melville Bugt, where traces of major dykes offshore are outlined by series of small gabbro islets, for example Ajukus Skær and the small skerries to the east-south-east. Dykes in Melville Bugt represent the thickest of the map region with several between 150 and 200 m thick. One master dyke that in places is more than 225 m thick crosses Levin Ø, Helprin Ø and Bryant Ø.

As discussed earlier (under *Dolerite dykes*), some dykes crossing the semi-nunatak Nunatarsuaq, just north of Harald Moltke Bræ, are regarded as part of MBDS although not marked as such on the map. Evidence for this is two-fold: (1) dykes are on direct strike with the $\mathbf{d_1}$ dykes around Mohn Gletscher in Melville Bugt (cf. Nielsen 1990, fig. 1), and (2) the one chemical analysis available from Nunatarsuaq (Fernald & Horowitz 1964, p. 39) matches the composition of other MBDS dykes (Group 1; see above under *Chemical characteristics and magmatic types*).

Few of the *NE–SW-trending dykes* (and related trends) of the region are designated $\mathbf{d_1}$ on the map, although it is considered likely that the majority are of this age. Of the three dykes discussed above under *Age*, the Balgoni Øer and Kivioq Havn dykes are too small to show on the map while the Sermiarsupaluk dyke is part of a swarm designated $\mathbf{d_1}$ by its grey colour. The northerly continuation of this swarm is on the nunatak to the north of Anngiusalipaluk, while sporadic dykes marked **d** occur to the west and farther north on Nunatarsuaq. These dykes are considered the north-eastern part of a swarm that is traceable to the Baffin Bay coast where dykes marked **d** occur between Kap Atholl and Sineriarsua. The intervening region includes the terrain shown on the maps of Davies *et al.* (1963, plate 1) and Fernald & Horowitz (1964, plate 1) where NE–SW-trending dykes are sporadically marked **d**. To the west, the dyke swarm is concealed by Thule Basin deposits and to the east by the Inland Ice. The easternmost dykes appear to be those at Sineriarsua and dykes on the nunataks bordering De Dødes Fjord, for example the dyke shown on the map north-north-east of the quartzite (**qt**) exposures.

Composition. Chemical analyses of eight $\mathbf{d_1}$ dykes define compositional group 1 of alkaline basalt (Fig. 40; Tables 1, 2 and under *Chemical characteristics and magmatic types*). Petrological descriptions of two olivine-bearing, NW–SE-trending dykes from Melville Bugt (Bryant Ø and Sundt Ø), referred here to the MBDS, are given in Callisen (1929) while a NE–SW-trending dyke is described in Davies *et al.* (1963, p. 38). The descriptions of Fernald & Horowitz (1964) embrace both $\mathbf{d_1}$ and $\mathbf{d_2}$ dykes.

Neoproterozoic dykes (**d**$_2$)

Name, direction and distribution. Dykes of this map unit are mainly WNW–ESE-trending with variation to E–W and NW–SE. Referred to as the 'Thule WNW dyke swarm' (Nielsen 1987) or simply the 'Thule dyke swarm' (TDS; Dawes 1988b; Dawes 2004, fig. 13), they are an expression of the Franklin magmatic event, defined from Arctic Canada. The swarm extends both to the north and south of the map region, and it strikes west into Ellesmere and Devon Islands (Fig. 1, inset; T. Frisch, personal communication 1980; Frisch 1984a, b, 1988; Dawes 1997, fig. 80). Its precise southern limit is uncertain but **d**$_2$ dykes are present on the map of Escher (1985b). To the north in Inglefield Land, the swarm disappears beneath the Cambrian strata of the Franklinian Basin, thus delineating a swarm more than 300 km wide (Dawes 2004, fig. 13).

However, the fact that older dykes of the same trend occur along the Lauge Koch Kyst makes correlation on direction alone spurious. For this reason, dykes in the south-east of the map sheet, for example around Duneira Bugt, although probably part of this swarm, are specified as **d.** The westernmost dyke of the map sheet on Nordvestø, Carey Øer, also marked **d**, is regarded as part of the TDS (see below under *Composition*). The long-standing correlation across Baffin Bay based on dyke trend and chemistry has recently been refined by geophysical signatures, which reveal that individual dykes can be traced uninterruptedly across Smith Sound (Fig. 1; Damaske & Oakey 2003; Oakey 2005).

Age. The Hadrynian K-Ar age range of 675–630 Ma given on the map is based on three dykes: two within the map region (676 ± 25 and 645 ± 26 Ma) and one (627 ± 25 Ma) in Inglefield Land to the north. A dyke south of Pituffik air base has a K-Ar age of 727 ± 30 Ma (Dawes *et al.* 1972, 1982b; Dawes & Rex 1986). Dykes of this group post-date Thule Basin sedimentation, **s**$_1$ sills and at least some of the sheets marked **s**, and early extensional faulting (Fig. 4; Table 1; see under *Age of the faulting*). Several dykes mapped as **d**$_2$ are now known to have a chemistry quite different from Neoproterozoic intrusions, and affinity to Mesoproterozoic magmatism is suggested (see below, *Dykes of uncertain age (**d**) at time of map compilation*).

Characteristics. The **d**$_2$ dykes form the most dense swarm of the map region and in areas such as Steensby Land, they are particularly conspicuous features, both in the landscape and on the map (see front cover illustration). Most of the dykes are vertical or nearly so and the few dips given on the map are steep (75°) to the north and south. A preference for northerly dips is recorded by Davies *et al.* (1963) for dykes south of Pituffik. Most dykes are composed of homogeneous dolerite but some are porphyritic, and several 'big feldspar dykes' have been noted, for example on the islands in Melville Bugt.

The dykes tend to weather in brownish hues and their morphological form depends much on the host rocks. Thus within Thule strata, dykes often form ridges, whereas within shield outcrops they tend to form depressions with poor dolerite exposure, or deeper gullies, for example, the cleft giving the name to Kløft Ø in Melville Bugt (see Munck 1941, figs 14, 16; Davies *et al.* 1963, fig. 15; Dawes 1997, figs 95, 106). Since **d**$_2$ dykes are subparallel with the older dykes (both MBDS and Mesoproterozoic dykes, see Table 1) that tend to form positive features in the landscape, weathering characteristics are useful distinguishing features. TDS dykes are parallel to faults of the Thule half-graben system and they are located along them, as for example the Itilleq Fault of the Olrik half-graben. Regionally, the swarm retains its WNW–ESE trend far to the east of the present exposures of the Thule Basin.

In the Steensby Land swarm, *en echelon* patterns have developed, dyke bifurcations are common and master dykes locally peter out into dykelets. It is also apparent that several generations exist shown by cross-cutting relations of dykes of slightly varying direction. In detail, dykes have exploited local fracture directions and at least some of those shown on the map trending towards the NW and NNW, are offshoots from dykes of regional direction. Similar intrusive features are described by Nutman (1984) from Smithson Bjerge from an E–W-trending swarm, marked **d** on the map sheet, but now referred to the TDS (Table 1).

Composition. The TDS dykes – predominantly tholeiitic with some alkaline basalts – are part of group 3 (Fig. 40; Tables 1, 2, and under *Chemical characteristics and magmatic types*). Some dykes are potassic (e.g. Table 2, analysis 20), often with lower TiO_2, and these together with a few **s**$_1$ sills, define a separate group (Fig. 40, group 4). Petrological descriptions of **d**$_2$ dykes south of Pituffik are given in Davies *et al.* (1963), including the Nunngarutipaluk dyke, north of Narsaarsuk, also studied by Munck (1941, table 2, fig. 16; see Table 2, analysis 17). The description of the quartz diabase dyke on Nordvestø, Carey Øer, by Munck (1941), marked **d** on the map sheet, suggests it to be part of TDS.

Dykes of uncertain age (**d**) at time of map compilation

Direction and distribution. This map unit comprises dykes within shield exposures that at the time of compilation could not be assigned with reasonable confidence to the pre- and post-Thule Basin swarms (**d**$_1$ and **d**$_2$). The dykes have a wide range of directions, with thin swarms having local preferences to the WNW, NW, NNW, N, NNE and E. A main concentration is in the region farthest away from Thule Basin, viz. in the south-eastern part of the map sheet, east of Docker Smith Gletscher, where small swarms of preferentially oriented dykes trend to the NNW, N and NNE. Some dykes have sinuous trends. In the same area, several dykes have trends matching dated regional swarms, viz. MBDS and TDS but the reasons for hesitancy to correlate what seems obvious have been mentioned earlier (see under *Dolerite dykes*).

Age. It is now known that dykes marked **d** have a wide range of ages representing the three main periods of Proterozoic magmatism. As mentioned above under *Map revision* and in the **d**$_1$ and **d**$_2$ map unit descriptions, several of the dykes marked **d** on the map can now be reclassified on the basis of refined petrological and chemical information (Table 1). The main examples are: (1) the poorly exposed swarm of E–W-trending dykes on Smithson Bjerge described by Nutman (1984) is part of TDS (**d**$_2$, Table 2, analysis 18), (2) several WNW–ESE-trending dykes, such as on Carey Øer, are regarded as part of TDS (**d**$_2$), (3) several NW–SE-trending dykes such as north of Harald Molkte Bræ, are referred to MBDS (**d**$_1$), (4) the NE–SW-trending swarm stretching from the Baffin Bay coast, south of Pituffik, to the Inland Ice is part of **d**$_1$ and (5) several WNW–ESE-trending dykes along the Lauge Koch Kyst (some also marked **d**$_2$ on the map) are part of a Mesoproterozoic swarm not recognised on the map sheet (Table 2, analyses 4, 5). Some of these dykes may well be feeders to the main episode of Mackenzie volcanism of the Thule Basin (Cape Combermere Formation; Fig. 4). One such dyke at Kivioq Havn, Melville Bugt, that cuts a NE–SW-trending **d**$_1$ dyke, has given a K-Ar whole-rock age of 1016 ± 30 Ma, a latest Mesoproterozoic (Stenian) age not far removed from the age of six sills cutting Thule strata within and north of the map region, that have a K-Ar range of 1190–1070 Ma (Dawes *et al.* 1973, 1982b; Dawes & Rex 1986).

A wide range of orientations also characterise the 'Hadrynian and ?older' dolerite dykes on the Canadian side of northern Baffin Bay (Frisch 1988). In addition to the western extension of the TDS (described as 'easterly' dykes), three favoured directions are: 'northerly', 'northeasterly' and 'northwesterly' matching **d** swarms mentioned above. Canadian dykes are characterised by high TiO_2 corresponding to the chemistry of the Neoproterozoic **d**$_2$ dykes of the map region (Fig. 40, group 3). Although by no means conclusive evidence, this comparative geochemistry strengthens the assumption from field characteristics that the majority of the **d** dykes are 'late' in the dyke chronology and products of the Franklin magmatic event.

Dolerite sills and sheets

Two groups of flat-lying to shallow-dipping tabular intrusions are distinguished on the map by colour: black (**s**) and blue (**s**$_1$). They vary from bodies a few metres to *c.* 100 m thick and the majority are exposed within Thule Basin strata. The few sheets known are shallow- to moderately-dipping bodies discordant to Thule strata, as well as subhorizontal bodies cutting shield lithologies. The most concentrated and conspicuous sills on the map are within the Dundas Group and are grouped as unit **s**$_1$. All others, including sheets of uncertain age within the shield, are marked **s**. The sills are of two main ages with respect to the Thule Basin: coeval with sedimentation (Mesoproterozoic) and post-sedimentation (Neoproterozoic). No sills of pre-Thule Basin age, matching the Palaeoproterozoic–Mesoproterozoic dyke magmatism, have been identified. The Neoproterozoic bodies represent several magmatic events: a main event prior to the major extensional faulting (**s**$_1$) and perhaps two post-faulting events (Table 1; see under *Map categories and their age*, section *Chronology*).

