Proterozoic to Phanerozoic geological development after formation of the Precambrian shield

The Greenland Precambrian shield is mainly composed of crystalline gneisses and plutonic rocks older than 1600 Ma. Younger rock units, Mesoproterozoic to Phanerozoic in age, are in part related to the formation of sedimentary basins and fold belts along the margins of the stable shield. Two major Palaeozoic fold belts – the Ellesmerian fold belt of Ellesmere Island (Canada) and North Greenland and the Caledonian fold belt of East Greenland – developed along the north and east margins of the shield respectively. In the descriptions that follow the onshore Proterozoic to Phanerozoic deposits and orogenic events throughout Greenland are presented chronologically within the framework of major depositional basins.

Palaeo- to Mesoproterozoic unfolded units

Independence Fjord Group, North Greenland

The earliest recorded major depositional basin developed on the Greenland shield is represented by the Independence Fjord Group [**31**] (Figs 18A, B) which is exposed over large areas of eastern North Greenland and North-East Greenland between north-eastern Peary Land (83°N) and westernmost Dronning Louise Land (77°N). The group is more than 2 km thick, with its base only exposed in western Dronning Louise Land.

The Independence Fjord Group has been studied primarily in the type area around Independence Fjord in North Greenland (see Geological map of Greenland 1:500 000, sheet 8, Peary Land; Bengaard & Henriksen 1986). It is dominated by alluvial clastic deposits, mainly sandstones that form three 300–900 m thick, laterally correlatable units. These are separated by two laterally extensive, much thinner (4–90 m) silt-dominated units that represent deposition in ephemeral lakes. Deposition of the Independence Group took place in an intracratonic sag basin and the development of extensive lacustrine conditions suggests that sedimentation was controlled by basin-wide changes in subsidence rates (Collinson *et al.* 2008).

Deposition of the Independence Fjord Group took place between the end of the Palaeoproterozoic orogenic events in northern Greenland at *c.* 1750 Ma and the intrusion of the Midsommersø Dolerites at 1380 Ma (see below). Rb-Sr dating of clay minerals from siltstones by Larsen & Graff-Petersen (1980) indicated an age for diagenesis at *c.* 1380 Ma, but the coincidence of this age with the time of emplacement of the Midsommersø Dolerites suggests that this is not the time of sediment deposition. Geochronological data on detrital zircons indicate that most of the detritus that formed the Independence Fjord sandstones was derived from Palaeoproterozoic sources (2000–1800 Ma; Kirkland *et al.* 2009).

The sandstones and siltstones of the Independence Fjord Group are cut by numerous mafic sheets and sills, the 'Midsommersø Dolerites' (Kalsbeek & Jepsen 1983; Kalsbeek & Frei 2006), for which a U-Pb baddeleyite age of 1382 ± 2 Ma has been obtained (Upton *et al.* 2005). The presence of sheets of 'rheopsammite' (intrusive rocks formed by partial melting of sandstone at depth; Jepsen 1971; Kalsbeek & Frei 2006) witnesses to the intensity of this magmatic event. Although the dolerites form a significant proportion of the outcrop area of the Independence Fjord Group, they are not shown on the present map, but appear on the Geological map of Greenland 1:500 000, Sheet 8, Peary Land, referred to earlier. They are depicted with other important dyke swarms on Fig. 20.

Zig-Zag Dal Basalt Formation, North Greenland

The Mesoproterozoic Zig-Zag Dal Basalt Formation [**30**] consists of an up to 1350 m succession of well-preserved tholeiitic flood basalts. Its main outcrop area is south of Independence Fjord in eastern North Greenland. The Zig-Zag Dal Basalt Formation conformably overlies the Independence Fjord Group and is itself disconformably overlain by the Hagen Fjord Group (Fig. 24). South of Independence Fjord the basalt succession crops out over an area of 10 000 km^2, but local occurrence of similar basalts in eastern Peary Land indicates that the formation once covered a large part of North Greenland. A close geochemical similarity with the Midsommersø

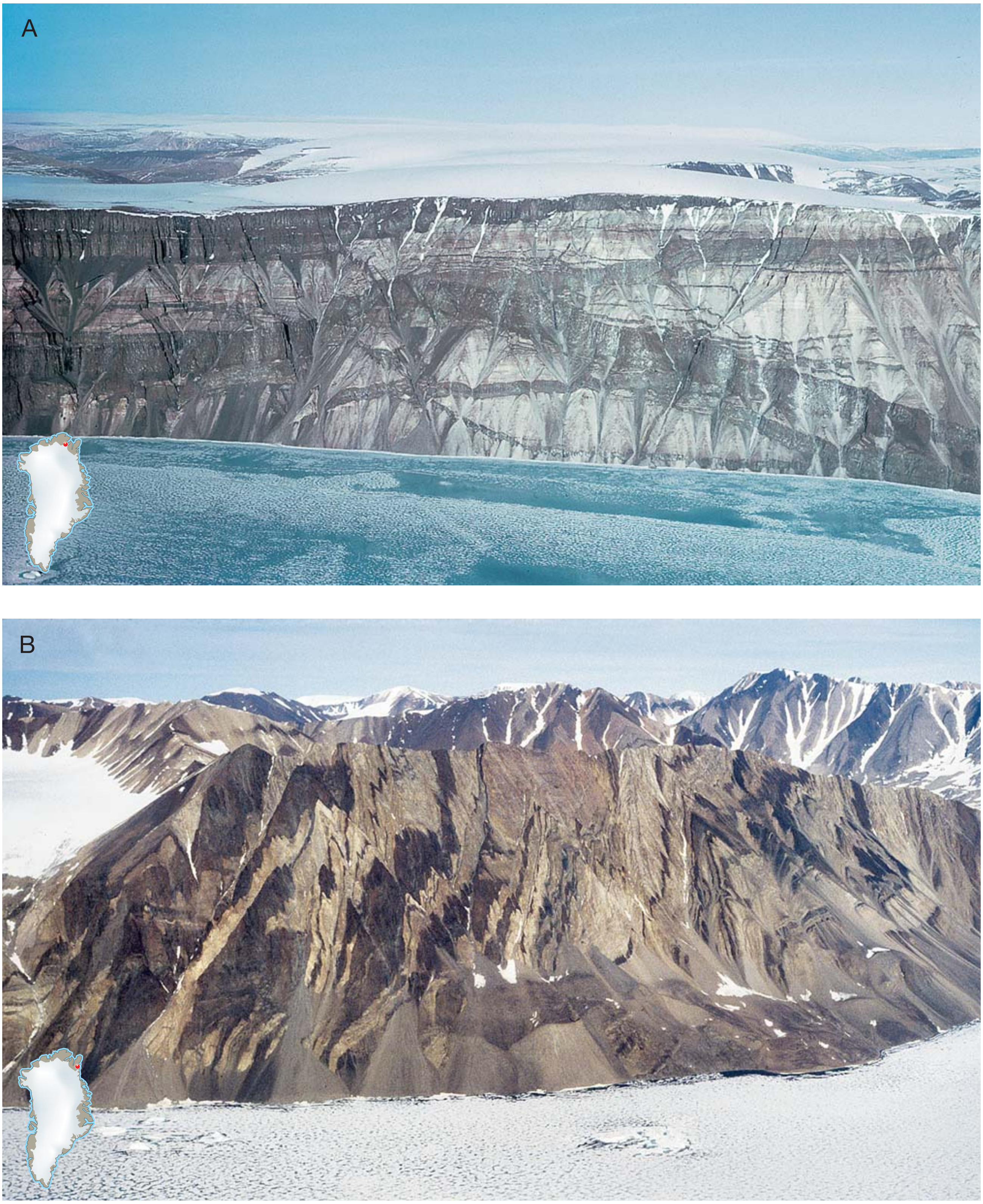


Fig. 18. Palaeoproterozoic Independence Fjord Group sandstones.
A: Undeformed succession on the south side of Independence Fjord cut by *c*. 1380 Ma Midsommersø Dolerite intrusions (*c*. 82°N), eastern North Greenland. Profile height is *c*. 800 m.
B: Folded and metamorphosed sandstones and dolerite sills within the Caledonian fold belt (see text). North of Ingolf Fjord (*c*. 80°30´N), Kronprins Christian Land, eastern North Greenland. Profile height is *c*. 1000 m.

Dolerites implies that the basalts are related to the same igneous event that produced the dolerites, and an age of *c.* 1380 Ma for the basalts is therefore indicated.

The Zig-Zag Dal Basalt Formation is divided into three main units. A 'Basal Unit' of thin aphyric basalt flows is 100–200 m thick and includes pillow lavas in its lower part. The overlying 'Aphyric Unit' (*c.* 400 m) and the uppermost 'Porphyritic Unit' (up to 750 m) together comprise 30 flows of mainly subaerial lavas. The present distribution pattern of the flows shows a maximum thickness of the succession in the area south of Independence Fjord, implying subsidence of this central region during the extrusion of the basalts and prior to the peneplanation which preceded deposition of the Hagen Fjord Group.

Detailed investigations of the basalts have been carried out by Kalsbeek & Jepsen (1984) and Upton *et al.* (2005). Based on trace element and isotope data the latter authors conclude that magma generation took place in an upwelling mantle plume underneath an attenuating continental lithosphere. The lavas of the Porphyritic Unit are considered to represent essentially uncontaminated plume-source melts.

Correlation with similar rocks in the northernmost part of the East Greenland Caledonides

Sandstones and conglomerates interpreted as strongly deformed representatives of the Independence Fjord Group [**31**] are found within the northernmost parts of the Caledonian fold belt in Kronprins Christian Land and areas to the south (Geological map of Greenland 1:500 000, Sheet 9, Lambert Land, Jepsen 2000; Pedersen *et al.* 2002; Collinson *et al.* 2008). As in the North Greenland platform, they are cut by numerous sheets of dolerite (Fig. 18B). Basaltic and andesitic lavas in this area are shown on the map as Zig-Zag Dal Basalt Formation [**30**], but SHRIMP U-Pb dating has yielded an age of 1740 Ma for associated rhyolitic rocks (Kalsbeek *et al.* 1999), and correlation with the 1380 Ma Zig-Zag Dal Basalt Formation is therefore excluded. The sandstones and conglomerates in Kronprins Christian Land are interbedded with the lavas, and an age of *c.* 1740 Ma is therefore indicated. This age is similar to that of the youngest granites within the crystalline basement in the Caledonian fold belt (see p. 31), and the sedimentary rocks can be regarded as molasse-type deposits related to the breakdown of the Palaeoproterozoic orogen in North-East Greenland. If a correlation with the Independence Fjord Group in the platform is assumed, the sandstones and conglomerates in Kronprins Christian Land must represent the lowermost part of that group.