Many more sills have been mapped than shown on the map. For example, sills are an integral part of the Cape Combermere Formation that is not graphically shown but included in the *Nares Strait Group, undivided* map unit (see under *Map revision,* section 9). It is also difficult to portray flat-lying tabular bodies in vertical sections that characterise many parts of the coast. Thickness is not a decisive factor since a thin sill in low-relief landscape can form appreciable outcrops whereas a thicker sill in a vertical cliff cannot be depicted. For more complete representation, the reader is referred to larger scale maps (Dawes 1988b).

Palaeoproterozoic?, Mesoproterozoic and Neoproterozoic sills and sheets (s)

Distribution and host rock. These intrusions have been seen in the central and northern part of the map region between Kap York in the south, Diebitsch Gletscher in the north and Carey Øer in the west. As diagrammatically represented in Fig. 4, they have four habitats: (1) sheets within the shield, as on Carey Øer and in the area between Parker Snow Bugt and Kap York (Fig. 42), (2) sills within the Nares Strait Group and in equivalent strata as on Piulip Nunaa, Prudhoe Land (see under *Map revision*, section 9), (3) sills within the Baffin Bay Group in Prudhoe Land (Figs 5, 37) and (4) sheets cutting the Dundas Group and later faults, as on Wolstenholme Ø.

Age. Sills or sheets of pre-Thule Basin age have not been recognised. However, since dykes of this age underlie the region, the presence of sills of similar age cannot be discounted. The sills within the *lower* Thule Supergroup have three main stratal levels, from base upwards: (1) within sandstones of the Northumberland Formation, (2) as an integral part of the Cape Combermere Formation and roughly coeval with extrusive rocks, and (3) at or above the boundary between the Nares Strait and Baffin Bay Groups (Figs 4, 5, 37; Dawes 1997, figs 12, 49A, 74, 85, 91). A baddeleyite age of 1268 Ma on a sill from the Cape Combermere Formation quoted previously (see under *Nares Strait Group*) refines the middle Mesoproterozoic (Ectasian) K-Ar age range of 1220–1205 Ma from rocks of the same formation (Table 1; Dawes & Rex 1986; see Dawes 1997, fig. 49A). Sills in the Northumberland Formation are regarded as coeval (see below under *Characteristics* and *Composition*). The K-Ar age of 1172 ± 40 Ma on a sill at Robertson Fjord, Prudhoe Land compares well with the 1190 ± 40 Ma age from Radcliffe Pynt, 10 km to the north of the map sheet (Dawes & Rex 1986; Dawes 1997, figs 27, 74).

The sills higher in the succession are of Neoproterozoic (Cryogenian) age as shown by the K-Ar age of 764 ± 30 Ma for the sill at the boundary between the Nares Strait and Baffin Bay Groups in Robertson Fjord (Dawes *et al.* 1973; see Dawes 1997, fig. 74). This date compares well with the age of 729 ± 22 Ma from Nordvestø, Carey Øer, which is the only age available from a sheet (Dawes & Rex 1986). The Wolstenholme Ø sheet is regarded as still younger in age since it post-dates major faulting (Fig. 4; Table 1; see below).

Characteristics. Sill and flow units of the Cape Combermere Formation are similar in appearance and difficult to distinguish apart (includes the sill marked **s** on the map between Bowdoin Fjord and McCormick Fjord; see under *Map revision*, section 9). Confirmed sill rock with chilled contacts may contain amygdules and what appears to be a single body may have a vesicular 'flow' top, yet retain intrusive features elsewhere. These relationships are taken to indicate a near-surface origin for the sills. Most are below 60 m thick and many are columnar-jointed suggesting they are single cooling units. The structurally lower and generally thinner sills in the Northumberland Formation are regarded has coeval as suggested by their isotopic age.

A sill up to 25 m thick occurs higher in the Thule succession, either at the boundary between the Nares Strait and Baffin Bay Groups or within the latter (Figs 4, 5, 37; see also Dawes 1997, fig. 12). This sill extends throughout Prudhoe Land where, on either side of Diebitsch Gletscher, it coincides with the plateau surface and forms outcrops fringing ice caps. In steeper dipping sections, for example on either side of Robertson Fjord, at McCormick Fjord and Castle Cliff (Kap Milne), it is not portrayed on the map, neither is it shown in the steep sea cliffs of western Steensby Land. It is, however, shown on the northern coast of Inglefield Bredning, west of Hubbard Gletscher (see Thomassen & Krebs 2004, fig. 5).

Basaltic rocks on Carey Øer have drawn frequent comment since several hill tops resembling 'skull-caps' are etched out of dolerite (Wordie 1938, p. 397; Munck 1941, fig. 2; Bendix-Almgreen *et al.* 1967, fig. 6). These summits represent the eroded remnants of a body that has the lower chilled contact preserved. At least two sheets occur. The topography of the islands is characterised by flat to shallow-sloping palaeosurfaces the age of which is uncertain (see earlier under *Erosion surfaces*). Although no outcrops of Thule strata exist (erratic blocks are profuse), the Mesoproterozoic unconformity cannot have been far above the present land surface and the basaltic magma may well have utilised it as an access route.

The sheets in the Parker Snow Bugt area, as well as the Wolstenholme Ø sheet, are shallow-dipping (Fig. 42). Davies *et al.* (1963, p. 37) recorded a dip of 27° to the south for a body (called a 'dike') on the north-eastern side of the island that was shown to reach the coast west of the northern cape. On the Thule map sheet, this body is depicted as a sheet cropping out around the north-eastern part of the island, and although also affected by faulting, the critical relationship is that it cuts the main fault juxtaposing Thule strata and the shield. In the sea cliffs of south-eastern Wolstenholme Ø, this sheet is cut by a basic dyke referred to the Thule dyke swarm ($\mathbf{d}_2$), thus fixing its Neoproterozoic age and position in Table 1 (see Davies *et al.* 1963, plate 1; Dawes 1997, fig. 93).

Composition. Chemical analyses are available of sills from the lower part of the Thule Basin (e.g. Table 2, analyses 9–11) and a single sheet within the shield (Table 2, analysis 13). The majority of Mesoproterozoic rocks are tholeiitic basalts of compositional group 2 (Fig. 40), having comparable chemistry to sills from Inglefield Land (Table 2, analysis 12) and from Ellesmere Island, Canada (see Frisch & Christie 1982). The sills in the Northumberland Formation (Table 2, analysis 9) have the same chemistry as sills and lavas from the Cape Combermere Formation (Table 2, analyses 6–8, 10, 11). The solitary sheet has higher silica but falls within the central part of the group 2 plot, suggesting affinity to Mesoproterozoic magmatism. The Mesoproterozoic sills are olivine-bearing; this mineral can be strongly altered or entirely replaced. The Neoproterozoic sills and sheets in the Baffin Bay Group

Fig. 42. Lower contact of an undeformed, shallow-dipping Neoproterozoic basic sheet (designated **s** on the map) showing apophyses cutting steeply dipping, foliated quartz metagabbro of the Kap York meta-igneous complex that shows compositional banding. Coast *c.* 10 km south-east of Parker Snow Bugt.

and on Carey Øer are quartz-bearing tholeiites. Petrological descriptions of 'quartz diabase' composing the sill at Robertson Fjord and the sheet on Carey Øer are given by Munck (1941, p. 30–31), who refers to "great quantities" of ore minerals. Her descriptions compare well with the Fe- and Ti-rich sills, the analyses of which fall in compositional group 3 (Fig. 40). The sheet on Wolstenholme Ø, regarded by the present author as a younger (post-faulting) intrusion, is described in Davies *et al.* (1963).

Neoproterozoic sills (s_1)

Name, distribution and host rock. Sills designated s_1 are concentrated within the Dundas Group. Several thin sills occur in the uppermost strata of the Baffin Bay Group, one of which is shown on the map on northern Herbert Ø (see Dawes 1997, fig. 102B). Also present but not shown in the map are occasional sills in the lower strata of the Narssârssuk Group (Imilik Formation) south of Pituffik. One sill is exposed (Dawes 1997, fig. 115) and several others are recorded in a 25 m interval of a drill core (Davies *et al.* 1963, p. 30). On the map, s_1 sills are restricted to a belt stretching from Northumberland Ø to the Pituffik area. The thickest stratigraphic section is in the Moriusaq half-graben where in southern Steensby Land the clastic strata host about 15 master sills that make up between 30 and 40% of the section (Dawes 1989). This is the *Steensby Land sill complex* (see Dawes 1997, fig. 106; also front cover illustration).

Age. Chronologically, s_1 sills post-date Thule Basin sedimentation but pre-date extensional faulting and d_2 dyking (Fig. 4; Table 1). The Hadrynian or latest Neoproterozoic (Cryogenian) K-Ar whole-rock range of 705–660 Ma given on the map is based on analyses of three sills: Dundas Fjeld, main cap and chill, 705 ± 21 Ma and 688 ± 20 Ma, respectively; Northumberland Ø, 662 ± 20 Ma and Booth Sund, Steensby Land, 661 ± 20 Ma (Dawes & Rex 1986). The youngest K-Ar ages of 610 ± 24 Ma and 532 ± 20 Ma come from samples of sill rock (possibly from the same sill) stratigraphically lower than the Dundas Fjeld cap but whose relationship to d_2 dykes is not established (Dawes *et al.* 1973). Moreover, the chemistry of this sill is notably different (see below, under *Composition*), adding to the suspicion that magmatic pulses may have continued into the latest Neoproterozoic (Sinian) and even into the Cambrian (Table 1; see earlier, under *Isotopic age determinations*).

Characteristics. The s_1 sills vary from a few metres to *c.* 100 m thick, with the majority between 20 and 50 m. They form the largest basalt outcrops of the map region, being conspicuous in the terrain due to their frequency and because the predominantly argillaceous host rocks weather recessively. Thus, sills protrude in the landscape: in slopes, flat to shallow-dipping sills form buttresses and ledges, and at the upper land surface, tablelands and the caps of mesa structures (e.g. Munck 1941, figs 4, 8 –11; Dawes 1997, figs 105, 106). Within inclined strata, cuestas are common. Sill rock can be deeply weathered, and on tablelands where the upper chill margin is eroded away, the gabbroic core is in a state of disintegration to a coarse sand (see Davies *et al.* 1963, fig. 16). In particularly exposed places, as for example the tops of table mountains like Dundas Fjeld where wind erosion is significant (see Frontispiece), irregular surfaces and honeycomb patterns are common. In well-jointed sills, like exposures at Nuulliit, spheroidal weathering is common. Most sills display columnar jointing to some degree.

Composition. The vast majority of $\mathbf{s_1}$ sills, like $\mathbf{d_2}$ dykes, are high-TiO_2 and -P_2O_5 tholeiitic basalts that together define a distinct compositional suite (Fig. 40, group 3). Two sills with lower TiO_2 (Table 2, analysis 22), one of which has given a younger isotopic age (see above), plot outside this field and together with two dykes, define a separate compositional group (Fig. 40, group 4). The petrography of sill rocks from the Wolstenholme Fjord – North Star Bugt area has been described by Munck (1941) and Davies *et al.* (1963). In most, quartz is present, either discrete or intergrown with feldspar; it forms up to 3 vol.% in three samples studied by Munck (1941, table 2). Sill rock is particularly rich in opaque minerals (magnetite and ilmenite) that reach 15% by volume.

Volcanic necks (not shown on the map)

Two basaltic structures have been interpreted as volcanic vents. One of Mesoproterozoic age on Northumberland Ø is a feeder to extrusive basaltand possible also to sills in the lower part of the Thule Supergroup (Dawes 1997, fig. 61; see above *under Palaeoproterozoic?, Mesoproterozoic and Neoproterozoic sills and sheets (**s**)*), the other within the shield is reported by Fernald & Horowitz (1964, pp. 37–38). This feature is a poorly-exposed, oval-shaped basalt outcrop with a brecciated core on the large semi-nunatak Nunatarsuaq, north of Harald Moltke Bræ. The angular breccia fragments are composed of porphyritic basalt, quartz and feldspar with a matrix rich in chlorite and hematite dust. The size and age of the structure are unknown.

Quaternary

History and status of research

Following cursory observations along the coasts passed by the early expeditions (e.g. Sutherland 1853a, b), systematic recording of glaciers and Quaternary geology was carried out in 1894 and 1895 by T.C. Chamberlin and Rollin D. Salisbury who published more than a dozen articles on the map region, focussed particularly on the Inglefield Bredning area (e.g. Chamberlin 1894–97, 1985a, b; Salisbury 1895, 1896). The first regional survey was by Koch (1928b) who described the entire Thule map region in a well-illustrated 70-page account. This includes several panoramic sketches showing the Inland Ice margin in Melville Bugt and elsewhere; invaluable material for comparative studies of recent glacial history.

Following the pre-war visits of Wordie (1938) and Wright (1939), it was the establishment of various military facilities at Pituffik and environs in the late 1940s and 1950s that fostered a range of geoscientific activities directed towards surficial deposits, ice and snow (e.g. Nicols 1953; Krinsley 1954; U.S. Army 1954; Schytt 1956; Washburn 1956; White 1956; Holmes & Colten 1960; Swinzow 1962; Davies *et al.* 1963; Dansgaard *et al.* 1969; Hooke 1970; Fountain *et al.* 1981). In addition to the main site (Thule Air Base) at the western end of Pituffik valley that was (and still is) a natural staging point for scientific ventures (see Frontispiece), the facilities included a satellite base at the ice margin just south of Store Landgletscher, and stations *on* and *within* the Inland Ice.

The satellite base called Camp Tuto (short for 'Thule take-off') was the 'gateway' to the ice and the support facility for many scientific programmes organised by the U.S. Army Polar Research and Development Center (for summary, see Fristrup 1966). These were mainly based on three experimental constructions: (1) an ice tunnel penetrating the Inland Ice that acted as an unique cold-environment laboratory, (2) a permafrost tunnel that penetrated moraine and allowed examination and testing of the characteristics of permafrost, and (3) Camp Century – the nuclear-powered 'City under the Ice' that was devoted to year-round polar research and manned in the period 1959–1967. This extraordinary subsurface installation, well known for its much-publicised ice coring, is located at 77°10′N and 61°08′W. Many results of the applied research carried out under the auspices of the U.S. Army were confidential, at least initially, but much was published in reports issued by the Corps of Engineers research agency SIPRE (*Snow, Ice and Permafrost Establishment*) and later CRREL (*Cold Regions Research and Engineering Laboratory*) (e.g. Schytt 1955; Bishop 1957; Rausch 1958; Benson 1959, 1962; Roethlisberger 1959, 1961; Goldthwait 1960, 1971; Griffiths 1960; Nobles 1960; Corte 1962; Clarke 1966; Davis 1967; Langway 1967).

The first radiocarbon dates from Greenland were obtained from deposits in the Pituffik region (Suess, 1954; Crane & Griffin 1959; Goldthwait 1960; Meyer Rubin, in Davies *et al.* 1963). Incorporation of these into the field observations of D.B. Krinsley, W.E. Davies and others, established the Pituffik region as the type area for glacial stratigraphy and chronology for North-West Greenland (Davies *et al.* 1963). Renewed field work supported by radiometric dating programmes in the 1960s and 1970s revisited and re-interpreted sections at Saunders Ø, Narsaarsuk and Wolstenholme Fjord, and also addressed Carey Øer and Olrik Fjord (e.g. Bendix-Almgreen *et al.* 1967; Blake 1975, 1977, 1987; Weidick 1976, 1978a, b; Kelly 1980, 1986). Kelly's field work in 1978 included observations and the first C-14 dates from the little-known Lauge Koch Kyst between Kap York and Skene Øer.

From the work cited above, it was known that the map region hosted a complex stratigraphic record that included several glacial and marine events extending back beyond the Last Glacial Maximum. However, many details of the stratigraphic record were lacking, including precise dating of the main events. Thus, the NORDQUA 86 expedition was launched in 1986 to carry out detailed work on the classical localities in the Pituffik area aided by modern dating techniques (Funder 1990; see under *History of geoscientific investigations*). This and later work in 1989 by Kelly *et al.* (1999), led to the conclusion that the Middle to Late Quaternary record is the product of three marine events – Saunders Ø (Saalian or earlier), Qarmat (Eemian) and Nuna (Holocene) – and three or four glacial events – Agpat (Saalian or earlier), Narsaarsuk (Saalian), Kap Abernathy(?) and Wolstenholme Fjord (Weichselian). The age of the oldest deposits (Agpat) is uncertain but they may have been laid down prior to 167 ± 16 ka B.P. Eemian non-marine biotas were studied by Bennike & Böcher (1992), Brodersen & Bennike (2003) and Hedenås & Bennike (2003).

In the context of the whole of Greenland, the Quaternary geology of the map region is dealt with by Funder (1989), the postglacial marine limits by Funder & Hansen (1996) and the deglaciation chronology by Bennike & Björck (2002).

Quaternary map units

The Thule map sheet is essentially a bedrock map. However, rather than display the Quaternary geology in a single 'undifferentiated' map unit, an attempt has been made to subdivide the deposits into five categories – in addition to showing primary sites of the Cape York meteorite shower. No *systematic* investigation of the Quaternary of the map region has been undertaken and the only specific mapping has been in the so-called 'North Star Bugt area' between Wolstenholme Fjord and Crimson Cliffs of the Kap York peninsula. Two maps at 1:100 000 scale of this area are published: one, entitled *Surficial geology* differentiates the Quaternary deposits into eight map units, the other displays *Glacial and related marine features* (Davies *et al.* 1963, plates 3, 4). These maps, although only of a relatively small area, proved useful in the interpretation of the glacial geology throughout the map region.

The five map units are based on field information gathered during the bedrock mapping between 1971 and 1980 (see under *Data sources, field work and map quality*), during which shells were collected for C-14 dating (e.g. Weidick 1976, 1978a). These observations were supplemented by extensive aerial photograph interpretation that included updating of ice boundaries (see below under *Recent glacial history*). The Quaternary geology is shown in more detail on the larger scale maps of Dawes (1988b), on which, for instance, the marine deposits are subdivided and features such as fluvial and marine terraces, raised beaches and high-level lateral moraines are marked.

Cape York meteorite shower

The Cape York iron meteorite shower – the only known source of meteoritic iron in Greenland – is depicted on the map by nine primary fall sites. The present state of corrosion of the pieces recovered suggests that it reached Earth more than 2000 years ago (Buchwald 1961, 1992; Buchwald & Mosdal 1985). Place names such as Meteorbugt, Meteoritø and Ironstone Fjeld, as well as many local names derived from the word 'savik' (Greenlandic for iron), pinpoint the location of the meteorite shower to the north-east of Kap York.

Meteoritic iron has been worked for generations by the Thule Inuit and it is known from archaeological sites, both as utensils and as unworked fragments. It is assumed that many fragments have been transported from fall sites near Kap York.

The eight localities shown on the map are all regarded as original landing sites; seven in the Meteorbugt area and a single site south-west of Harald Moltke Bræ. The recovered blocks range from *c.* 8 to 31 000 kg and they are now in museums in USA, Denmark and Greenland. The largest piece, called Ahnighito, was removed from Meteoritø in 1894 (Peary 1898); the last fragment discovered in 1984 was at sea level on the same stretch of coast. The largest unworked pieces found at secondary localities in Greenland are at Dundas, Northumberland Ø and at Nuulliit, Steensby Land; pieces have also been found in Ellesmere Island, Canada.

The nine map sites delimit a NW–SE-elongated fall

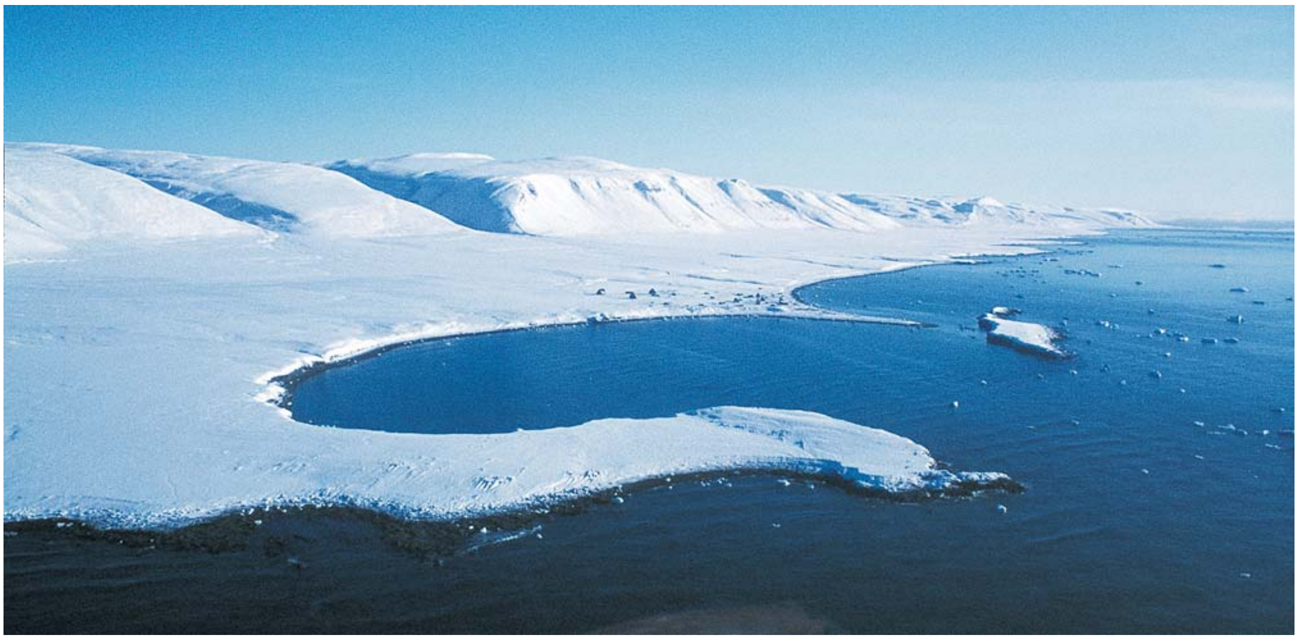


Fig. 43. Uplifted coastal plain of southern Steensby Land. View is to the east where the plain is *c.* 1 km wide, with the settlement of Morisuaq situated at the coastal spit. A dolerite sill of the Steensby Land sill complex forms the island and crops out along the beach in the foreground. Note the black colour of the active sand beaches (including the spit) due to ilmenite derived from the sills within the Steensby Land Formation (Dundas Group). The active and uplifted beaches have a potential for placer deposits. The summit level of the hinterland hills exceeds 300 m a.s.l. Photo: 14 September 1975.

pattern that is almost 100 km long; Buchwald's (1992) conclusion that fragments have been scattered over at minimum 125 × 20 km must include those found at Dundas and elsewhere. Based on the local geography characterised by relatively small strips of ice-free land, it is obvious that the recovered material represents but a fraction of the shower that reached Earth. Many fragments are assumed lost under the ice and to the waters of Melville Bugt. Since the Inland Ice is in retreat, the chances of finding more of the meteoritic shower increases with time (see under *Recent glacial history*).

Marine deposits, including raised deltas

Included in this map unit are isostatically raised marine to littoral deposits scattered along the coastline and forming rather extensive plains, tiered beaches and delta terraces. The deposits and associated marine features can form conspicuous elements of coastal geology, as for example along southern Steensby Land (Fig. 43), along Olrik Fjord and at the western end of the broad valley linking McCormick Fjord and Bowdoin Fjord.