Gardar Province, South Greenland

The Mesoproterozoic Gardar Province (Upton & Emeleus 1987; Kalsbeek *et al.* 1990; Upton *et al.* 2003) is characterised by faulting, deposition of sediments and volcanic rocks, and alkaline igneous activity. An approximately 3400 m thick succession of sandstones and lavas referred to as the Eriksfjord Formation (Poulsen 1964) accumulated within an ENE–WSW-trending continental rift, preserved at about 61°N. Within and outside the rift, major central intrusions and numerous dykes were emplaced (see also dyke map Fig. 20). An intrusive com-

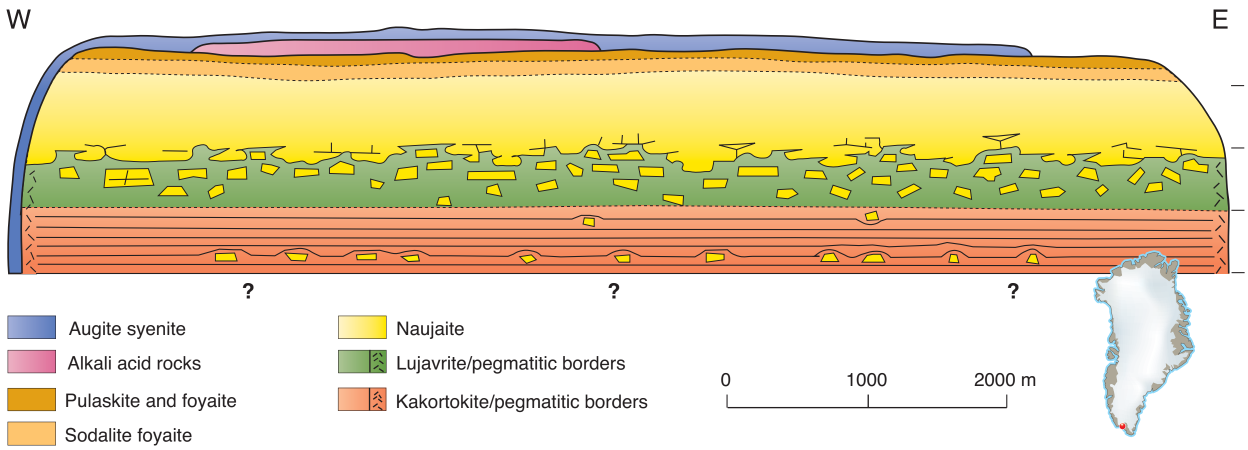


Fig. 19. Diagrammatic cross-section of the Ilímaussaq intrusion, Gardar Province, west of Narsaq in South Greenland. The intrusion has an outcrop area of 17 × 8 km and has been dated at 1143 ± 21 Ma (see review by Kalsbeek *et al.* 1990; H. Sørensen 2006a). Slightly modified from Andersen *et al.* (1981).

Dykes in Greenland

Undeformed Proterozoic dolerite dyke belonging to the 'MD' dyke swarm, cutting Archaean orthogneisses, northern Fiskefjord region, southern West Greenland. Photo: A.A. Garde.

Deformed and fragmented Archaean Ameralik metabasic dyke cutting Eoarchaean 'Amîtsoq' gneisses, Godthåbsfjord region, southern West Greenland. Width of view *c*. 1.5 m. Photo: A.A. Garde.

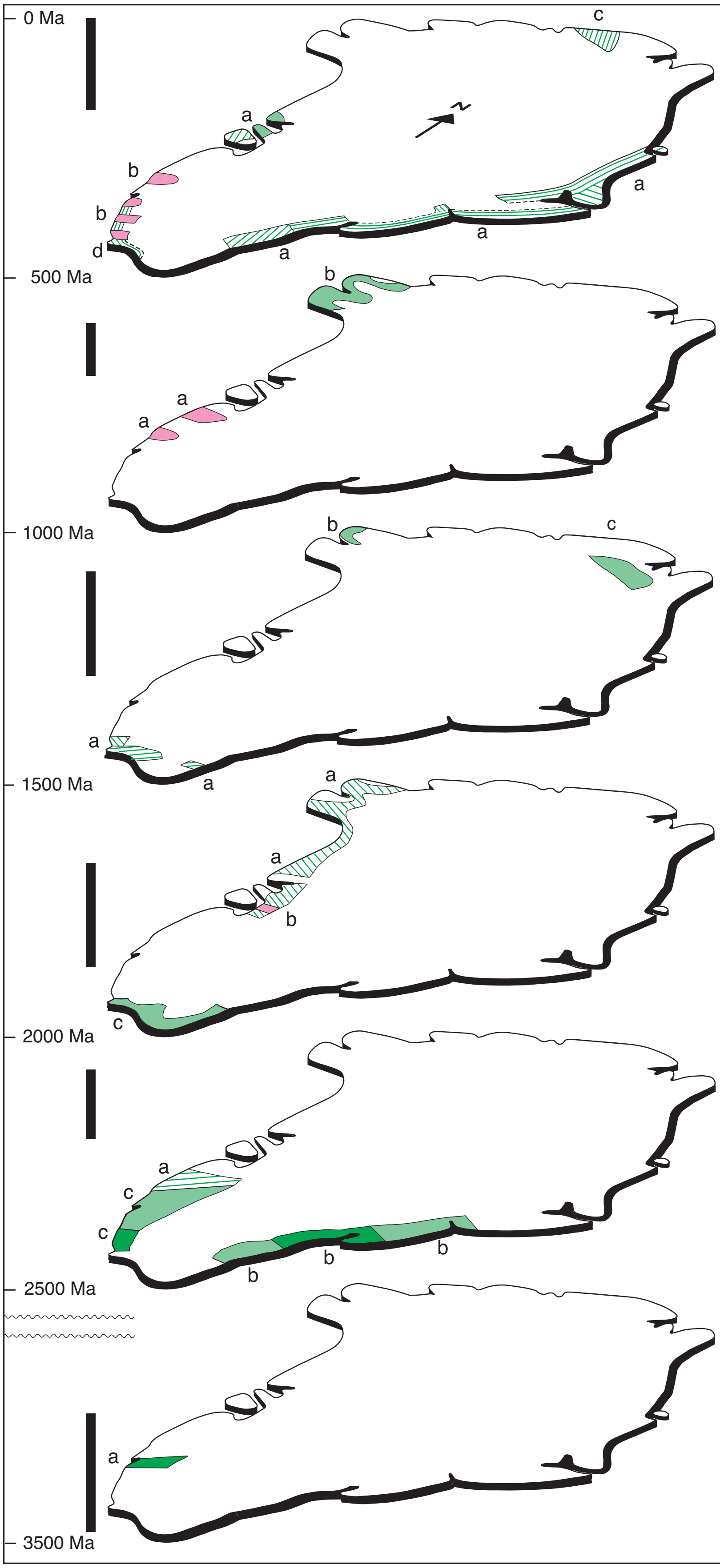
There are few areas in Greenland where the rocks are not cut by mafic dykes. The dykes range in age from Palaeoarchaean in the Godthåbsfjord area to Cenozoic in parts of North, East and West Greenland.

It is very difficult to date mafic dykes, especially where they have been deformed and metamorphosed, and early K-Ar and Rb-Sr age determinations have proved to be imprecise and sometimes entirely misleading. In many cases the age of the dykes is therefore imperfectly known. Moreover, in cases where precise age determinations have been carried out, results show that dykes previously believed to belong to a single swarm may have significantly different ages. The diagrams on the opposite page illustrate the history of dyke emplacement in Greenland, based on the best age estimates available at present.

Among the best known dyke swarms in Greenland are the Ameralik dykes in the Godthåbsfjord area, which were intruded into Eoarchaean gneisses, but are cut by Meso- and Neoarchaean granitoid rocks; this permits distinction between Eoarchaean and Meso- and Neoarchaean lithologies. The Kangâmiut dykes in West Greenland are well preserved in the Archaean craton, but deformed and metamorphosed in the Palaeoproterozoic Nagssugtoqidian orogen to the north; this makes it possible to monitor the influence of Nagssugtoqidian metamorphism and deformation on the host rocks.

Legend	with one trend direction	with two or more trends	deformed and metamorphosed
Dolerites and associated dykes	▨	🟩	■
Kimberlites, lamproites and lamprophyric dykes		🟪	

Fig. 20 (*above* and *facing pages*): Diagrammatic representation of the major suites of mafic dykes and sills in Greenland. Compiled by J.C. Escher and F. Kalsbeek 1997.



		(Age in Ma)
a	Dykes and sills related to Tertiary rifting, associated with basalts	*c.* 15 – *c.* 60
b	Kimberlites and lamprophyres	152–166
c	Mafic alkaline dykes	*c.* 65
d	'TD' dykes	*c.* 135

a	Kimberlites and lamprophyres	*c.* 555–604
b	Sills and dykes	*c.* 630 – *c.* 730

a	Gardar sills and dykes	*c.* 1100 – *c.* 1300
b	Sills and dykes of the Nares Strait and Smith Sound groups	*c.* 670 – *c.* 1310
c	Midsommersø Dolerites, associated with basalts	*c.* 1380

a	Dolerite swarm	*c.* 1650
b	Lamproites	*c.* 1750
c	Appinites *(sensu lato)*	*c.* 1780 – *c.* 1850

a	Kangâmiut dykes		*c.* 2040
b	Umîvik dyke swarm		*c.* 2050
c	'MD' dykes	(tholeiite)	*c.* 2150
		(norite)	*c.* 2200

a	Ameralik and Tarssartôq dykes	*c.* 3460 – *c.* 3510

plex at the head of Danell Fjord (*c.* 60°50′N, 43°30′W) in South-East Greenland is indicated on the map as Ketilidian rapakivi granite [77], but later radiometric dating has yielded a Gardar age (Garde *et al.* 2002).

The sedimentary [**12**] and volcanic rocks [**11**] of the Eriksfjord Formation rest uncomformably on Ketilidian granites. The Eriksfjord Formation comprises *c.* 1800 m of sedimentary strata and 1600 m of volcanic rocks. The sedimentary rocks, mainly found in the lower part of the succession, are fluvial and aeolian arkosic to quartzitic sandstones and conglomerates (Clemmensen 1988; Tirsgaard & Øxnevad 1998). The volcanic rocks are dominated by basaltic lavas, with subordinate trachytes and phonolites in the upper part and a carbonatite complex in the lower part (Stewart 1970; Larsen 1977; Upton & Emeleus 1987). The age of the Eriksfjord Formation is *c.* 1170–1200 Ma (Paslick *et al.* 1993).

The Gardar intrusive complexes [**56**] range in age from *c.* 1300 to *c.* 1120 Ma and have been divided into three age groups (Upton & Emeleus 1987; Upton *et al.* 2003). They comprise central ring intrusions, complexes with several individual intrusive centres, and giant dykes (Emeleus & Upton 1976; Upton & Emeleus 1987). Petrologically, the intrusive complexes are dominated by differentiated salic rocks including syenites, nepheline syenites, quartz syenites, and granites (Fig. 19); mildly alkaline gabbros and syenogabbros are subordinate but are dominant in the giant dykes. The intrusions were emplaced in the middle part of the Gardar rift as well as in the areas to the north-west and south-east. Major swarms of basic dykes of Gardar age occur throughout South and South-West Greenland (see dyke map, Fig. 20).

Early Neoproterozoic orogenic units reworked in the East Greenland Caledonian fold belt

A suite of early Neoproterozoic augen granites and leucogranites [55] is widely distributed within the Krummedal supracustal sequence of the high-grade uppermost Caledonian (Hagar Bjerg) thrust sheet between Scoresby Sund (70°N) and about 74°N; the granitoids have yielded protolith ages of 940–910 Ma (Jepsen & Kalsbeek 1998; Kalsbeek *et al.* 2000; Watt & Thrane 2001). These magmatic events are contemporaneous with high-grade metamorphism dated in overgrowth rims on detrital zircons (Kalsbeek *et al.* 2000; Watt *et al.* 2000; Watt & Thrane 2001), as well as ductile deformation that, at least locally, produced nappe-scale recumbent folds in the reworked migmatite and paragneiss complex [52].

A comparable scenario is recorded in eastern Svalbard where 970–940 Ma events are recorded and augen granites have been emplaced synchronously with deformation (Johansson *et al.* 2000); in Scotland zircon geochronology has revealed a range of tectonothermal events from 840–730 Ma (Leslie *et al.* 2008).