Smaller areas of well-preserved terraced beaches including ridges and berms, occur in three main settings: (1) at bay heads, for example, Parker Snow Bugt, the broad bays along Hvalsund (east of Kap Leiningen, east of Kap Powlett, east of Asungaaq on Northumberland Ø) and at North Star Bugt where beaches flank Dundas Fjeld, showing its earlier status as an island (see Frontispiece); (2) in deltas at the mouths of rivers, such as at Narsaarsuk (see Funder 1990, fig. 7) and in McCormick Fjord, and (3) as cuspate forelands, such as at Umiivik and Inersussat, the northeastern and south-western points of Saunders Ø (see Fig. 45A). Various types of patterned ground characterise the upper surfaces of the deposits, for example large-scale polygons are common on raised delta terraces (see Davies *et al.* 1963, fig. 19; Fig. 45A).

The deposits vary from grey silt and sand, variously stratified and laminated, to coarse sand and gravel and to loose cobbles and boulders. Much of the outcrops shown on the map are of mixed facies being associated with glacial and glaciofluvial material, as exemplified by the main outcrops on Saunders Ø, southern Steensby Land (Iterlak), Dundas and Narsaarsuk (Davies *et al.* 1963; Blake 1975; Funder 1990; Kelly *et al.* 1999). Cobble to boulder beaches draping emerged bedrock terraces characterise some parts of the coast, for example on Carey Øer (Wordie 1938; Blake 1975, fig. 3) and at Qeqertarsuaq, eastern Herbert Ø (see Fig. 45B).

Shells can usually readily be recovered from marine silt and sand, and even from coarser deposits. Recent accounts of the fauna of the deposits are found in Funder (1990) and Kelly *et al.* (1999).

Alluvium and deltaic deposits

Alluvial deposits, including both fluvial and glaciofluvial material, vary from narrow thin outcrops along rivers to the thicker and more extensive areas shown on the map, as for example along braided watercourses (see Fig. 48), flat-bottomed valleys and as deltas at the mouths of major rivers. Areas of outwash sands and gravels occur in front of many glaciers, for example Scarlet Heart Gletscher, and small inland outwash plains occur, for example in the valley to the west of Tuttu Gletscher. Steep-sided valleys, such as Five Glacier Dal (striking north from McCormick Fjord), have thick alluvium on the valley floor, with coalesced alluvial fans covering the lower valley slopes.

The map unit comprises both active occurrences as well as inactive uplifted terraces that occur in some of the major coastal deltas. Fluvial terraces are shown on the larger scale maps of Dawes (1988b). Along several coastal stretches, for intance south-east coast of Piulip Nunaa, in McCormick Fjord, at the head of Granville Fjord and in Olrik Fjord, substantial submarine estuaries and deltas occur, and these can be hazardous for boats. For example, the large broad delta in front of the unnamed expanded-foot glacier reaching Olrik Fjord continues into the fjord as an extensive submarine fan so that passage at low water for vessels other than a small boat is problematic. Similar fans characterise the coast north-west of the town of Qaanaaq.

Ground moraine, glaciofluvial deposits and colluvium

This map unit comprises the most widespead of all Quaternary deposits being composed primarily of ground moraine or glacial till (non-stratified drift) that is draped over the bedrock as a thin discontinuous veneer. Only the most extensive areas are shown on the map. Deposits of purely glacial origin are preserved on many parts of the upper plateau surface, for example the inland area of shield rocks between Pituffik Gletscher and Inglefield Bredning and particularly on areas of subdued topography with flat to slightly sloping surfaces. Coarse to medium till and boulder fields are the main deposits but with gradations into areas characterised by deeply-weathered bedrock developed as felsenmeer mixed with glacial erratics. Glaciofluvial material is found in the broad river valleys and lowland plains. The till and glaciofluvial deposits have been modified by solifluction, periglacial and fluvial processes, as well as mechanical frost shattering.

Classical colluvial deposits, such as loose and incoherent scree and talus accumulations in the lower reaches of slopes or cliffs, are ubiquitous but rarely large enough to be depicted on the map (see earlier under *Exposure*). However, also included are a range of material in the lower reaches of shallower slopes in which fluvial and solifluction processes have assisted down-hill movement.

Historical moraine

This map unit comprises unvegetated, ice-marginal moraines that are associated with historically receding glaciers, such as the recent lateral moraines flanking Harald Moltke Bræ and the coarse till ridges flanking the front of Store Landgletscher (Davies *et al.* 1963, fig. 18; Fig. 27). Several moraines form prominent features, for example where lateral moraines are left isolated as promontories or spits protruding seawards, such as the rugged ridge at Pitoraavik or the northern moraine of Harald Molkte Bræ, the end of which is now *c.* 5 km west of the glacier front.

Well-preserved, arc-shaped terminal moraines characterise several glaciers. Some of the most spectacular are those encroached by the sea along the coast of Hvalsund, just west of Itilleq, and along the northern coasts of Northumberland Ø and Herbert Ø (Fig. 44A). The steep coasts of Herbert Ø characterised by cirques and scree slopes, display several very prominent moraines, some of which are composed of multiple arcuate ridges. Some of these deposits lack visible glacier ice and represent impressive rock glaciers (Fig. 44B).

Ice margin deposits and medial moraine

A green dotted line is used on the map to mark two types of linear morainic deposit: (1) the medial moraines of active glaciers, and (2) older features on bedrock or ground moraine now isolated from glacier ice, such as the high-level moraines on nunataks bordering Chamberlin Gletscher and the morainal ridges in the broad, lake-filled valley east of the head of McCormick Fjord. The latter locality preserves the recessional positions of a major ice mass that once filled the low ground between McCormick and Bowdoin Fjords. The moraine system, shown in more detail on the 1:100 000 map (sheet 2, Qaanaaq, Dawes 1988b) is best preserved on the south side of the valley. It comprises up to eight parallel to subparallel ridges traceable from just above lake level at *c.* 50 m to *c.* 250 m and just below a series of the alluvial fans below a bedrock escarpment. The ridges are most continuous in the western end of the valley north-east of Scarlet Heart Gletscher; towards the front of Tuttu Gletscher, where there are several small morainic lakes, the ridges have been disturbed by colluvial and solifluction processes, and are less distinct.

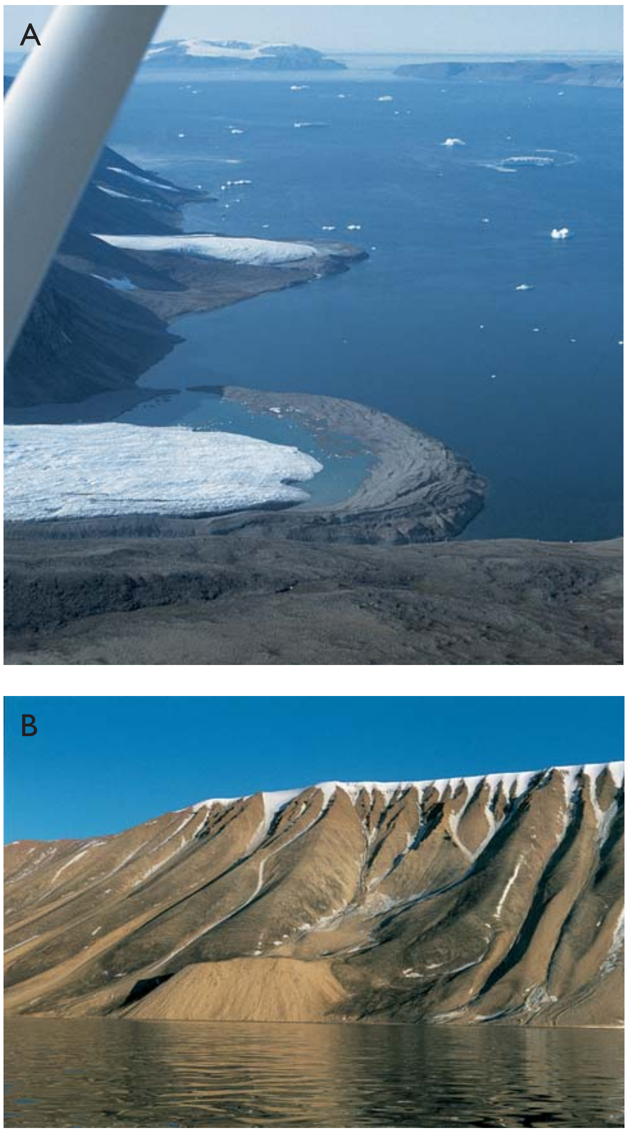


Fig. 44. Historical moraines and permafrost features. **A**: Terminal moraines of receding glaciers, Politiken Bræ (foreground) and Berlingske Bræ, south coast of Hvalsund, with Northumberland Ø and Herbert Ø in background. Photo: 10 August 1983. **B**: Active rock glacier composed of arcuate, steep-sided talus and ridge with a depression behind. Height of talus is *c.* 100 m, with ice-capped background cliffs at 800 m a.s.l. Southern coast of Herbert Ø, west of Qeqertarsuaq village (now abandoned). Photo: 19 August 1974.

Marine limits

The highest shell-bearing marine silt and sand in the map region are *c.* 60 m a.s.l. Well-developed, terraced beach systems, such as those at Qeqertarsuaq, eastern Herbert Ø and along Hvalsund contain up to a dozen tiered low-gradient levels and in several, beach deposits are continuous from the marine limit down to modern storm-wave beach ridges. Ten levels, some very conspicuous but others weakly developed, have been measured by hand-level at Qeqertarsuaq. The rounded-off altitudes are: 9 m, 16 m, 23 m, 28 m, 36 m, 41 m, 49 m, 62 m, 69 m and 84 m a.s.l. (Fig. 45B). All levels are regarded as marking marine events since there is no evidence of prominent fluvial action and within the system there are also emerged sea cliffs etched out of bedrock. The upper level at *c.* 84 m, that is partly overriden by talus, is taken as the upper Holocene marine limit.

This level matches the *c.* 86 m marine limit established to the north of the map region around Smith Sound (Fig. 1; Nichols 1969). Accurate determinations of the marine limit between Herbert Ø and Inglefield Land are sparse but to the south, in the well-studied Carey Øer – Bylot Sund – Inglefield Bredning area, it is markedly lower, between 35 and 65 m a.s.l. (Kelly *et al.* 1999). Farther south along the Lauge Koch Kyst and south of the map region there are few determinations but these suggest a much lower marine limit, less than 20 m a.s.l. (Funder & Hansen, fig. 3). Thus, seen regionally, the Holocene marine limit falls to the south-east.

Higher altitude shoreline features, such a bench marks, also occur and in some delta terraces, for example those east of Kap Leiningen, Hvalsund, there is a water-worn level at *c.* 90 m a.s.l. Since it is now known that there are at least two pre-Weichselian marine events, such high-level features might be of pre-Holocene origin. Another possibility is that they are derived from an ice-dammed lake when ice blocked the entrance of Hvalsund.

Glacial erratics and deglaciation

Glacial erratics occur throughout the map region including the outermost islands – Carey Øer in the west and Sabine Øer in the south – and from sea-level to the highest plateau elevations of the 'Thule Upland' that near the Inland Ice margin in eastern Steensby Land are in excess of 1100 m a.s.l. Along the Lauge Koch Kyst, erratics have been recorded on ground as high as *c.* 1250 m a.s.l. but no information is available from higher summits such as Haffner Bjerg (see earlier under *Physiography*). The presence of mainland erratics of unmetamorphosed Thule strata on the shield rocks of Carey Øer and the outer islands in Melville Bugt, indicate the large expansion of the Greenland ice sheet over the present coast and shelf. Directional data for ice movements have been summarised by Kelly *et al.* (1999).