Supracrustal rocks

The Krummedal supracrustal sequence [**46**] consists of a 2500–8000 m thick suite of pelitic, semipelitic and quartzitic rocks generally metamorphosed at amphibolite facies (Henriksen & Higgins 1969; Higgins 1974, 1988; Higgins & Leslie 2008; Figs 21, 22). Lateral and vertical lithological variations are considerable and correlation between the various local successions has not been possible. Contacts with the underlying Archaean [**74**] and Palaeoproterozoic gneisses [**70**] are generally

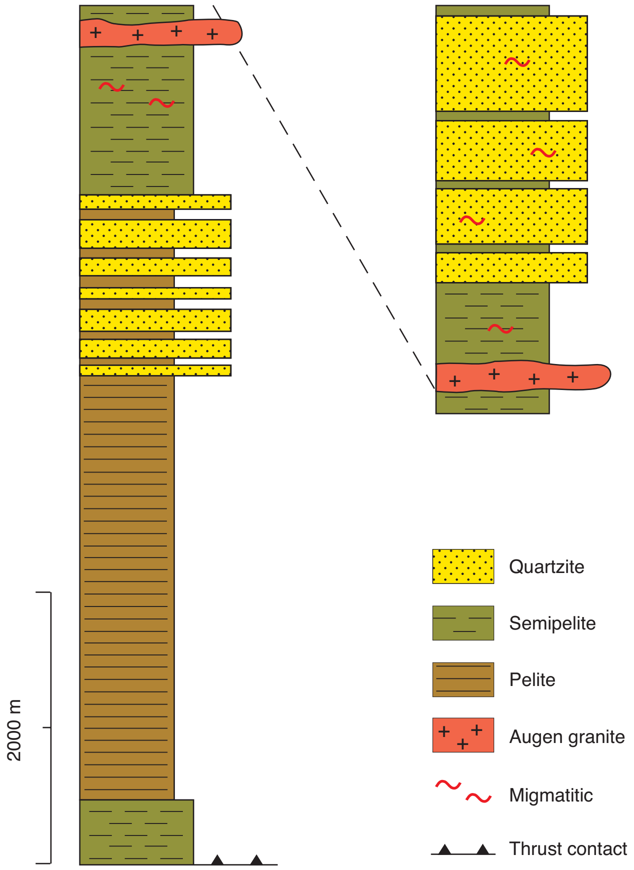


Fig. 21. Sections of the Mesoproterozoic Krummedal supracrustal sequence, north of inner Nordvestfjord/Kangersik Kiatteq (71°30′N), Scoresby Sund region, central East Greenland. Based on Higgins (1974).

Fig. 22. Krummedal supracrustal sequence comprising rusty garnetiferous gneissic schists and siliceous paragneisses, inner Nordvestfjord/Kangersik Kiatteq (71°30´N), Scoresby Sund region, central East Greenland. Profile height is *c.* 1500 m.

conformable, but rare discordances may reflect preservation of an original unconformity (Higgins *et al.* 1981). The 'Smallefjord sequence' [**46**] that crops out between Grandjean Fjord (75°N) and Bessel Fjord (76°N) (Friderichsen *et al.* 1994) is comparable in lithology and development to the Krummedal succession. Age determinations on zircons suggest deposition of both sequences later than *c.* 1100 Ma, and high-grade metamorphism during an early Neoproterozoic event at *c.* 950 Ma (Strachan *et al.* 1995; Kalsbeek *et al.* 1998b). The Krummedal sequence of the lowermost Caledonian (Niggli Spids) thrust sheet appears to lack the early Neoproterozoic granitoids and migmatitic developments recorded in similar rocks within the uppermost (Hagar Bjerg) thrust sheet (see later).

Migmatites and granites

The Krummedal supracrustal sequence of the uppermost Hagar Bjerg thrust sheet in the southern part of the East Greenland Caledonian fold belt has been intensely migmatised and transformed into paragneiss [**52**], and as noted above, has been intruded by sheets of augen granites up to 1000 m thick as well as other granite bodies [**55**] (Steiger *et al.* 1979). In the Scoresby Sund region these rock units have been deformed into major recumbent folds (Leslie & Nutman 2003). A second generation of Caledonian granite intrusions [**54**] was produced by partial melting of the Krummedal supracrustal sequence, and some of these granites migrated upwards into the overlying Eleonore Bay Supergroup [**44**].

Mesoproterozoic – early Neoproterozoic sedimentary basin in North-West Greenland and Ellesmere Island

Thule Supergroup

The Thule basin is defined by a thick undeformed sedimentary-volcanic succession – the Thule Supergroup – that straddles northern Baffin Bugt and Smith Sund (Dawes *et al.* 1982; Dawes 1997, 2004, 2006). The eastern and western parts of the basin are exposed in North-West Greenland and south-eastern Ellesmere Island (Canada), with extensive sections offshore (Funck *et al.* 2006). As such, the Thule Basin is one of several Meso–Neoproterozoic intracratonic depocentres fringing the northern margin of the Canadian–Greenland shield. In Greenland, the rocks are widely exposed between Inglefield Land (79°N) and Thule Air Base/Pituffik (76°N).

The Thule Supergroup has a cumulative thickness of at least 6 km and comprises continental to shallow marine sedimentary rocks, basaltic rocks and a conspicuous num-

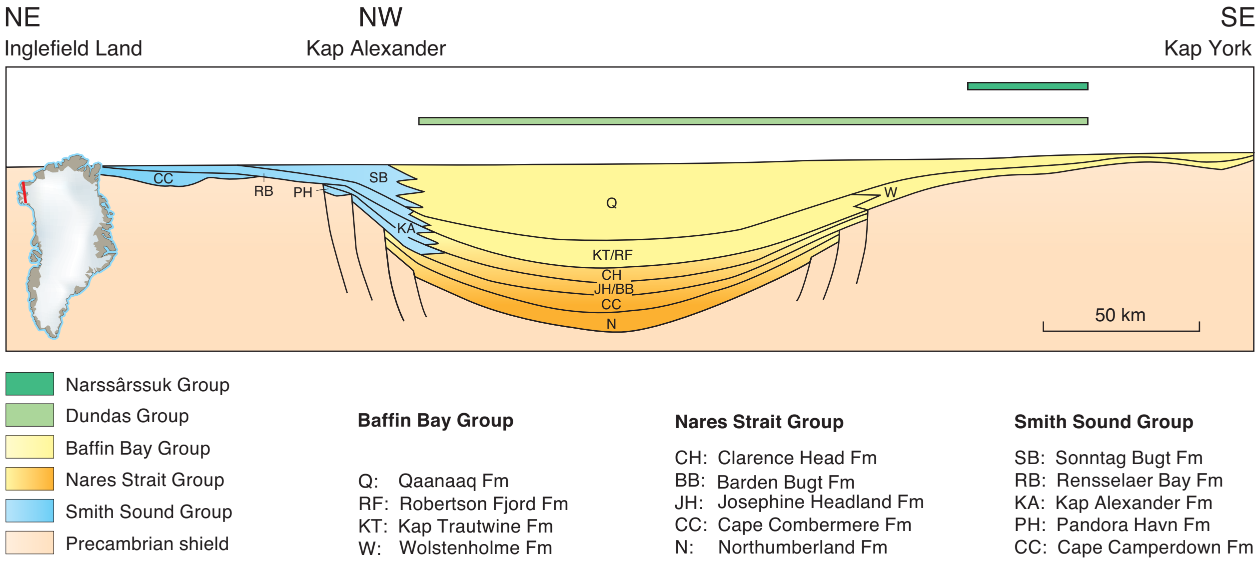


Fig. 23. Cross-section through the Thule Basin, North-West Greenland, with the lower Thule Supergroup as basin fill, showing the relationships of groups and their formations. The spatial relationship of the Dundas and Narssârssuk Groups superimposed on this Mesoproterozoic evolutionary stage is shown by the **green bars**. Vertical exaggeration × 25. Slightly modified from Dawes (1997).

ber of doleritic sills. Resting with a profound unconformity on the peneplained Archaean–Palaeoproterozoic crystalline shield, the basin developed between *c.* 1270 Ma and around 900 Ma ago (for discussion, see Dawes 1997, 2006; Samuelsson *et al.* 1999). It is dissected by a half-graben system dominated by WNW–ESE-trending faults.

The Thule Supergroup is divided into a lower part of three groups [5] and an upper part of two [3, 4]. All of the groups contain red beds. When the map was compiled, a Middle – Late Proterozoic age was assigned (Dawes & Vidal 1985; Dawes & Rex 1986), but reappraisal of the acritarch fauna suggests a middle Mesoproterozoic to early Neoproterozoic age for the entire succession (Samuelsson *et al.* 1999; Dawes 2006). The lower part comprises: (1) the Smith Sound Group of mainly shallow marine sandstones and multicoloured shales with stromatolitic carbonates; (2) the Nares Strait Group which at its base consists of inner shelf mudstones and fluvial sandstones, succeeded by terrestrial basaltic extrusive rocks and volcaniclastic red beds overlain by stromatolitic carbonate and shales topped by shallow marine sandstones; (3) the Baffin Bay Group of multicoloured sandstones and conglomerates with intervals of shale–siltstone, mainly of mixed continental to shoreline origin. The upper part of the Thule Supergroup comprises: (4) the Dundas Group [4] of deltaic to coastal plain deposits, dominated by dark shales, siltstones and fine-grained sandstones with thin carbonate-rich beds, and (5) the Narssârssuk Group [3], representing deposition in a low-energy environment, with a cyclic carbonate and red-bed siliciclastic succession. The latter comprises interbedded dolomite, limestone, sandstone, siltstone and shale with evaporites. The Narssârssuk Group, the youngest unit, has a very restricted occurrence in a half-graben on the south-eastern margin of the Thule Basin (Fig. 23).

Neoproterozoic sedimentary basins in North, North-East and East Greenland

Hagen Fjord Group, North Greenland

Neoproterozoic basin deposits laid down between 800 and 590 Ma ago occur extensively in eastern North Greenland, where they crop out over an area of 10 000 km^2 west of Danmark Fjord. These deposits, assigned to the Hagen Fjord Group (Figs 24, 25), overlie sandstones of the Palaeoproterozoic Independence Fjord Group and basalts of the Mesoproterozoic Zig-Zag Dal Basalt Formation together with their (1380 Ma) correlatives the Midsommersø dolerite intrusions (Sønderholm & Jepsen 1991; Clemmensen & Jepsen 1992; Sønderholm *et al.* 2008). The easternmost occurrences of the succession are represented in the Caledonian Vandredalen thrust sheet in Kronprins Christian Land that has a demonstrable westward displacement of 35–40 km (Higgins *et al.* 2001a, b, 2004b; Leslie & Higgins 2008).

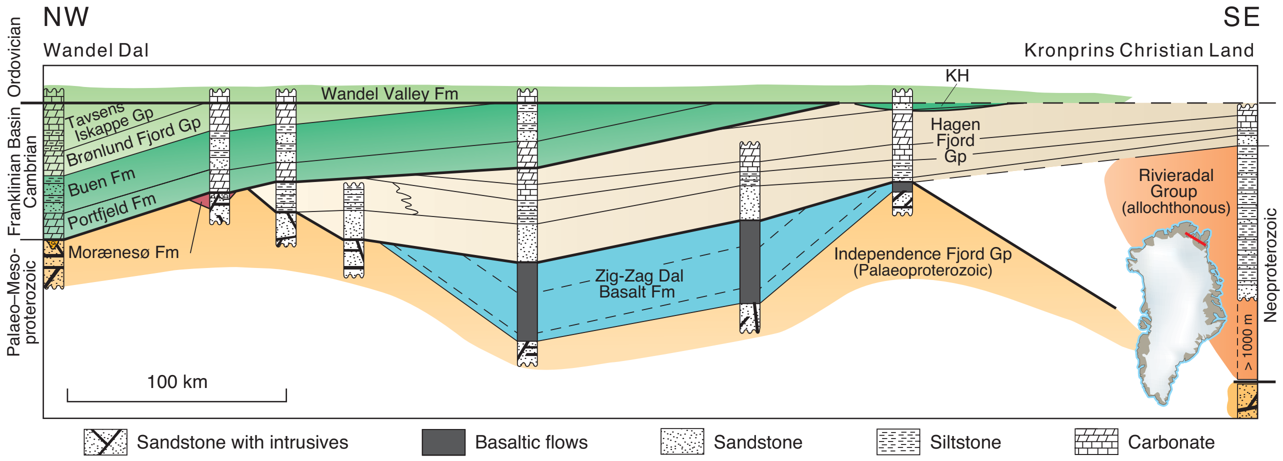


Fig. 24. Schematic cross-section of the Proterozoic–Ordovician succession in eastern North Greenland between Wandel Dal (*c.* 82°N) and Kronprins Christian Land (*c.* 80°N). The cross-section shows the relationships between the Mesoproterozoic Zig-Zag Dal Basalt Formation, the Neoproterozoic Hagen Fjord Group with correlatives, and the underlying and overlying sequences. **Colours** correspond to those used on the map. **Bold lines** represent erosional unconformities. Slightly modified from Clemmensen & Jepsen (1992). **KH**, Kap Holbæk Formation.

The Hagen Fjord Group [27] has a maximum thickness of 1000–1100 m and comprises a succession of siliciclastic and carbonate sedimentary rocks deposited on a shallow-water shelf. Its lower part mainly comprises sandstones which are overlain by a sandstone-siltstone association. The upper part is characterised by limestones and dolomites with abundant stromatolites (Fyns Sø Formation). The overlying sandstone unit (Kap Holbæk Formation) is now known to be early Cambrian, and is excluded from the Hagen Fjord Group (Smith *et al.* 2004). The age of the Hagen Fjord Group is poorly constrained, but a pre-600 Ma age is now suggested (Sønderholm *et al.* 2008).

The Rivieradal sandstones [29], now the Rivieradal Group (Smith *et al.* 2004), are confined to the allochthonous, Caledonian, Vandredalen thrust sheet in the Kronprins Christian Land area, and are interpreted as deep-marine deposits equivalent in age to the lower part of the Hagen Fjord Group (Clemmensen & Jepsen 1992; Sønderholm *et al.* 2008). This succession is 7500 to 10 000 m thick and comprises conglomerates, sandstones, turbiditic sandstones and mudstones that accumulated in a major east-facing half-graben basin; the bounding western fault was reactivated as a thrust during the Caledonian orogeny (Higgins *et al.* 2001b).

A succession of diamictites and sandstones up to 200 m thick, believed to be late Precambrian (Marinoan, *c.* 635 Ma) in age, forms isolated small outcrops in eastern North Greenland; these are known as the Morænesø Formation [28]. The formation is not included in the redefined Hagen Fjord Group of Clemmensen & Jepsen (1992) but is in part equivalent or slightly younger in age (Collinson *et al.* 1989; Sønderholm & Jepsen 1991; Smith & Rasmussen 2008).

Eleonore Bay Supergroup, East and North-East Greenland

The Eleonore Bay Supergroup comprises a more than 14 km thick succession of shallow-water sedimentary rocks which accumulated in a major sedimentary basin exposed between latitudes 71°40′ and 76°N in East and North-East Greenland (Sønderholm & Tirsgaard 1993; Sønderholm *et al.* 2008). Exposures only occur within the present Caledonian fold belt, and in general the sedimentary rocks are moderately deformed and weakly to moderately metamorphosed. The nature of the lower contact of the Eleonore Bay Supergroup has been widely debated. The oldest sedimentary rocks are in contact with the Krummedal supracrustal succession, with the contact described in some areas as an extensional detachment (Hartz & Andresen 1995; Andresen *et al.* 1998; White *et al.* 2002), and in other areas as a westward directed thrust (Higgins & Leslie 2008; Leslie & Higgins 2008). Relationships are complicated by extensive anatexis and the presence of Caledonian granites. Sedimentation is constrained to the interval between *c.* 900 Ma and *c.* 665 Ma by the youngest ages on detrital zircons from the lowest levels of the Eleonore Bay Supergroup and the Marinoan (*c.* 635 Ma) age of the overlying Tillite Group (Sønderholm *et al.* 2008).

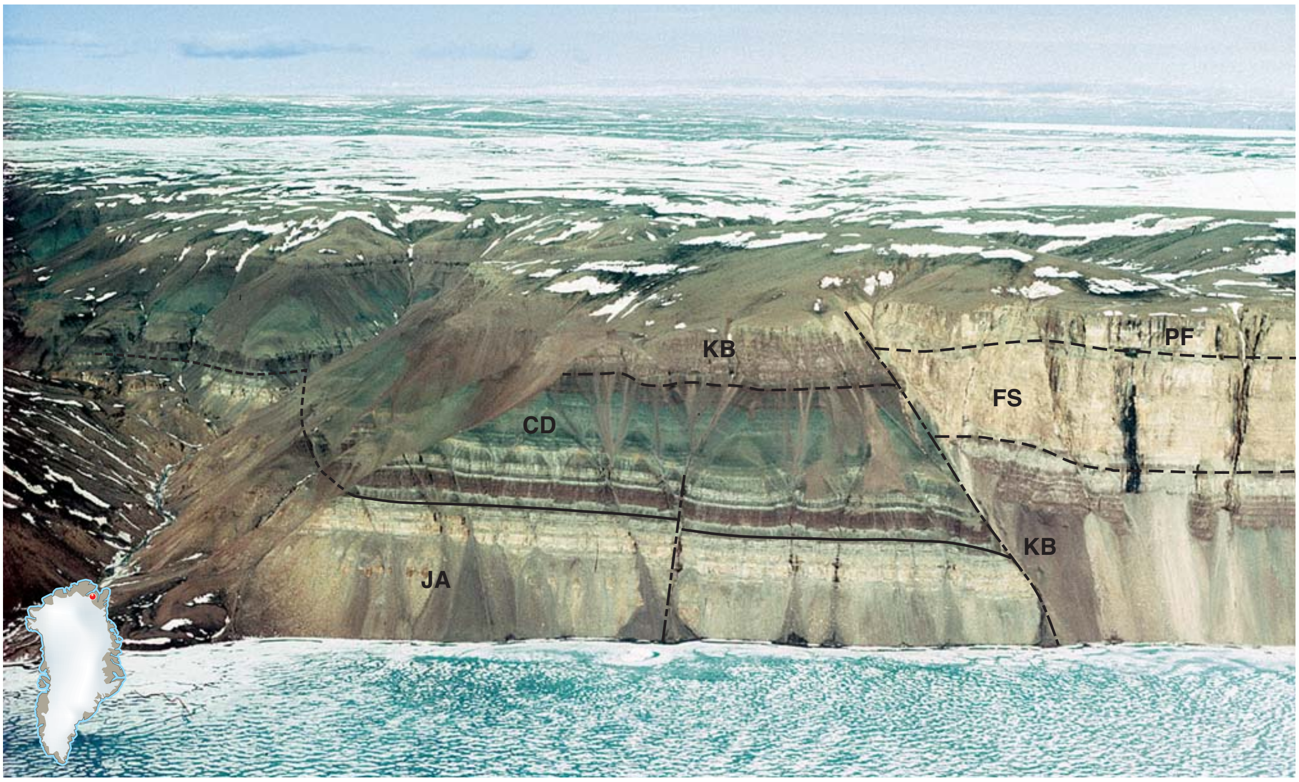


Fig. 25. Hagen Fjord Group on the north-west side of Hagen Fjord, eastern North Greenland. A lower light coloured sandstone (Jyske Ås Formation, **JA**, 400 m) is overlain by a multicoloured sandstone-siltstone association (Campanuladal and Kap Bernhard Formations, **CD** and **KB**, 450 m), with a light coloured limestone–dolomite succession at the top (Fyns Sø Formation, **FS**, 170 m, and Portfjeld Formation, **PF**). The fault has a displacement of *c.* 300 m down to the right (north). The section is *c.* 600 m high. From Sønderholm *et al.* 2008.

The lower part of the Eleonore Bay Supergroup (Fig. 26) consists of up to 9000 m of sandstones, siltstones and minor carbonates assigned to the Nathorst Land Group [**44**]; these were deposited in a shelf environment with facies associations indicating outer to inner shelf environments (Smith & Robertson 1999; Sønderholm *et al.* 2008). The upper part comprises three groups (Lyell Land, Ymer Ø and Andrée Land Groups) depicted on the map by a single colour division [**43**]. Alternating sandstones and silty mudstones of the Lyell Land Group (Fig. 27) reflect deposition in marine shelf environments (Tirsgaard & Sønderholm 1997; Sønderholm *et al.* 2008). Individual units are 40–600 m thick with a total thickness of 2800 m. The overlying 1100 m thick Ymer Ø Group records two significant phases of shelf progradation. Depositional environments range from siliciclastic basinal and slope deposits through carbonate slope and shelf deposits to inner shelf siliciclastics and evaporites (Sønderholm & Tirsgaard 1993; Sønderholm *et al.* 2008). The latest stage of basin fill is mainly represented by the up to 1200 m thick Andrée Land Group of bedded limestone and dolomites, with 10–30 m thick units of stromatolitic dolomite. Deposition took place in a carbonate ramp system, with a steepened ramp towards the deep sea to the north-east and a sheltered inner lagoon behind an inner shallow-barrier shoal (Frederiksen & Craig 1998). The uppermost sequence heralding the Marinoan glaciation of the Tillite Group consists of a strongly retrogradational succession indicating drowning of the carbonate platform and deep marine deposition, followed by a short period of carbonate platform progradation (Sønderholm *et al.* 2008).

Tillite Group, East Greenland

The Tillite Group [**42**] consists of a 700–800 m thick succession of Marinoan–Ediacaran age (*c.* 635 – *c.* 575 Ma) and includes two Marinoan glacigene diamictite formations (Hambrey & Spencer 1987; Sønderholm *et al.* 2008). It crops out in East Greenland between latitudes 71°40′ and 74°N where it overlies the Eleonore Bay Supergroup with no major hiatus, but locally with an erosional unconformity. The Tillite Group is subdivided into five formations which include sandstones, shales and dolostones in addition to the diamictite formations.