Apart from the clear provenance shown by the Thule strata erratics, the most useful shield rocks for transport modelling are anorthosite and related lithologies that are known *in situ* only at the head of Inglefield Bredning (see under *Smithson Bjerge magmatic association*). Erratics derived from the Qaqujârssuaq anorthosite occur along the coasts of Inglefield Bredning – for example, unmistakable metre-size anorthosite and leucogabbro boulders can be readily identified along the beach at Qaanaaq – whereas cobbles are sporadic along the coast of Herbert Ø and Hvalsund. The lithologies of the blocks can be readily matched with *in situ* outcrops (Fig. 11). A variety of feldspar and feldspar-rich erratics of smaller size occur farther afield and at least some of these are deemed to have the same derivation. These observations provide convincing evidence for major ice movement from the head of Inglefield Bredning and through Hvalsund and possibly Murchison Sund.

Following work by many persons cited above under *History and status of research*, the chronology of ice sheet recession of the Thule region has been discussed by Funder (1990) and Kelly *et al.* (1999). The latest compilation of all radiocarbon dates from Greenland pertaining to the last deglaciation suggests that the present ice-free part of the map region was not deglaciated until the early Holocene, 11 000 to 9000 years ago (Bennike & Björck 2002).

Recent glacial history

Throughout western Greenland including the map region, the margin of the Inland Ice and its outlet glaciers are in retreat (Weidick 1995). However, one unnamed glacier in central Steensby Land at the head of Bowdoin Fjord is anomalous since it is in a state of advance and has been for at least 50 years (see below). Based on information from the early visitors to the region in the late 19th and early 20th centuries, much of which was summarised by Koch (1928b), this overall recession is known to have been in play for at least 100 years. Evidence of the general retreat including changes in the glaciers at the head of Wolstenholme Fjord and the appearance of new nunataks was collected by Wright (1939). Thus, Davies & Krinsley (1962), Davies *et al.* (1963) and Mock (1966) could document that in the period from 1916, the terminus position of Harald Moltke Bræ was nearly in continuous retreat interrupted by one slight advance from 1926 to 1932. The frontal recessions of the main glaciers in the map region north of Kap York have been recorded by Davies & Krinsley (1962), with an update by Kollmeyer (1980) that included the ice front in Melville Bugt.

The terminal positions of the ice margin and glaciers shown on the map sheet are compiled from aerial photographs taken in 1985. These ice limits were plotted on topographic maps constructed from aerial photography from 1947–49 (see Dawes 1992). Both positions are shown on the 1:100 000 and 1:200 000 maps that form the base material of the Thule map sheet (Dawes 1988b). These show that while some ice fronts have been almost stationary or show only minor recession in this 35-year period, for example, some of the glaciers of Prudhoe Land (Bowdoin Gletscher and Verhoeff Gletscher), others in the same area show a retreat of more than 1 km (Diebitsch Gletscher). They also show that the largest retreats have occurred on glaciers with fronts that are afloat. Thus, the largest ice wastage in the map region in this period is shown by the floating tongue of Rink Gletscher in Melville Bugt that has retreated more than 6 km on a broad front, closely followed by Tracy Gletscher at the head of Inglefield Bredning. Immediately south of the map sheet, the floating ice margin of Hayes Gletscher also shows appreciable ice wastage with the appearance of new land as nunataks (Kollmeyer 1980).

The general pattern seen in the 35-year period to 1985 has continued until today. Thus, the floating

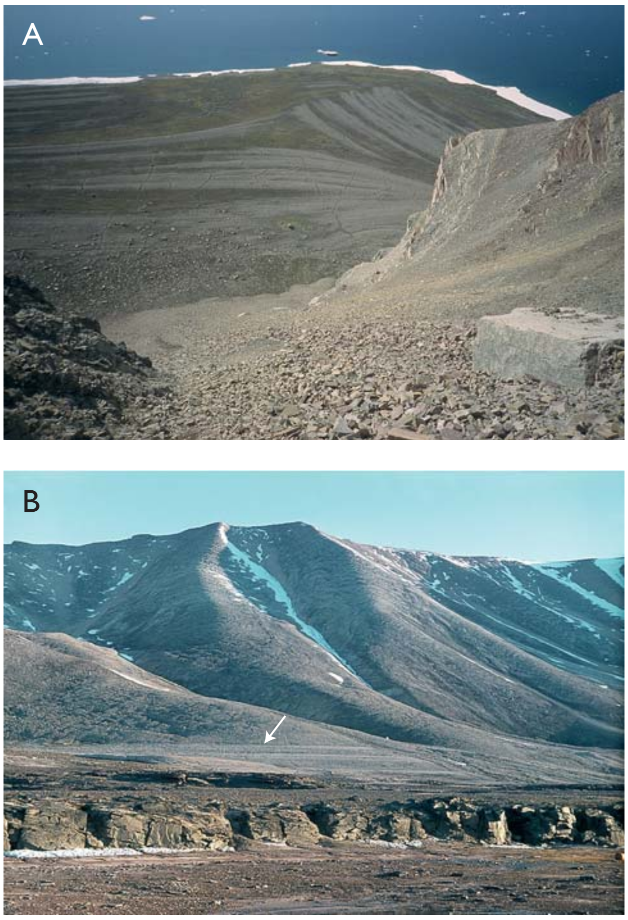


Fig. 45. Holocene littoral and marine features. **A**: Emerged beach ridges showing large-scale polygons. Cuspate foreland at Inersussat, Saunders Ø. **B**: Raised beach system west of the now abandoned village of Qeqertarsuaq, Herbert Ø, showing a prominent bedrock terrace. **Arrow** marks the uppermost strandline measured by hand-level to *c.* 84 m a.s.l.

tongue of Tracy Gletscher at the head of Inglefield Bredning that in 1947 was attached to Josephine Peary Ø and today has a front just west of the 200 m contour shown on the map sheet, shows a retreat of almost 10 km. Since the position of this glacier is also well documented in the 1890s when its front was attached to the northern coast of Josephine Peary Ø and was west of Melville Gletscher, the total withdrawal in the 120 years has been at least 12.5 km. In stark contrast, the front of Heilprin Gletscher on the south side of Smithson Bjerge has shown only limited retreat in the same period.

The overall consequence of this long-lasting recession for the nature of the coastline is considerable, particularly along the Lauge Koch Kyst, where new land is being released from the ice and where nunataks, semi-nunataks and peninsulas are being transformed to semi-nunataks, peninsulas and islands, respectively. One case of massive ice wastage in Sidebriksfjord is illustrated by Fig. 18.

The anomalous unnamed glacier mentioned above at the head of Granville Fjord forms the western extent of the 'North Ice Cap' so named in U.S. Army (1954). Evidence of ice advance along the eastern side of this ice cap has been described by Goldthwait (1960, 1971). The Granville Fjord glacier has advanced in the period 1948 to 1985 by more than 2.5 km, a movement that has changed its front from being land-grounded to a floating tongue. As mentioned in the description of the *Itillersuaq half-graben*, the glacier has now overriden rock exposures that were studied by the present author in the 1970s.

Economic geology

The commodites named on the map, and the economic geology reviewed here, relate to the three onland geological provinces: Precambrian shield, Thule Basin and Quaternary/Recent cover. The hydrocarbon resource potential of the Phanerozoic sedimentary succession in offshore basins (e.g. Carey Basin, Kap York Basin and Melville Bay Graben) is not dealt with, and for petroleum geology, the reader is referred to the literature, for example Whittaker *et al.* (1997). Here, the four metallic commodities shown on the map (**mg**, **Cu**, **py**, **il**), together with the most notable of recent discoveries, are described. The region has attracted commercial interest but drill targets have not been located, and the occurrences are of no immediate economic interest.

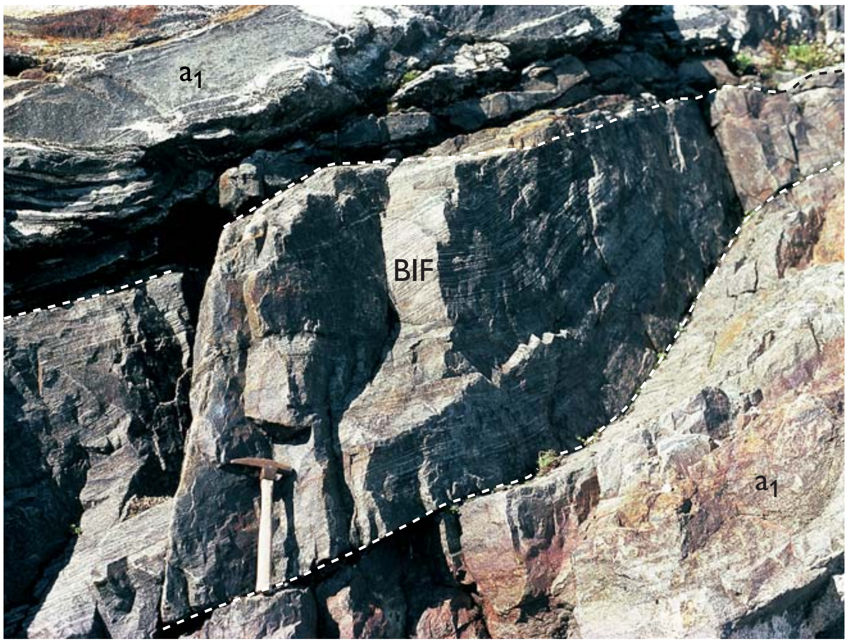
Non-metallic mineral occurrences such as evaporites are not indicated on the map. Gypsum and anhydrite occur in the Dundas and Narssârssuk Groups, with gypsum forming one bed up to 8 m thick (see under *Imilik Formation (**Ni**)*) while the Qaqujârssuaq anorthosite at the head of Inglefield Bredning – the largest single anorthosite mass in Greenland – represents a source of alumina. Raw materials of local handicraft potential, including the two shown on the map (**ag**, **sp**), have not been sufficiently publicised. This is corrected here.

Information on mineral occurrences has been added to in the last 15 years by exploration throughout much of the region *north of Kap York*, financed by the Danish and Greenlandic governments, as well as by industry (see under *History of geoscientific investigations*). Thus, many of the known metallic mineral showings have been re-investigated (Gowen & Sheppard 1994; Gowen & Kelly 1996; Thomassen *et al.* 2002a, b; Thomassen & Krebs 2004). The exceptions are the ilmenite placers (**il**) reviewed by Dawes (1989) and the iron-formation of Lauge Koch Kyst and the islands of Melville Bugt, that was last visited in the 1970s and 1980 (Dawes 1976a, 1979; Dawes & Frisch 1981) although localities around Kap Seddon were re-examined in 1998 (Thomassen *et al.* 1999a, b).

Parts of the region have been covered by geochemical surveys based on stream sediments, which have revealed anomalous concentrations of gold, copper, lead, zinc and nickel, with some exploration supported by Landsat studies (Gowen & Sheppard 1994; Gowen & Kelly 1996; Steenfelt 2002; Steenfelt *et al.* 2002; Krebs *et al.* 2003). Mineralised samples collected by the indigenous population for the so-called Greenland mineral hunt programme, *Ujarassiorit* (Ujarassiorit 1993, 1995; Dunnells 1995; Olsen 2002) include some notable anomalous metal concentrations that have been assessed in terms of the map sheet geology by Thomassen *et al.* (2002b) and Thomassen & Krebs (2004).

An important source for mineral economic occurrences is the Survey's database GREENMIN (**Green**land **Min**eralisation Data Bank; Lind *et al.* 1994; Thorn-

Fig. 46. Banded iron-formation (**BIF**) within amphibolite (**a**$_1$) of the Lauge Koch Kyst supracrustal complex; the lower amphibolite shows rusty weathering. The lensoid outcrop is part of a amphibolite unit within the Melville Bugt orthogneiss complex. Sorte Fjeldvæg, for location, see Fig. 17. Hammer is *c.* 35 cm long.



ing *et al.* 2002), that at the time of writing contains 28 entries of mineral occurrences from the map region. The reader is referred to this database for specific descriptions of the mineral showings and for analytical results.

Metalliferous commodities on the map

Only one of the four metallic commodities included on the map – black mineral sands (**il**) – reflects present-day distribution. Since map publication, new occurrences of magnetite-rich rocks (**mg**), copper mineralisation (**Cu**) and iron-sulphide mineralisation (**py**) have become known.