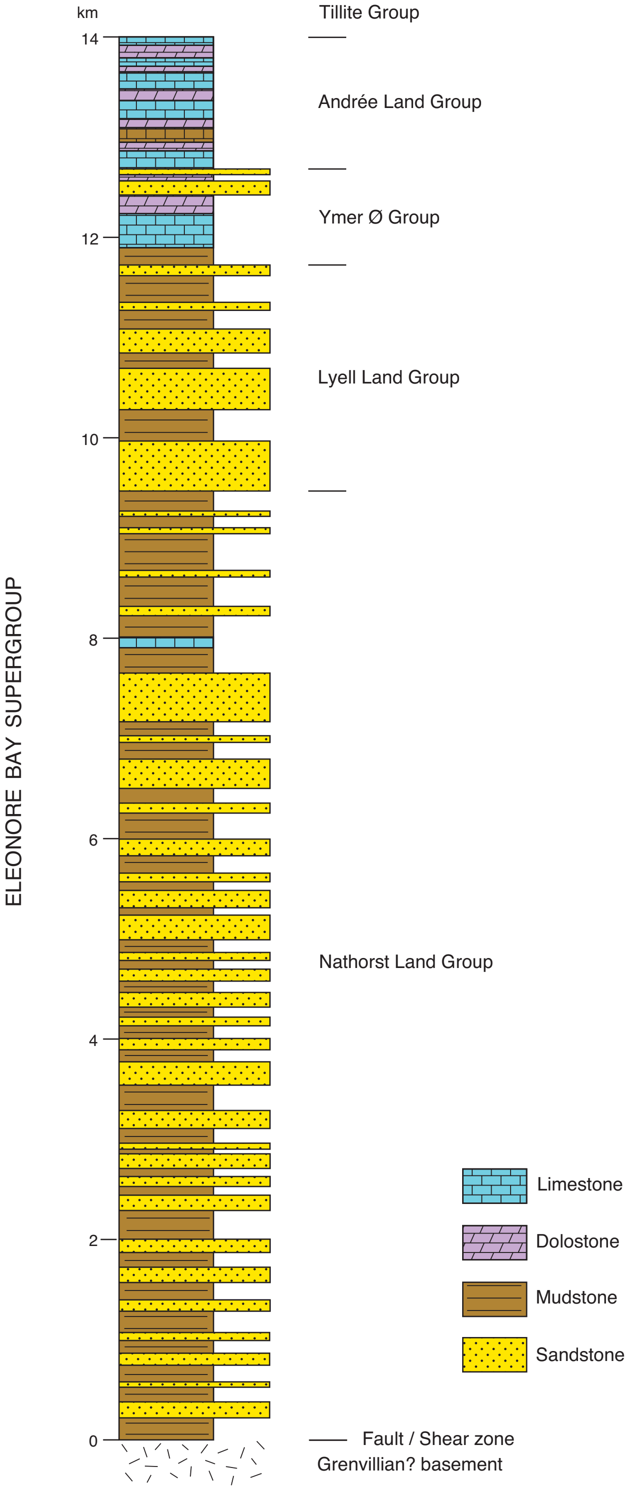


Fig. 26. Schematic composite section of the Neoproterozoic Eleonore Bay Supergroup, central fjord zone (72–74°N), North-East Greenland. Units on the map: Nathorst Land Group [44]; Lyell Land, Ymer Ø and Andrée Land Groups [43]; Tillite Group [42]. Based on Sønderholm & Tirsgaard (1993) and Sønderholm *et al.* (2008).

Isolated occurrences of diamictites correlated with the Tillite Group directly overlie crystalline basement complexes in Gåseland (70°15′N), Charcot Land (71°52′N) and in the Målebjerg window (73°38′N), all located in the Caledonian foreland (Henriksen 1986; Moncrieff 1989; Smith & Robertson 1999); the first two of these are shown on the map by a special symbol [41]. These foreland tillites are directly overlain by Cambrian quartzites or truncated by the Caledonian sole thrust.

Sedimentary rocks of unknown age in the East Greenland Caledonides

Two successions of low-grade metamorphic rocks occur in the nunatak region between 70° and 74°N underlying Caledonian thrusts. Their correlation with other known successions was uncertain when the map was compiled, and they have been indicated on the map as of 'unknown age' [45].

One succession crops out in the Gåseland window in the south-west corner of the Scoresby Sund region (70°15′N), overlying Archaean crystalline basement rocks. A thin sequence of weakly metamorphosed marbles and chloritic schists, often highly sheared adjacent to the Caledonian sole thrust, overlies diamictites [28] preserved in erosional depressions in the gneiss surface (Phillips & Friderichsen 1981). The diamictites are now correlated with the Marinoan Tillite Group of the fjord zone (Moncrieff 1989), suggesting the overlying sheared marbles and schists are either of early Palaeozoic age or belong to a thin lowermost thrust assemblage of diverse lithologies distinguished as the Gemmadal thrust sheet in the central part of the fjord region (*c.* 73°30′N; Higgins & Leslie 2008).

The second succession, traditionally known as the 'Eleonore Sø series', crops out in Arnold Escher Land (74°N; Katz 1952). Field studies in 1997 have shown the succession to occur in a tectonic window beneath Caledonian thrust units of metasedimentary rocks and gneisses. The Eleonore Sø series comprises low-grade metamorphic sandstones, shales and carbonates associated with volcanic rocks (tuffs and pillow lavas). U-Pb ion probe studies on zircons from a quartz porphyry intruding the Eleonore Sø series indicate a minimum emplacement age of 1915 ± 16 Ma (Kalsbeek *et al.* 2008). This succession is overlain unconformably by a thick Cambrian quartzite unit which preserves abundant *Skolithos* (Slottet Formation) and a few hundred metres of Lower Palaeozoic carbonates (Målebjerg Formation), recently described and defined by Smith *et al.* (2004).

Fig. 27. Part of the upper Eleonore Bay Supergroup, west side of Ymer Ø (*c.* 73°N), North-East Greenland. Succession is approximately 2 km in thickness and includes from left to right: Lyell Land Group (apart from the two lowest formations) and to the right of the black dashed line Ymer Ø Group (the lowest five of seven formations). Photo: M. Sønderholm.

Carbonatites, kimberlites and associated rocks, West Greenland

In addition to the 3007 Ma Tupertalik carbonatite [**84**] mentioned earlier, two younger occurrences of carbonatite are shown on the geological map, the 565 Ma Sarfartoq carbonatite complex [**61**] south of Søndre Strømfjord at 66°30′N (Secher & Larsen 1980), and the *c.* 165 Ma (middle Jurassic) Qaqarssuk carbonatite complex [**59**], east of Maniitsoq/Sukkertoppen at 65°23′N (Knudsen 1991). Since the compilation of the map another occurrence of carbonatitic rocks has been detected within the Archaean craton, the 158 Ma Tikiusaaq carbonatite complex at 64°N, 49°46′W, *c.* 100 km east of Nuuk/Godthåb (Steenfelt *et al.* 2006). Carbonatites also occur within some of the intrusive complexes in the Mesoproterozoic Gardar Province (Upton *et al.* 2003). A review of all alkaline-ultramafic and carbonatitic rocks in West Greenland (except the newly discovered Tikuusaaq occurrence) has been presented by Larsen & Rex (1992). These rocks are invariably related to episodes of continental rifting. They were formed from small melt fractions generated deep within the lithospheric mantle, and many dykes contain xenoliths of both mantle and crustal origin.

Most carbonatite complexes are associated with swarms of ultramafic dykes, kimberlites, aillikites etc. (Nielsen *et al.* 2009), here collectively termed ultramafic lamprophyres (*sensu lato*) (UML dykes). The dykes are too small to be shown on the geological map, but they are important for diamond exploration. Hundreds of diamonds have been recovered from a single dyke in the Sarfartoq region, the largest of which are *c.* 4 carats and of good gem quality (Hutchison & Heaman 2008). A regional overview of diamond occurrences in southern West Greenland is given by Jensen *et al.* (2004).

Recent investigations of UML dykes have concentrated on the areas around Sisimiut/Holsteinsborg, Sarfartoq and Maniitsoq/Sukkertoppen, the 'Diamond Province' of southern West Greenland (Nielsen *et al.* 2009). They fall in several age groups (Secher *et al.* 2009). UML dykes in the Sisimiut region have yielded ages of *c.* 590 Ma (Scott 1981). Dykes in a wide region around the Sarfartoq carbonatite complex have Neoproterozoic ages between 604 and 555 Ma. Similar ages were found for dykes in the Maniitsoq region, but samples collected around the Qaqarssuk carbonatite complex are of Jurassic age 152–166 Ma. Only Neoproterozoic dykes have as yet proved to be diamondiferous (Secher *et al.* 2009).

The Palaeozoic Franklinian Basin of North Greenland and Ellesmere Island

The Palaeozoic Franklinian Basin extends from the Canadian Arctic Islands across North Greenland to Kronprins Christian Land in eastern North Greenland, an E–W distance of 2000 km (Peel & Sønderholm 1991); only part of the Canadian segment of the basin is represented on the map. The preserved part of the succession shows that deposition in this E–W-trending basin began in the latest Precambrian and continued until at least the earliest Devonian in Greenland and later Devonian to earliest Carboniferous in Canada; sedimentation was brought to a close by the mid- to late Palaeozoic Ellesmerian orogeny. In the Canadian Arctic Islands deposition continued more or less continuously throughout the Devonian and probably into the earliest Carboniferous. Deposition of clastic sediments of Middle and Late Devonian age in the southern part of the Franklinian Basin in the Canadian Arctic Islands reflects an early orogenic event with uplift and erosion starting in latest Silurian time (Trettin 1991, 1998).

Deposition in the Franklinian Basin in North Greenland took place along a passive continental margin, and its evolution during the Early Palaeozoic resulted in a distinctive differentiation into a southern, broad, shallow shelf bordered to the north by a slope with moderate water depths and a broad deep-water trough (Higgins *et al.* 1991). The shelf succession is dominated by carbonates and reaches 3 km in thickness, whereas the trough deposits are dominated by siliciclastic rocks and have a total thickness of *c.* 8 km (Fig. 28). The shelf–trough boundary was probably controlled by deep-seated faults, and with time the trough expanded southwards to new fault lines, with final foundering of the shelf areas in the Silurian. The sedimentary successions in the North Greenland and Canadian (Ellesmere Island) segments of the basin show close parallels in development, although different lithostratigraphic terminologies are employed (Trettin 1991, 1998).

The evolution of the Franklinian Basin in North Greenland has been divided into seven stages, with significant changes in the sedimentary regime linked to southward expansion of the basin margin (Higgins *et al.* 1991; Henriksen & Higgins 2000).

Uppermost Neoproterozoic – Silurian in North Greenland

The oldest shelf deposits range from latest Neoproterozoic to Cambrian in age, and consist of a mixture of carbonates and siliciclastic sediments [**25**]; they crop out in a narrow, almost continuous zone extending from Danmark Fjord in the east through southern Peary Land to southern Wulff Land in the west (Ineson & Peel 1997). The southernmost outcrops farther to the west in Inglefield Land rest on crystalline basement. Three principal divisions are recognised: a lower varied sequence of sandstones, dolomites and mudstones (Skagen Group), a middle dolomitic unit locally with stromatolites (Portfjeld Formation), and an upper siliciclastic unit (Buen Formation). Total thickness reaches 1–2 km. The Buen Formation in North Greenland is noted at one location for its well-preserved soft-bodied fossil fauna (Conway Morris & Peel 1990, 1995, 2008).

Early Cambrian deep-water turbidite trough sediments [**26**] dominate the northernmost parts of Greenland bordering the Arctic Ocean, and they also crop out in a broad E–W-trending belt north of Lake Hazen in Ellesmere Island. The lower part (Nesmith Beds in Canada, Paradisfjeld Group in Greenland) comprises calcareous mudstones and dolomites with, in Greenland, carbonate conglomerates at the top. The upper division (Polkorridoren Group) is made up of thick units of sandy turbidites and mudstones. The thickness of these two divisions totals about 3–4 km (Friderichsen *et al.* 1982; Higgins *et al.* 1991).

Carbonate sedimentation resumed on the platform in the late Early Cambrian (Ineson *et al.* 1994; Ineson & Peel 1997) and continued with minor siliciclastic intervals until the early Silurian, giving rise to an up to 1500 m thick succession of carbonate lithologies (Brønlund Fjord, Tavsen Iskappe, Ryder Gletscher and Morris Bugt groups, and Petermann Halvø and Ymers Gletscher formations [**23**]). Throughout the period sedimentation was influenced by differential subsidence and southwards expansion of the deep-water trough. Uplift in eastern North Greenland led to erosion of the Cambrian to late Early Ordovician succession in Kronprins Christian Land, after which the Middle Ordovician to Early Silurian platform succession was deposited. A broad zone of outcrop can be traced from Danmark Fjord to Washington Land, with outliers to the south-west in northern Inglefield Land. On Ellesmere Island extensive outcrops are found on Judge Daly Promontory. The up to 1500 m thick succession (Fig. 29) of massive dolomites, carbonate grainstones, carbonate mass-flow deposits and evaporites reflects both progradation and aggradation phases of platform evolution.