Magnetite (mg)

Magnetite-rich rocks or ironstones including classical banded iron-formation (BIF), are marked on the map within the Thule mixed-gneiss, the Lauge Koch Kyst supracrustal and the Melville Bugt orthogneisses complexes. The term 'iron-formation' (adopted in these notes rather than the 'ironstone' of the map legend), represents the most widespread mineralisation of the region. Of the 22 localities shown, all except one (Smithson Bjerge, see below) are located in a WNW–ESE-trending belt traceable for 350 km from Kap Seddon in the south-east throughout the Lauge Koch Kyst to Magnetitbugt and Wolstenholme Ø.

Although not identified on the map, magnetite-bearing gneiss occurs farther to the west on Nordvestø, Carey Øer, and the description of a banded 'red schistose gneissic rock' from the same island given by Bendix-Almgreen *et al.* (1967) strongly suggests the presence of iron-formation. This rock is composed of quartz, magnetite and altered feldspar, with the banding caused by alternating dark magnetite-rich and pink leucocratic bands. This observation extends the iron-formation belt another 85 km westwards.

The distribution of oxide-facies iron-formation shown on the map can also be expanded by occurrences within large tracts of the Thule mixed-gneiss complex where magnetite is enriched in paragneisses, for example in quartzitic rocks at Magnetitbjerg, north of Harald Moltke Bræ (Fernald & Horowitz 1964). One of the 'new' occurrences, the 'Mount Gyrfalco showing' in inner Olrik Fjord, has been mentioned under *Map revision* (Thomassen *et al.* 2002a, fig. 5; 2002b, figs 7, 8). The iron-formation within the Lauge Koch Kyst supracrustal complex occurs both in metasedimentary lithologies (map units **ms**, **qt**,), for example at De Dødes Fjord, Docker Smith Gletscher, Thom Ø and Bushnan Ø and in the amphibolitic rocks (map unit **a**$_1$), as at Sorte Fjeldvæg, Sidebriksfjord and north of Pituffik Gletscher (Figs 17–19, 25, 46). Iron-formation occurs in units of varying thickness: less than a metre at Kap Seddon, *c.* 3 m at Docker Smith Gletscher, *c.* 4 m at Thom Ø, *c.* 20 m at 'Mount Gyrfalco' and up to 40 m in De Dødes Fjord. Exposures of the supracrustal units containing iron-formation from the Lauge Koch Kyst supracrustal complex are illustrated in Dawes & Schønwandt (1992, fig. 3) and Schønwandt & Dawes (1993, fig. 3).

Oxide-facies iron-formation forms a very variable suite of rocks from low-grade disseminated magnetite in gneiss, amphibolite and metasediments to iron-for-

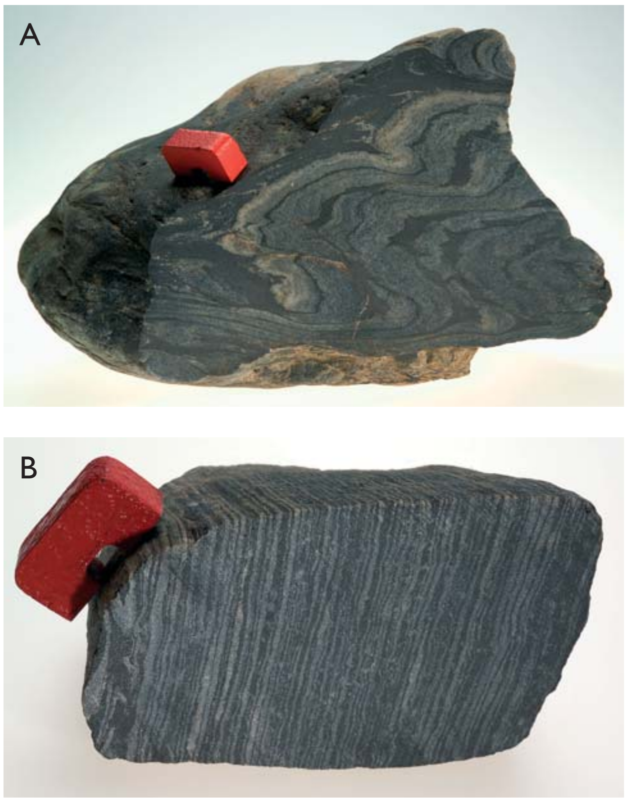


Fig. 47. Cut slabs of oxide-facies iron-formation. **A**: thin bedded variety with small-scale folds; **B**: banded iron-formation with mm-thick bands of magnetite and quartz. Erratic blocks, Camp Tuto, Pituffik, GGU 272298 and 272300. Both types form attractive stones when cut and polished. The magnet is 2.2 cm long. Photos: Peter K. Warna-Moors.

mation and high-grade massive pure magnetite beds (Figs 25, 46, 47). Banded iron-formation (BIF) composed of alternating light and dark bands varies from types in which the quartz or quartz-rich (± feldspar ± magnetite) beds more than 1 cm thick have diffuse to sharp contacts with magnetite beds, to regularly banded types in which sharp-bordered quartz and magnetite bands are of mm-scale. Structurally, iron-formation varies from laminated, and in places rather slaty rock, to small-folded types (Fig. 47). Massive layers and lenses, and monomineralic magnetite units that lack obvious macrostructure, are up to *c.* 25 cm thick.

Varying amounts of hematite and iron sulphides can be present, a factor that determines the degree of rusty weathering. Apart from iron, no anomalous metal concentrations have been recorded. The highest Fe values are from the Lauge Koch Kyst, where five BIF samples give a mean value of *c.* 33.5% (max. *c.* 41%; M. Lind, personal communication 1992). Chip samples over 6.5 m at 'Mount Gyrfalco' returned 30.5% Fe with 2.1% Mn whereas 17 samples from the Thule mixed-gneiss complex have a mean value of *c.* 28% (max. 35.5%; Thomassen *et al.* 2002b). In the literature, BIF samples are illustrated in Thomassen *et al.* (2002b, figs 6, 9, 10), with analyses in Davies *et al.* (1963), Thomassen *et al.* (2002b) and Thomassen & Krebs (2004).

The solitary **mg** symbol on the map outside the major WNW-ESE-trending belt is on Smithson Bjerge where subordinate ferruginous garnet-bearing quartzites containing magnetite and iron suphides are interlayered with quartzofeldspathic paragneisses. These meta-quartzites have been regarded as chemical sediments "perhaps akin to silicate facies banded iron formation" (Nutman 1984, p. 9; Thomassen *et al.* 2002b, fig. 11). Similar rocks exposing silicate-facies iron-formation are exposed on the east side of Hubbard Gletscher, where rusty-weathering units of garnet quartzites up to 4 m thick intercalated with paragneiss contain disseminated magnetite, pyrrhotite and pyrite with minor chalcopyrite and sphalerite (Thomassen & Krebs 2004, figs 2–4). Erratic blocks of quartz-garnet (± pyroxene ± amphibolite) rocks with a variable suite of iron minerals are common in several localities in the inner reaches of Inglefield Bredning. The Fe content of the silicate-facies iron-formation is lower than the oxide-facies. Thus, ten samples from Smithson Bjerge have returned an average of *c.* 18% Fe (max. *c.* 27% Fe) while 17 samples from the section east of Hubbard Gletscher have yielded a mean of *c.* 15% Fe (max. 20% Fe).

With its regional strike extent of more about 400 km, the Archaean magnetite province of the Thule region is spatially the largest in Greenland. It has been regarded as a correlative of the Algoma-type iron deposits of the Mary River Group of the Committee Fold Belt of northern Baffin Island and adjacent Melville Peninsula that show anomalous gold and base-metal values (Fig. 1 inset; Wilson & Underhill 1971; Dawes 1994; Jackson 2000, fig. 114; see below under *Gold*).

Copper mineralisation (**Cu**)

Three localities characterised by malachite staining are marked on the map: from north to south, on the south coast of Olrik Fjord, at Naajat on the north side of Wolstenholme Fjord and on Salve Ø north-east of Kap York. The first two within Thule Basin lithologies have been re-investigated since map compilation but found to have only modest metal concentrations; the Salve Ø locality awaits investigation.

The *Olrik Fjord locality*, known in the Survey's data bank GREENMIN and in literature as the 'Hill 620 showing', is an isolated, 100 m^2, bright green showing near a hill top within pale sandstones of the Qaanaaq Formation just north of the Itilleq Fault, the bounding fault of the Olrik half-graben (Fig. 48; Stuart-Smith and Campbell 1971; Cooke 1978). Nearby are several N–S-trending cross faults. It is composed of cm–dm-sized malachite-disseminated cobbles and slabs that generate a green tail downslope. Five primary sulphides have been identified: chalcopyrite, pyrite, bornite, digenite and covellite. The mineralisation may be controlled by the faults along which fluids entered the permeable sandstones, but copper enrichment is low. A composite grab sample shows 0.4% Cu. Several other localities of this supposed 'redbed type' mineralisation exist showing malachite staining of Qaanaaq Formation sandstones, including the chalcopyrite-pyrite mineralisation near the Kap Cleveland Fault at 'Red Cliffs', McCormick Fjord, that has yielded Cu values up to 1.5% Cu (Thomassen *et al.* 2002b, fig. 20).

The *Naajat showing*, discovered by Gill (1975), involves dark shales and thin carbonate beds of the Dundas Group and basic intrusions of the Thule dyke swarm (**d**$_2$) and Steensby Land sill complex (**s**$_1$). The malachite staining is caused by veinlets and pods of Cu- and Fe-sulphides within dolerite and host rocks. A carbonate sample returned only 0.03% Cu with 1.8% Zn (Gowen & Sheppard 1994). This mineralisation has a comparable setting to Nuulliit, where malachite staining is derived from chalcopyrite associated with pyrite mineralisation (Cooke 1978; see under *Iron-sulphide mineralisation (**py**)* below).

The *Salve Ø locality* represents several areas of vivid green staining in the sea cliffs that are composed of gneisses and metasedimentary rocks, the adjacent exposures to which contain magnetite in more than anomalous amounts.

The most notable of the occurrences discovered after map compilation are: (1) quartzite-hosted and amphibolite-hosted copper mineralisation in the Prudhoe Land supracrustal complex (Thomassen *et al.* 2002b, fig. 17; Thomassen & Krebs 2004, frontispiece); (2) malachite-stained paragneiss in the Thule mixed-gneiss complex, east of Quinnisut, Inglefield Bredning, an area that is the site of a multi-element stream-sediment anomaly (Cu, Ni, Zn, Pb) pointing to a potential for base-metal mineralisation (Thomassen 2002a, fig. 6; Thomassen *et al.* 2002b, fig. 12; Steenfelt *et al.* 2002) and (3) malachite coatings and blebs on agglomeratic rocks of the Cape Combermere Formation, studied mainly on Northumberland Ø and from where one malachite-hematite sample has returned a Cu value > 10%, with *c.* 32% Fe (Thomassen & Krebs 2004, figs 8–13). Such iron-copper mineralisation may well represent a 'redbed type deposit', possibly associated with the Kiataq Fault and thus defining a structural setting comparable to that of the 'Hill 620' copper showing farther east (Fig. 48; see under *Fault-related mineralisation*).