The Cambrian – Early Silurian starved slope and trough deposits (Surlyk & Hurst 1984) are represented by a condensed succession, dominated for the most part

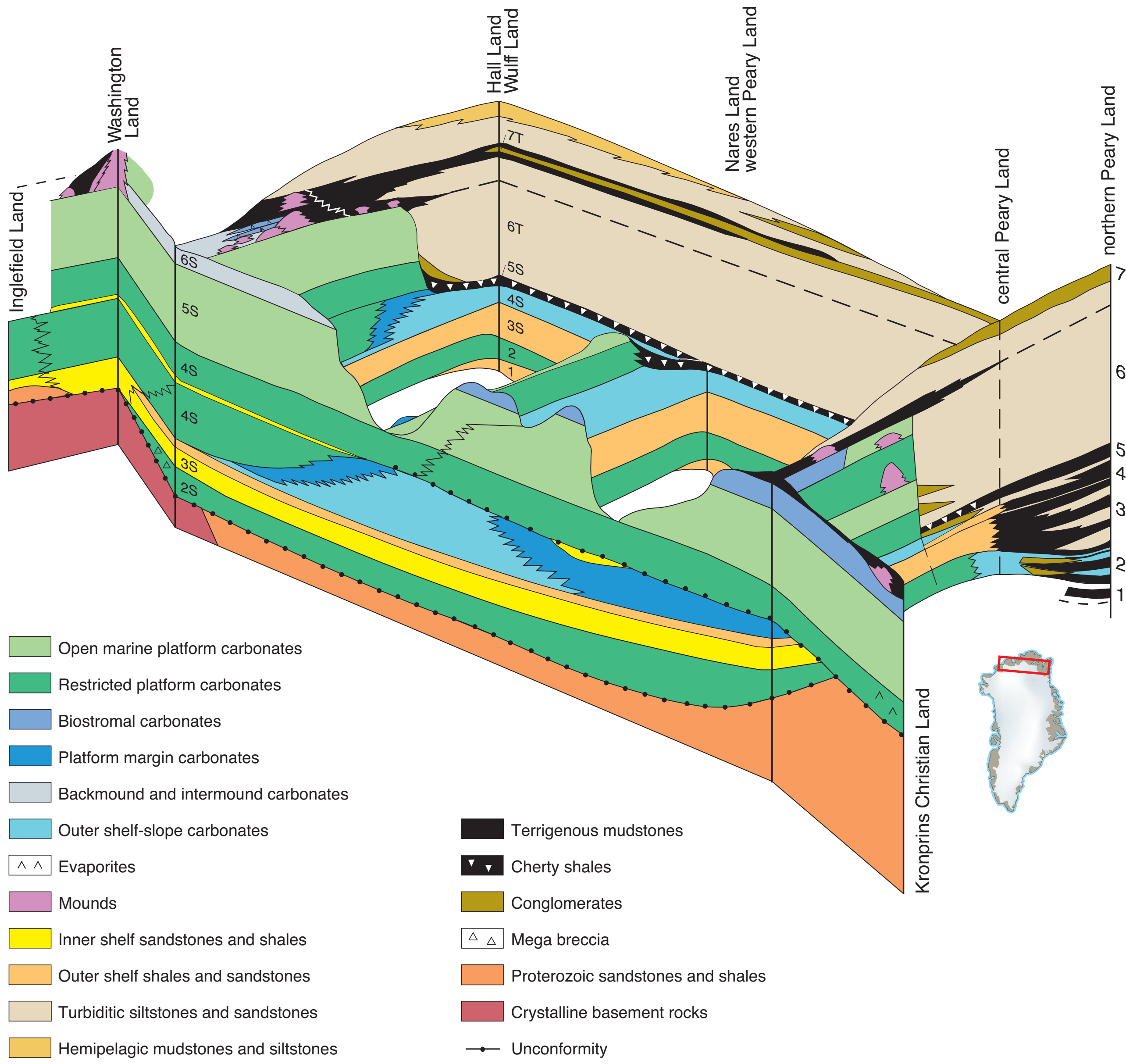


Fig. 28. Block diagram illustrating relationships between shelf, slope and trough sequences in the Lower Palaeozoic Franklinian Basin of North Greenland. The schematic fence diagram covers a region of *c.* 700 km east–west and *c.* 200 km north–south. Shelf stages (**S**) and trough stages (**T**) are divided into time intervals. **1**: late Neoproterozoic? – Early Cambrian; **2**: Early Cambrian; **3**: Early Cambrian; **4**: Late Early Cambrian – Middle Ordovician; **5**: Middle Ordovician – Early Silurian; **6**: Early Silurian; 7: later Silurian.
Units on the map: Portfjeld and Buen Formations [25] – stages 2–3 S; Brønlund Fjord, Tavsen Iskappe, Ryder Gletscher and Morris Bugt Groups and Petermann Halvø and Ymers Gletscher Formations [23] – stages 4–5 S; Washington Land Group exclusive above mentioned formations [21] – stages 6–7 S; Skagen, Paradisfjeld and Polkorridoren Groups [26] – stages 1, 2–3 T; Vølvedal and Amundsen Land Groups [24] – stages 4–5 T; Peary Land Group [22] – stages 6–7 T. Modified from Higgins *et al.* (1991) and with information from M. Sønderholm (personal communication 1998).

by carbonate mudstones and carbonate conglomerates in the lower part (Vølvedal Group) and by cherts and cherty shales in the upper part (Amundsen Land Group) [24]. In central North Greenland thin-bedded turbidites characterise both the lower and upper parts of the succession. In Greenland these deposits occur in thrust slices and anticlinal fold cores (Fig. 30; Soper & Higgins 1987, 1990); in Ellesmere Island they occur mainly in scattered anticlinal fold cores. Thicknesses vary greatly, from a minimum of 50–150 m to a maximum of about 1 km.

Silurian carbonate ramp and rimmed shelf deposits (Washington Land Group [**21**]) crop out in an almost continuous narrow strip extending from Kronprins Christian Land in the east to Washington Land in the west (Hurst 1980, 1984; Sønderholm & Harland 1989; Higgins *et al.* 1991). The comparable deposits of this age in Ellesmere Island have been included in an extension of unit [**23**] – see legend. Sedimentation on the platform was closely linked to the dramatic increase in deposition rates in the trough and was initiated in the Early Silurian (early Late Llandovery) by a major system of sandstone turbidites (Peary Land Group [**22**]) derived from the rising Caledonian mountains in the east (Hurst & Surlyk 1982; Surlyk & Hurst 1984; Larsen & Escher 1985). Loading effects of the turbidites led to downflexing of the outer platform and expansion of the trough. With progressive drowning of the shelf, carbonate deposition was only locally maintained on isolated reef mounds up to 300 m high (e.g. Samuelsen Høj Formation, Hauge Bjerge Formation). Mound formation terminated over much of the region during the Late Llandovery, but persisted in western North Greenland into the Late Silurian (Early Ludlow).

The Silurian turbidite trough deposits occur in a broad belt traceable across North Greenland (Peary Land Group [**22**]) and Ellesmere Island; the commencement of turbidite sedimentation was essentially synchronous in both regions within the limits of biostratigraphic resolution (Trettin 1991). The trough sediments represent the deposits of a major E–W-trending sand-rich turbidite system. Palaeocurrent directions in North Greenland indicate a source area in the rising mountains of the Caledonian fold belt to the east (Higgins *et al.* 1991; Henriksen & Higgins 2000), whereas current directions in Ellesmere Island demonstrate an additional source area in the north. The initial phase of sandstone turbidite deposition in North Greenland laid down between 500 and 2800 m of sediment within the Early Silurian (Late Llandovery); this filled the deep-water trough, buried the former shelf escarpment and led to deposition of black mudstone over extensive former shelf areas. Renewed prograding fan systems built up and turbidite deposition continued throughout the Silurian, punctuated by an episode of chert conglomerate deposition in the middle Wenlockian (Surlyk 1995). Palaeontological evidence from the youngest deposits in North Greenland indicates a Late

Fig. 29. Cambro-Ordovician platform margin sequence in the foreground and Ordovician shelf sequence clastic rocks in the middle distance. View from the south, inner J.P. Koch Fjord, central North Greenland. Profile height in the foreground is *c.* 500 m.

Fig. 30. Middle Ordovician – Lower Silurian sediments in the deep-water sequence of the Franklinian Basin (Amundsen Land Group dark unit; Merqujôq Formation light coloured unit). The sedimentary rocks were folded into south-facing tight folds during the Ellesmerian orogeny. North-east cape of Victoria Fjord, central North Greenland, view towards the east. Profile height is *c.* 400 m.

Silurian (Pridoli) to Early Devonian age (Bendix-Almgreen & Peel 1974; Blom 1999). In Ellesmere Island this phase of turbidite deposition persisted into the Lower Devonian; farther to the west in the Canadian Arctic Islands clastic sedimentation associated with the advance of Ellesmerian deformation continued through the Devonian into the earliest Carboniferous.

Proterozoic–Silurian exotic terrane of Ellesmere Island (Pearya)

The geological province of Pearya, now recognised as an exotic terrane, is confined to northernmost Ellesmere Island (Trettin 1991, 1998). Pearya appears to have been accreted during the latest Ordovician to early Silurian,

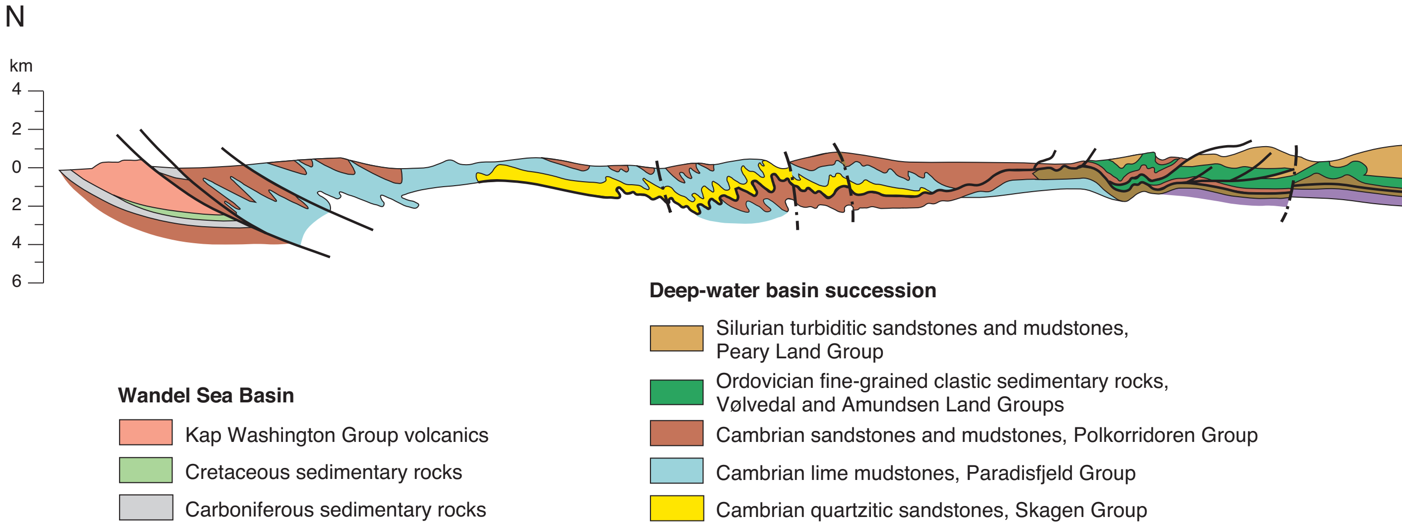
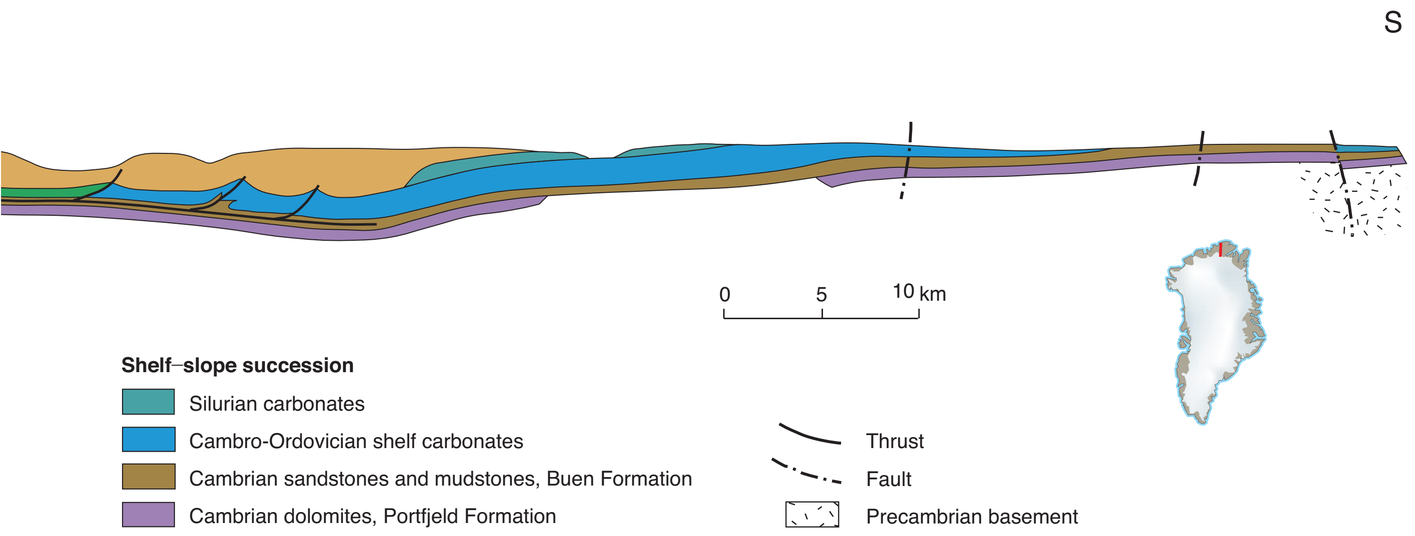


Fig. 31. N–S structural cross-section through the North Greenland (Ellesmerian) fold belt and its southern foreland in North Greenland (*c.* 39°W, westernmost Peary Land). Compiled from Soper & Higgins (1990) and Henriksen (1992).

and underwent further convergence or accretion during the late Silurian (de Freitas *et al.* 1999; Tessensohn & Roland 2000). On the geological map it is represented by two divisions: late Mesoproterozoic crystalline rocks [52] and a Neoproterozoic to Late Silurian complex of undifferentiated metasedimentary and metavolcanic rocks (the mainly exotic terrane [2] of the map legend). The rocks of the latter division are stratigraphically or structurally associated with the formation of the Franklinian deep-water basin. The crystalline rocks consist of granitoid gneisses and lesser amounts of amphibolite, schist, marble and quartzite in several outcrop areas with different structural settings and trends. The younger supracrustal complexes include different carbonate and clastic sediments together with varied acid and mafic volcanic rocks. These supracrustal rocks have been folded and constitute the Markham Fold Belt, which is a complex region that fringes the Pearya terrane on the south-east. The Pearya exotic terrane is noted for emplacement of granite plutons associated with the early Middle Ordovician M'Clintock orogeny, not recorded elsewhere in Ellesmere Island.

Ellesmerian orogeny in North Greenland and Ellesmere Island

The Palaeozoic Ellesmerian orogeny, which brought sedimentation in the Franklinian Basin to a close, involved compression of the Lower Palaeozoic trough succession against the carbonate shelf to the south following collision with an unknown continent to the north (Higgins *et al.* 2000). The resulting Ellesmerian fold belts of both North Greenland and northern Ellesmere Island are characterised by E–W- to NE–SW-trending chains of folds, broadly parallel to the main facies boundaries within the Franklinian Basin. In the North Greenland fold belt deformation is most intense in the north, where three phases of folding are recognised and metamorphic grade reaches low amphibolite facies. Deformation decreases southwards, and the southern part of the fold belt is a thin-skinned fold and thrust zone (Soper & Higgins 1987, 1990; Higgins *et al.* 1991) that coincides with the region which was transitional between the platform and trough for much of the Cambrian (Fig. 31). A prominent belt of major folds is traceable between northern Nyeboe Land and J.P. Koch Fjord, and farther east spectacular imbricate thrusts occur north of the head of Frederick E. Hyde Fjord (Pedersen 1986). The same general pattern of Ellesmerian deformation is seen in Ellesmere Island, except that the southernmost belt of folding propagated some 100 km southward into the platform, producing the large-scale, concentric-style folding seen north-west of Kennedy Kanal. The age of the Ellesmerian orogenic deformation in North Greenland is not well constrained, but is assumed to be Late Devonian to Early Carboniferous.



Lower Palaeozoic of East Greenland

Cambrian–Ordovician sediments in the Caledonian fold belt

Cambrian–Ordovician rocks [**40**] make up an approximately 4500 m thick succession within the East Greenland Caledonian fold belt between latitudes 71°40′ and 74°30′N (Haller 1971; Peel 1982; Henriksen 1985), and were placed in the Kong Oscar Fjord Group by Smith *et al.* (2004). The sedimentary rocks laid down in this Lower Palaeozoic basin are disturbed by large-scale folding and faulting, but are non-metamorphic. Limestones and dolomites dominate the succession which spans the period from the earliest Cambrian to the Late Ordovician (Fig. 32); uppermost Ordovician to Silurian sediments are not known in East Greenland (Smith & Rasmussen 2008).

The Lower Palaeozoic succession begins with *c.* 200 m of Lower Cambrian sandstones and siltstones with trace fossils, interpreted as deposited in a tidal to shallow marine environment. These are overlain by a *c.* 2800 m thick Lower Cambrian – Middle Ordovician (Darriwilian) succession of alternating limestones and dolomites, containing a diversified shelf-type Pacific fauna (Cowie & Adams 1957; Peel & Cowie 1979; Peel 1982).

Stable shelf conditions prevailed throughout the Early Palaeozoic, with the progressive lithology changes considered to reflect increasing isolation from detrital sources (Swett & Smit 1972). Sedimentary and organic–sedimentary structures indicate generally very shallow depositional environments, implying that sedimentation and subsidence rates were roughly equal. The absence of angular unconformities reflects a non-tectonic environment. The Pacific fauna indicates that these areas were developed on the western margin of the proto-Atlantic (Iapetus) ocean.

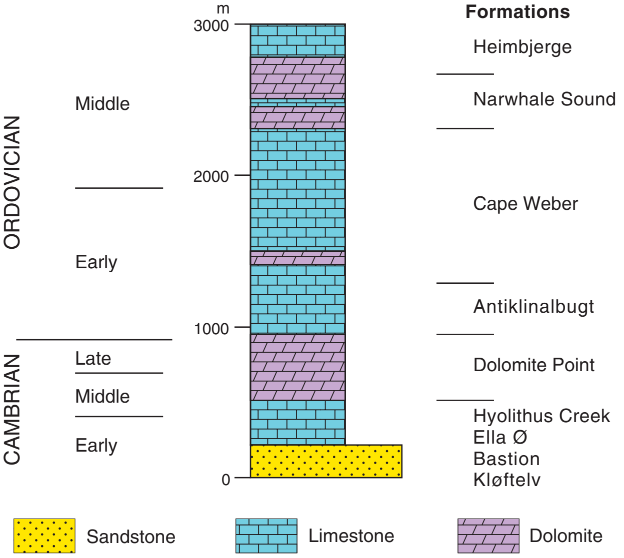


Fig. 32. Schematic lithostratigraphic composite section of the Cambro-Ordovician sediments in East Greenland (*c.* 71°30′–74°30′N). Unit [**40**] on the map. Thicknesses after Smith & Rasmussen (2008).

Caledonian orogeny in East and North-East Greenland

The Caledonian fold belts on both sides of the North Atlantic developed as a consequence of collision between the continents of Laurentia to the west and Baltica to the east following closure of the proto-Atlantic ocean (Iapetus; Higgins *et al.* 2008). The East Greenland Caledonian fold belt is well exposed between 70° and 81°30′N as a 1300 km long and up to 300 km wide coast-parallel belt. Large regions of the fold belt are characterised by reworked Precambrian basement rocks [**74**, **70**, **52**], overlain by Meso- to Neoproterozoic [**46–43**] and lower Palaeozoic [**40**] sedimentary rocks (Fig. 33), all of which form parts of westward-directed major thrust sheets. The Palaeoproterozoic basement gneiss complexes locally preserve traces of Proterozoic fold structures (Fig. 34), and have been reworked during Caledonian orogenesis.

The onshore East Greenland Caledonian orogen is composed of far-travelled, foreland-propagating thrust sheets that were derived from the Laurentian margin and translated westward across the orogenic foreland (Higgins & Leslie 2000, 2008). The deepest preserved level of the orogen is found north of Danmarkshavn (76°40′N) where abundant Caledonian eclogitic enclaves occur in the Palaeoproterozoic basement gneisses (Gilotti 1993; Brueckner *et al.* 1998; Gilotti *et al.* 2008). Medium-temperature high-pressure eclogite facies metamorphism has been dated at 410–390 Ma (Gilotti *et al.* 2008).

Central parts of the orogen (70–75°N) are formed by a pile of several thrust sheets that in their western parts overlie foreland windows (Higgins *et al.* 2004a). The individual thrust sheets include Archaean–Palaeoproterozoic gneiss complexes overlain by thick successions of latest Mesoproterozoic to earliest Neoproterozoic sedimentary rocks (Krummedal supracrustal sequence). In the highest thrust sheet these sedimentary rocks preserve evidence of early Neoproterozoic orogenesis (migmatites and 940–910 Ma augen granites). Caledonian metamorphism led to emplacement of a suite of Caledonian granites, some of which migrated into the basal parts of