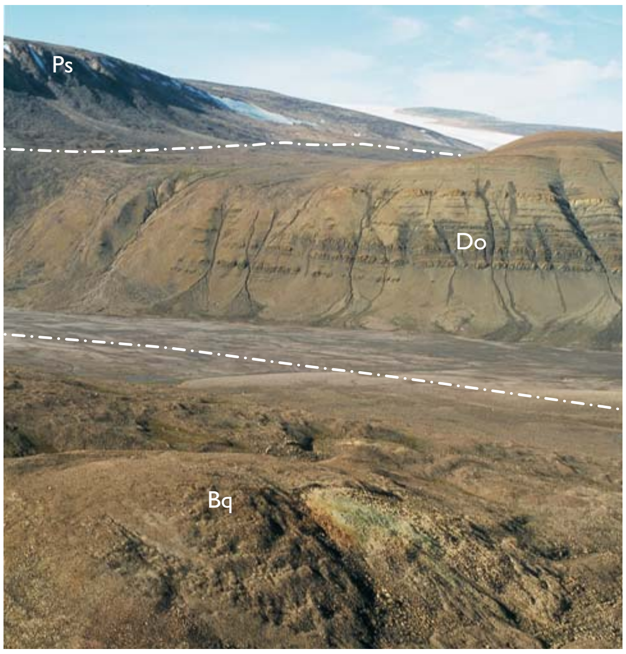


Fig. 48. 'Hill 620 showing' is the green patch on the foreground hill composed of disseminated malachite in pale sandstone of the Qaanaaq Formation (**Bq**). The showing is in the Olrik half-graben close to two major faults. The Itilleq Fault causing the escarpment in the background is the bounding fault of the half-graben juxtaposing Dundas Group (**Do**, Olrik Fjord Formation) against the shield (**Ps**); the fault in the alluvium-floored valley is a cross fault downdropping the Dundas Group against the Baffin Bay Group, the upper part of which is unit **Bq**. View is to the west with Dundas section above valley floor *c.* 300 m thick. Photo: Bjørn Thomassen.

It should be noted that some of the most promising metal values stem from the *Ujarassiorit* mineral hunt programme, for example chalcopyrite-rich rocks from Robertson Fjord and Northumberland Ø that returned Cu values > 10% (Dunnells 1995).

Iron-sulphide mineralisation (**py**)

Pyrite from southern Steensby Land has been used by the Thule Inuit for generations for producing fire, with one well-known 'firestone' locality at Nuulliit (Peary 1898). This and two other localities are marked on the map near the mouth of Granville Fjord within Dundas Group that is invaded by the Steensby Land sill complex. Although **py** indicates the predominance of iron sulphides, traces of chalcopyrite, pyrrhotite and sphalerite occur, with surfaces showing green malachite staining (Dawes 1975; Cooke 1978; Gowen & Sheppard 1994). The three localities are characterised by rusty shales and subordinate dolomites: massive pyrite pods and lenses up to 15 cm thick occur in carbonate rocks, with disseminated pyrite cubes mainly in the shales. Thin pyrite-rich sulphide veins penetrate both sediment and dolerite. The typical position of this type of mineralisation is just beneath a sill suggesting that the sulphides entered the system with the dolerite.

Many sediment/sill and sediment/dyke contacts within the Dundas Group are characterised by rusty weathering. Most seem to be indicative of the same type of mineralisation as described above that has only given modest metal values. Variations are: carbonate veins up to 50 cm wide with up 2% chalcopyrite-pyrite following fractures in sills, semi-massive pyrrhotite within a dyke at Moriusaq and galena-baryte mineralisation on Northumberland Ø (Gowen & Kelly 1996; Thomassen *et al.* 2002a). Minor sphalerite mineralisation has also been observed in the Dundas Group on Northumberland Ø with one composite sample returning 2.1% Zn (Thomassen *et al.* 2002a, fig. 7).

Apart from Archaean iron-formation mentioned above, the most promising target in the shield for sulphide enrichment is the Prudhoe Land supracrustal complex, where certain metasedimentary tracts generate conspicuous red and yellow rust zones. In sections around Bowdoin Fjord, pyrite and pyrrhotite occur in units of highly graphitic schists tens of metres thick, in which some of the sulphides have been remobilised into quartz-rich segregations during hydrothermal overprinting (Thomassen *et al.* 2002b, figs 13–16). Base-metal concentrations are low but stream-sediment geochemistry suggests units with concentrations of REE-rich minerals (Steenfelt *et al.* 2002).

Black sands, mainly ilmenite (**il**)

Black heavy mineral sands occur throughout the map region being collectively referred to as the *Thule black sand province* (Dawes 1989). The selected placer deposits marked on the map are at Kap Edvard Holm in Melville Bugt and the entire coastal stretch from Pituffik north to Kap Parry in western Steensby Land. Northernmost occurrences that are not shown on the map are in Prudhoe Land, for example at Sonntag Bugt (just beyond the map), at Siorapaluk in Robertson Fjord and in McCormick Fjord and Bowdoin Fjord. The southern localities, in Melville Bugt and around Parker Snow Bugt, have a hinterland of shield rocks, and magnetite and/or titanomagnetite form the dominant opaque fraction.

The sands within the Thule Basin are enriched in ilmenite, derived from titanium-rich dolerite sills ($\mathbf{s_1}$) and dykes ($\mathbf{d_2}$). The *Steensby Land ilmenite showing,* a coastal stretch 80 km long, is the most economically promising area since extensive uplifted beaches add prospective tonnage to the placers of the active beaches. Around the settlement of Moriusaq, the intertidal zone of up to 10 m is backed by raised beaches up to 1 km wide along a 20 km coastal stretch (Fig. 43). The Pituffik–Moriusaq area has attracted commercial interest (Christensen 1985).

The highest grades recorded are from the river flats at Pituffik, the sands from which contain an opaque fraction of up to 95%, with *c.* 73% absolute ilmenite. At Moriusaq, the grade in the active beaches, which is constantly higher than that in the older raised material, attains 60 wt% ilmenite with an average *c.* 37%. The uplifted beaches have an average TiO_2 of *c.* 12%. The TiO_2 content of the ilmenite concentrates from all sands is very constant at *c.* 46%. Elsewhere, active beach sands are of lower grade, for example at Siorapaluk they contain 21% TiO_2 (Thomassen *et al.* 2002b, p. 13). Potential tonnage of the active beaches is low but the possibility of offshore placers considerably increases this potential. The uplifted beaches contain viable tonnage if sufficient grade could be maintained (Dawes 1989).

Mineralisation not on the map

Gold

The long-surviving rumour from the 1960s about gold exploitation at Pituffik from the river Sioqqap Kuua (‘Fox Canyon’) is still alive. Although consequential panning of the river produced only two small gold colours (Cooke 1978), the fact remains that the most significant geochemical anomaly of the entire map region comes from that river’s alluvium. A heavy mineral concentrate has yielded 2710 ppb Au while 174 ppb is recorded in the river at Narsaarsuk to the south (Ujarassiorit 1993). The gold source is assumed to be rocks of the Thule mixed-gneiss complex and one candidate must be the prominent occurrences of iron-formation (see under *Magnetite (**mg**)*).

Banded iron-formation provinces have a potential for gold to the extent that BIF in Canada, and elsewhere, is often used as an exploration guide for gold (Kerswill 1996). Many Canadian iron-formation occurrences of Algoma-type show anomalous gold and base-metal values and the iron ore deposits of the Mary River Group of northern Baffin Island are no exception (Jackson 1966, 2000; Wilson & Underhill 1971). The Archaean province of the map region is now generally accepted to be the eastern extension of the Committee Fold Belt of Arctic Canada (Fig. 1, inset; Dawes 1994; Jackson 2000), thus adding to the potential for sedimentary-exhalative gold and lead-zinc deposits in the map region.

Apart from Pituffik, the highest gold concentration recorded during geochemical surveys is 97 ppb Au from west of Hubbard Gletscher, Inglefield Bredning

(Thomassen & Krebs 2004). The gold source of this anomaly has not been pin-pointed but it could stem from heavy-mineral horizons in sandstones or possibly from with vein-type mineralisation hosted by faults (see below).

Fault-related mineralisation

The WNW–ESE- to NW–SE-trending regional faults cutting both the shield and Thule Basin constitute a major exploration target (Fig. 35). Fault-controlled copper mineralisation has been mentioned above in relation to the bounding fault of the Olrik Fjord half-graben, i.e. the Itilleq Fault, and its western extension on Northumberland Ø, the Kiatak Fault.

It transpires that both fault segments are also barium-anomalous with 5000 ppm in crushed rock, and 4400 and 5400 ppm in stream-sediment samples (Gowen & Sheppard 1994; Steenfelt *et al.* 2002; Thomassen *et al.* 2002b). The mineralisation occurs in strata of the graben (Dundas Group), as well as in the hanging-wall gneisses (in Olrik Fjord) and Baffin Bay Group strata (on Northumberland Ø). It is seen as yellow clay alteration and pyritisation, as well as quartz-baryte-pyrite contact mineralisation in association with a basic dyke ($\mathbf{d_2}$) (Thomassen & Krebs 2004, fig. 16). In addition to barium, the Kiatak Fault on Northumberland Ø is also registered by stream-sediment samples to be gold anomalous, with a highest value of 57 ppb Au. Clay-altered gneisses with pyrite enrichment is also reported along faults in Prudhoe Land (Gowen & Kelly 1996).

It should be stressed that *systematic* geochemical sampling and mineral prospecting of anomalies and faults have been carried out only in the *northern* part of the map region (Thomassen *et al.* 2002a, b; Thomassen & Krebs 2004). Similar surveys are necessary from the southern part of the region before a full economic appraisal of the map region can be made. Part of that region is covered by a Landsat study, which has identified some two dozen anomalies with mineralisation potential (Krebs *et al.* 2003).

Mineral potential: Thule Basin

In addition to the metallic mineral showings discussed above, any economic description of the map region should include the potential of at least two other geological settings. Both relate to the Thule Basin that is one of several mid-Proterozoic depocentres on the northern rim of the North American craton that have comparable development histories. For example, the basins have thick sandstone and basalt units at lower levels that are succeeded by carbonate/shale-dominated sequences (Young 1979; Campbell 1981). Two of these basins are the Athabasca Basin of northern Saskatchewan and the Borden Basin of northern Baffin Island known for their productive mineralisations, uranium and lead-zinc, respectively.

Worldwide, mid-Proterozoic rift basins containing thick continental clastic sediments and with well-preserved unconformities above varied crystalline rocks, are exploration targets for uranium mineralisation (Ferguson 1984; Marmont 1987; Pirajno 1992). In Greenland, in accordance with the political climate, no specific exploration for such U-deposits has been encouraged. Nonetheless, the main elements of the unconformity U-model occur in the map region (and beyond in Inglefield Land), where basal strata with permeable sandstones overlie a Neoarchaean–Palaeoproterozoic basement that includes granites and thick metasedimentary tracts, including pelitic schists (Fig. 34; see under *Prudhoe Land supracrustal complex*). Alteration including hematite enrichment occurs above and below and the unconformity has certainly acted as a passageway for oxidising/reducing solutions. Regolithic products are locally preserved (see under Thule Basin*, Structure and metamorphism* and *Nature of the unconformity*).

In Canadian basins, a wide range of mineral deposits have been discovered in the thick successions, including sediment- and volcanic-hosted copper in lower formations, with stratigraphically higher carbonate-hosted zinc-lead (Gibbins 1991). Copper mineralisation at Thule in connection with sandstones and the Cape Combermere volcanics has been mentioned above. The Borden Basin – geographically the closest basin to the map region – shows many similarities in structural setting and sedimentary development to the Thule Basin (Jackson & Iannelli 1981, 1989; Jackson 1986; Dawes 1997).

Different types of metallic mineral showings are known, the majority of which involve lead-zinc, both sediment-hosted stratiform-type and Mississippi Valley-type (MVT; Jackson & Sangster 1987). One fault-controlled lead-zinc-silver deposit was mined until recently at Nanisivik (Fig. 1, inset; Olson 1984; Sutherland & Dumka 1995; Sherlock *et al.* 2004). The Nanisivik MVT deposit is within the Uluksan Group dominated by shallow-water stromatolitic dolostones of comparable facies to those of the Narssârssuk Group of the Thule Basin, thus focussing attention on the base-metal potential of this part of the Thule succession. Although no mineralisation of this type has been recorded, a glance at the map shows that much of the anticipated extent of the Narssârssuk Group is covered by surficial deposits, leaving ample scope for the presence of subsurface mineralisation.

Handicraft and other raw materials

Several minerals and rocks have potential as raw materials for local handicraft industries and some have gained acceptance for lapidary work. These include agates from Siorapaluk, a semi-precious stone known in Greenland beyond the Thule region, and pyrite crystals from dolomite in the neighbourhood of the settlement Moriusaq. Soapstone has been used for generations for household items, like blubber lamps and food vessels, and today it is still collected for sculpturing. In the 1960s some local interest was fostered for jewellery stone, and the lapidary facilities in Siorapaluk and Qaanaaq seen by the present author in the 1970s and early 1980s, have supported modest industries. Cutting and polishing stones has been a recreational pastime at Pituffik air base since the 1950s.

Two raw materials are shown on the map sheet: soapstone (**sp**) from the shield lithologies and agate (**q**) from Thule Basin basalts.

Soapstone (sp)

Rocks used for carving that fall under the general term 'soapstone' vary markedly in quality, from soapstone *sensu stricto* – a massive impure variety of talc – to much harder talc-poor rocks. At the best end of this range are pale grey to pale green, homogeneous talc-rich ultramafic rocks usually containing serpentine and that can be sawn from their outcrop and cut by a knife. Used for generations by the Thule Inuit, such stone has been quarried out from several localities in the Pituffik Gletscher area. At the other end of the range, usable stone includes a variety of usually darker rocks which may only contain small amounts of talc but are dominated by chlorite, muscovite and amphibole. When massive, these rocks have to be hacked or heaved out of the outcrop by a pick or crowbar and can only be worked by a file. Both types occur in the map region.

Fig. 49. Siorapaluk agate, *c*. natural size. Silica-filled vugs in the Cape Combermere Formation vary from fully concentric agate to those with a core of chalcedony, to mixed agate-quartz – like the rather fractured example figured here – to larger druses lined by brown to smokey quartz crystals. Photo: Peter K. Warna-Moors.

Soapstone is mainly found within ultramafic pods and lenses associated with amphibolites of map unit **a**, as well as in talc-bearing amphibolite (see section *Ultramafic rocks (**u**) and Amphibolite (**a**)*). Some chlorite-muscovite (± hornblende ± quartz) schists within map unit **ms** may also carry talc, and some localities, for example at Parker Snow Bugt, have produced poor-quality workable stone.

Three **sp** occurrences are marked on the map but others are identified on the larger scale maps in Survey archives (Dawes 1988b). The main localities are south-east of Bylot Sund where several localities, shown to the present author by local inhabitants, are accessible in the sea cliffs between Kap Atholl and Parker Snow Bugt (Dawes 1975). The sea cliffs 2–5 km north-west of Pituffik Gletscher, aptly known as Ukkusissaq (Greenlandic for soapstone) have historically produced much workable stone as described by Silis (1968) and Olsen (2004). On the Thule map, these cliffs coincide with a 50° strike-and-dip symbol. Other soapstone localities not marked are in inner Olrik Fjord, on its northern shore within the mafic–ultramafic body showing a mineral lineation of 15°, and in small, vivid green-weathering ultramafic bodies, too small to be shown on the map, situated farther west at the 27° dip-and-strike symbol.

Several areas of serpentine between Wolstenholme Ø and the Inland Ice are shown on the geological map of Davies *et al.* (1963, plate 1), although soapstone is not mentioned. The inland soapstone locality marked on the Thule map sheet north of Pituffik Gletscher is associated with serpentine but is of poor quality.

Agate (q) and quartz druses

Agates and quartz druses occur in the basalts of the Cape Combermere Formation (Fig. 49). On the map sheet, this formation is included within the unit *Nares Strait Group, undivided* (***N***) and in basal beds at Tikeraasaq, Inglefield Bredning (see under *Map revision*, section 10). Two localities are shown on the map: on the north-western side of Robertson Fjord, north-east of Siorapaluk, and on the west side of Robins Gletscher, Northumberland Ø. Poorer-quality agates, not

Fig. 50. Manganese dendrites or so-called 'Thule flowers' on pale sandstone slab of the Clarence Head Formation, Northumberland Ø. GGU 212534; slab is 17 cm across. Photo: Jakob Lautrup.

Fig. 51. 'Thule sandstone' slab with one large reduction spot and parts of others, so-called 'fish-eyes'. The main spot is a perfect circle 8 cm across. Slabs like this, 1 to 2 cm thick, with bleach patterns and/or ripple marks, have handicraft potential, for example as table mats. Photo: Jakob Lautrup.

found *in situ*, occur in the basalt section at Tikeraasaq, Kap Trautwine and Barden Bugt.

The agates from these localities are mainly reddish brown, with subsidiary grey to pink varieties, and up to *c.* 10 cm across. Often an outer agate coat composed of thin white and reddish brown layers gives way inwards to grey to pale blue chalcedony, with or without idiomorphic quartz crystals in the centre. Some vugs are characterised by a mix of cryptocrystalline agate/chalcedony with crystalline quartz (Fig. 49). The largest pure agate druses seen by this author are *c.* 8 cm in diameter. The agate-bearing unit near Siorapaluk intersects the coast, and agates can be collected at sea level in weathered basaltic rocks and in beach sands. When cut and polished the Siorapaluk agates are attractive stones that have been used in local jewellery production (see illustrations in Secher *et al.* 1981, p. 119 and Ljungdahl 2004, p. 12).

Quartz druses are commonly only centimetres across but may reach 15 cm. However, judged by samples collected by local inhabitants, one of which seen by the present author measured *c.* 30 × 15 cm, druses lined with quartz crystals can reach another dimension. Some of these slabs with clusters of idiomorphic brown to smoky quartz crystals up to 8 cm long, are of museum quality and form attractive and decorative display objects. One locality in the sea cliffs east of Kap Trautwine is unfortunately of difficult access.

Ornamental stones

Five rocks are listed here that are deemed to have potential as ornamental stone in a local handicraft industry.

1. Banded iron-formation of alternating bands of black magnetite and white quartz forms an attractive stone when cut and polished. Many *in situ* localities are along the Lauge Koch Kyst (see above under *Magnetite (**mg**)*) but much more accessible material can be collected as moraine blocks, in the Pituffiup Kuussua valley for example, in alluvial deposits of the main river and near the Inland Ice margin below the western end of the airstrip at Camp Tuto (Fig. 47).

2. Manganese dendrites – the so-called 'Thule flowers' – form attractive brown, yellow and black fern-like patterns on bedding surfaces of pale sandstone of the Clarence Head Formation (Fig. 50). One accessible locality is at Parish Gletscher, Northumberland Ø, where slabs of fissile, pale mauve sandstone with dendrites form scree slopes and can be easily extracted from *in situ* exposure.

3. The red and purple banded sandstones, popularly known as 'Thule sandstone', are decorative rocks and even more so when liesegang rings and reduction phenonema such as 'fish-eye' spots are present (Figs 33, 51, 52; see *Structure and metamorphism* under Thule Basin). Such features become more pronounced when cut and varnished but even as unworked blocks, the sandstones are attractive when conspicuously banded. Well-preserved ripple marks and mud cracks add to their charm as a potential sales item. The Northumberland and Wolstenholme Formations contain the most decorative rock types and slabs can be extracted at several coastal outcrops. Erratics are prominent in many morainic and fluvial deposits.

Fig. 52. Block of 'Thule sandstone': a decorative stone either in this raw state or cut and polished. A potential bookend. The quartz arenite shows ferruginous liesegang banding and pseudo-bedding. Bedding is faintly visible with orientation shown by **arrows**. Liesegang rings are secondary features that here simulate cross-stratification and sedimentary discordancies. Block is *c.* 20 cm across. Photo: Peter K. Warna-Moors.

Fig. 53. Well-rounded cobbles of banded 'Thule sandstone' collected from active beaches. The six shown range from 5 to 8 cm across. Potential paperweights. Photo: Jakob Lautrup.

4. Well-rounded pebbles from the fluvial 'pudding-stone' beds in the Wolstenholme and Qaanaaq Formations can be collected at beach level at many places (see Dawes 1997, figs 96, 101). The pebbles are predominantly vein quartz, pale coloured with some green and pink varieties, but grey to black chert, red quartzite and reddish granitic and gneissic pebbles occur. When polished, such pebbles are attractive display objects.

5. Well-rounded cobbles and pebbles of banded sandstone from both raised and active beaches are also attractive stones, for example, the mauve-striped cobbles that form the present beaches on Hakluyt Ø and Northumberland Ø that in summer are incessantly pounded by the high seas of Baffin Bay (Fig. 53).

Aggregate and road metal

Large areas of frost-free gravel and sand were exploited for construction purposes during establishment of the air base at Pituffik in the 1950s. Basalt, the most resistant rock and available in quantity from sills and dykes, has been utilised as crushed rock and was, for example, used in the building of the pier. Today, it is quarried mainly as road metal. One other formation in the district, not previously exploited, has a potential as road metal and as aggregate. This is the Clarence Head Formation of the Nares Strait Group that in many places is composed of clean, quartz beach sands, free from impurities and that are locally indurated. The most attractive outcrops at sea level are on the southern coast of Northumberland Ø, just west of Asungaaq and at Qangattaat (see Dawes 1997, fig. 48; also *Map revision*, section 7).

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Appendix 1

Spelling of place names: old and new orthography

New orthography used in these explanatory notes	Old orthography used on the map sheet
Aafeerneq	Aorfêrneq
Ajukus Skær	Ajakos Skær
Anngiusalipaluk	Angiussalipaluk
Asungaaq	Asungâq
Inersussat	Inerssússat
Innaaqqissorsuq	Ivnârqigsorssuaq
Isussik	Isuvssik
Itilleq	Itivdleq
Itillersuaq	Itivdlerssuaq
Kangerlussuaq	Kangerdlugssuaq
Kinginneq	Kingingneq
Moriusaq	Moriussaq
Naajat	Naujat
Narsaarsuk	Narssârssuk
Nallortoq	Navdlortoq
Niaqornarsuaq	Niaqornarssuaq
Niaqornaarsuk	Niaqornârssuk
Nunapalussuaq	Nunapalugssuaq
Nunatarsuaq	Nunatarssuaq
Nunngarutipaluk	Núngarutipaluk
Nuulliit	Nûgdlît
Nuussuaq	Nûgssuaq
Pingorsuit	Pingorssuit
Pitoraavik	Pitorâvik
Pituffik	Pitugfik
Piuffik Gletscher	Pitugfik Gletscher
Piulip Nunaa	Piulip nunâ
Puisilik	Puissilik
Puisiluusarsuaq	Puissitdlûssarssuaq
Qangattaat	Qangâtait
Qaqujaarsuaq	Qaqujârssuaq
Qattarsuit	Qâtarssuit
Qeqertarsuaq	Qeqertarssuaq
Quaraatit Nuna	Quarautit nûa
Quinnisut	Quínissut
Savissivik	Savigsivik
Savissuaq Gletscher	Savigssuaq Gletshcer
Sermiarsupaluk	Sermiarssupaluk
Sineriarsua	Sineriarssua
Sioqqap Kuua	Siorqap kûa
Sukkat	Súkat
Tikeraasaq	Tikeraussaq
Tuttu Gletscher	Tugto Gletscher
Tuttulipaluk	Tugtulipaluk
Tuttulissuup Tuttoqarfia	Tugtuligssûp tugtogarfia
Ulli	Uvdle
Umiivik	Umivik
Ummannaaq	Umànaq

Danmarks og Grønlands Geologiske Undersøgelse (GEUS)

Geological Survey of Denmark and Greenland

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Denmark

The national map sheet coverage of Greenland

The national map sheet coverage of Greenland consists of map sheets of two scales: 1:500 000 and 1:100 000. The 1:500 000 coverage comprising 14 sheets was designed as two series covering bedrock and Quaternary geology. The bedrock coverage was completed in 2004 while just four Quaternary geological sheets have been published. Fifty-five sheets of the 1:100 000 series have so far been released.

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