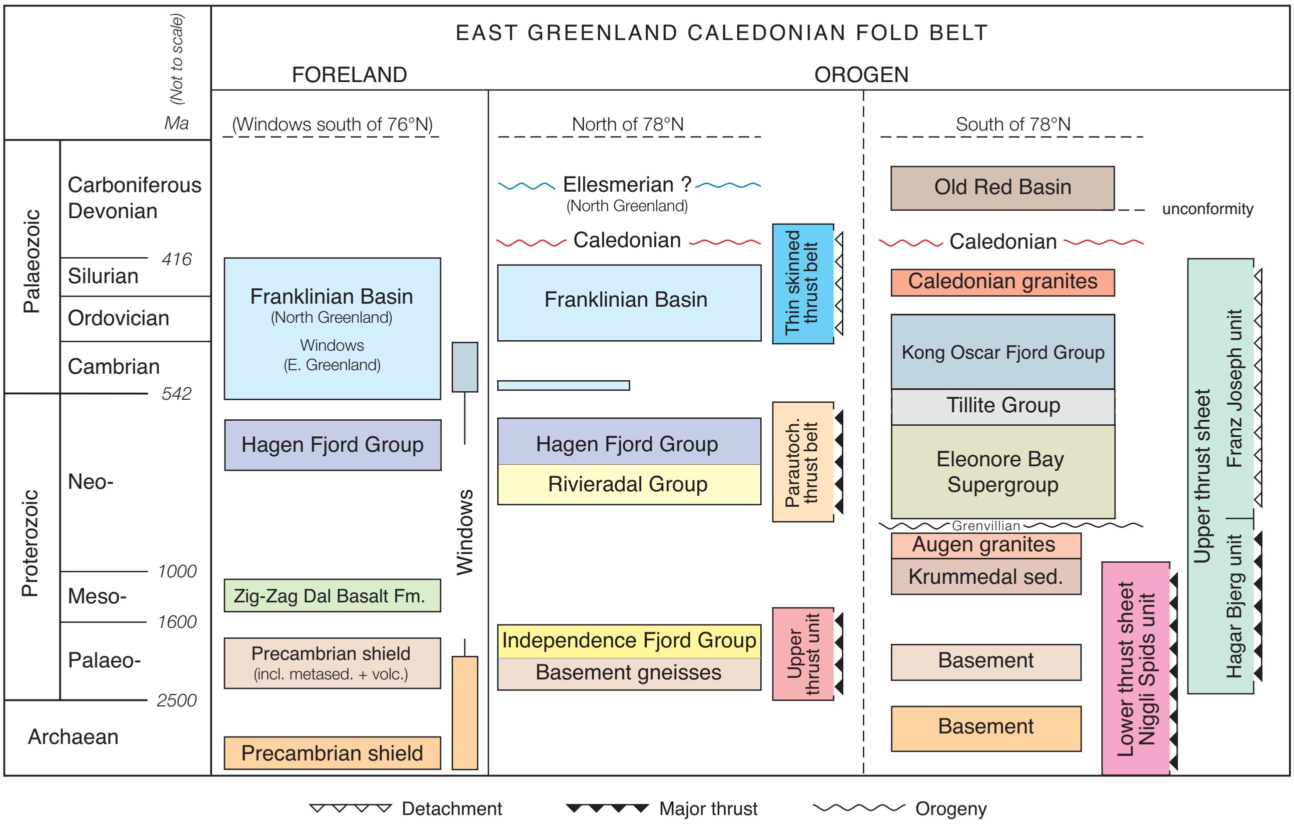


Fig. 33. Schematic diagram showing lithostratigraphy and structural units with pre-Caledonian and Caledonian elements occurring in the East Greenland Caledonian fold belt.

the overlying Eleonore Bay Supergroup (see also below; Kalsbeek *et al.* 2008b). Extensional structures characterise some of the late tectonic phases (Strachan 1994; Hartz & Andresen 1995; Andresen *et al.* 1998; Gilotti & McClelland 2008). The northernmost part of the fold belt in Kronprins Christian Land preserves high-level thin-skinned structures. Reviews of the East Greenland Caledonides have been presented by Haller (1971), Henriksen & Higgins (1976), Henriksen (1985) and Higgins *et al.* (2008).

Caledonian intrusions and plutonic rocks

During the Caledonian orogeny widespread migmatisation took place in the crystalline complexes in the southern part of the fold belt and a suite of late to post-kinematic plutons [**54**] was emplaced in the region between Scoresby Sund (70°N) and Bessel Fjord (76°N).

North of latitude 72°N the intrusions were emplaced mainly in the boundary zone between the Neoproterozoic Eleonore Bay Supergroup sedimentary rocks and the adjacent metamorphic complexes (Jepsen & Kalsbeek 1998; Fig. 35), whereas in southern areas plutonic bodies are widespread within the crystalline complexes. Granodiorites and granites are the most abundant types and have yielded intrusive ages ranging from 466 Ma to *c.* 420 Ma. Most ages occur in the range 440–425 Ma (Kalsbeek *et al.* 2008b). The Caledonian granites in the northernmost part of their region of occurrence (75–76°N) were emplaced about 430–425 Ma ago and these contain a large proportion of crustally derived components (Strachan *et al.* 2001).

The southernmost known 'Caledonian' intrusion is the Batbjerg complex (Brooks *et al.* 1981) which occurs in a late Archaean granulite facies terrain at Kangerlussuaq 68°40′N, *c.* 200 km south of the nearest exposed part of the Caledonian orogenic belt. The Batbjerg complex consists largely of pyroxenites including some leucite-bearing types [**60**], and has been dated at *c.* 440 Ma (Brooks *et al.* 1976).

Fig. 34. Major isoclinal fold in reactivated Palaeoproterozoic grey orthogneisses, comprising units of darker banded gneisses and lighter coloured more homogeneous granitoid rocks. The earlier structures have been refolded by N–S-trending open folds with steeply inclined axial surfaces. North side of innermost Grandjean Fjord (*c.* 75°10´N), North-East Greenland; *c.* 40 km south-west of Ardencaple Fjord. The cliff is approximately 1200 m high.

Fig. 35. Caledonian granite with large sedimentary xenoliths of the Neoproterozoic Eleonore Bay Supergroup. East of Petermann Bjerg (*c.* 73°N), North-East Greenland. Summit about 2100 m high; upper *c.* 700 m of cliff face shown.

Devonian continental sediments in East Greenland

Following the Caledonian orogeny the extensional collapse of the overthickened crustal welt led to the initiation of Devonian sedimentary basins in central East Greenland (Larsen & Bengaard 1991; Hartz & Andresen 1995; Larsen *et al.* 2008). The Devonian sediments unconformably overlie Ordovician and older rocks, and the deposits were accommodated by SE–NW-oriented dip-slip faulting and are preserved in N–S-trending graben-like structures.

The basin fill is of Middle and Late Devonian age [**39**] and consists of more than 8 km of mainly coarse continental siliciclastic sediments with some volcanic intervals. Four lithostratigraphic groups have been established, each corresponding to a tectonostratigraphic basin stage (Fig. 36). The stages are separated by unconformities related to tectonic events, which took place both during and after sedimentation (Haller 1971; Olsen & Larsen 1993). Each basin stage is composed of several depositional complexes and shows approximately similar drainage patterns, with deposition mainly from the west and north. The earliest deposits (Vilddal Group, up to 2500 m thick) are interpreted as laid down by eastwards draining gravelly braided rivers and sandy and silty allu-

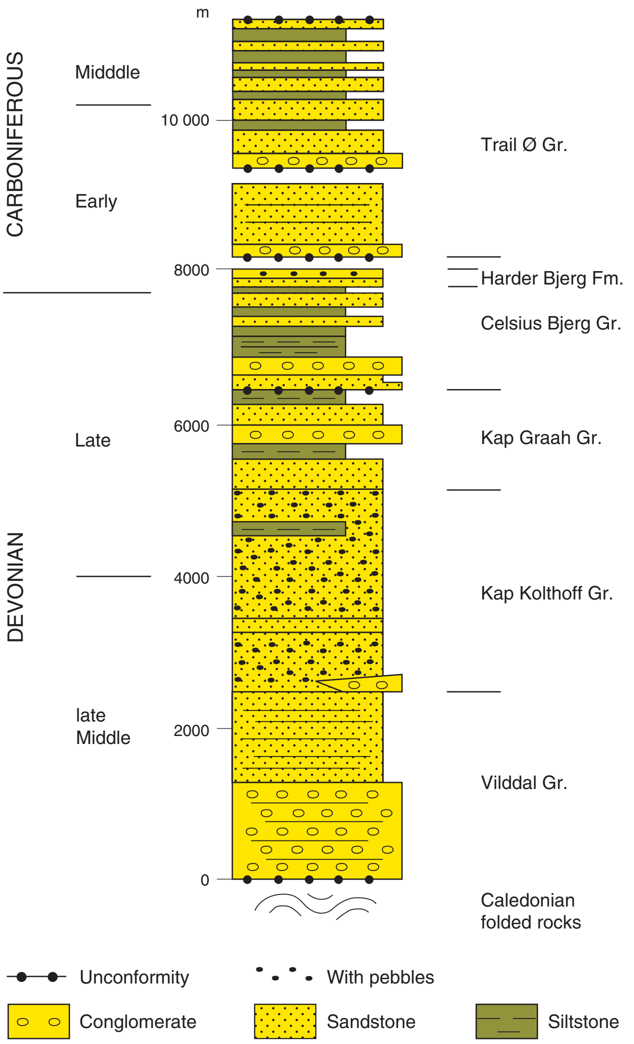


Fig. 36. Schematic, lithostratigraphic composite section of Devonian – Lower Permian continental clastic deposits in central East Greenland (71–74°30′N), units [**39**] and [**38**] on the map. Compiled from Olsen & Larsen (1993), Stemmerik *et al.* (1993) and P.-H. Larsen *et al.* (2008).

vial fans, which gave way to meandering streams and flood plains. The overlying sandstones (Kap Kolthoff Group, up to 2700 m thick) were deposited by extensive coalescing braidplain systems with southward drainage patterns (Olsen & Larsen 1993; Olsen 1993) dominated by sandy deposits; this group contains intervals of basic and acid volcanic rocks. During the following stage (Kap Graah Group, up to 1300 m thick) sedimentation was dominated by aeolian deposits succeeded by an alluvial and aeolian complex, which was dominated by fine-grained sandstones and siltstones. The following stage (Celsius Bjerg Group, 1550 m thick) is characterised by northwards drainage patterns. The deposits comprise fluvial sandstones, flood basin sediments and lacustrine siltstone. The uppermost *c.* 200 m thick part of the continental Celsius Bjerg stage is now considered early Tournaisian (Carboniferous) in age (Marshall *et al.* 1999).

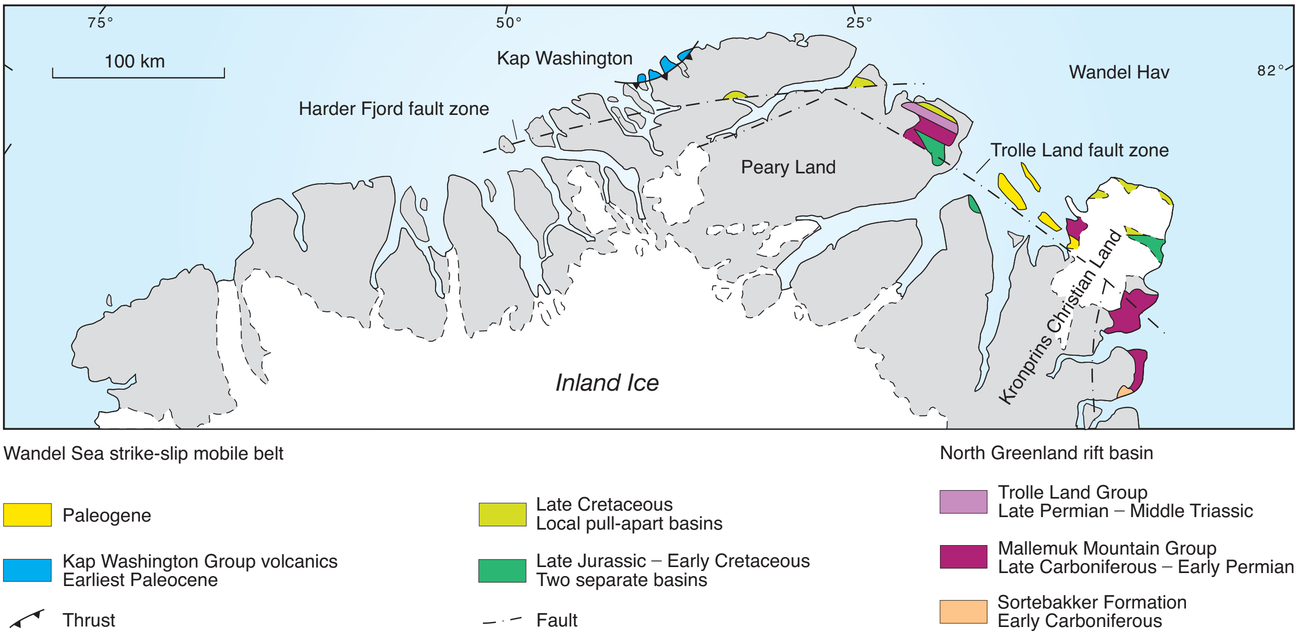


Fig. 37. Distribution of the Wandel Sea Basin sequences in central and eastern North Greenland. Modified from Håkansson *et al.* (1994).

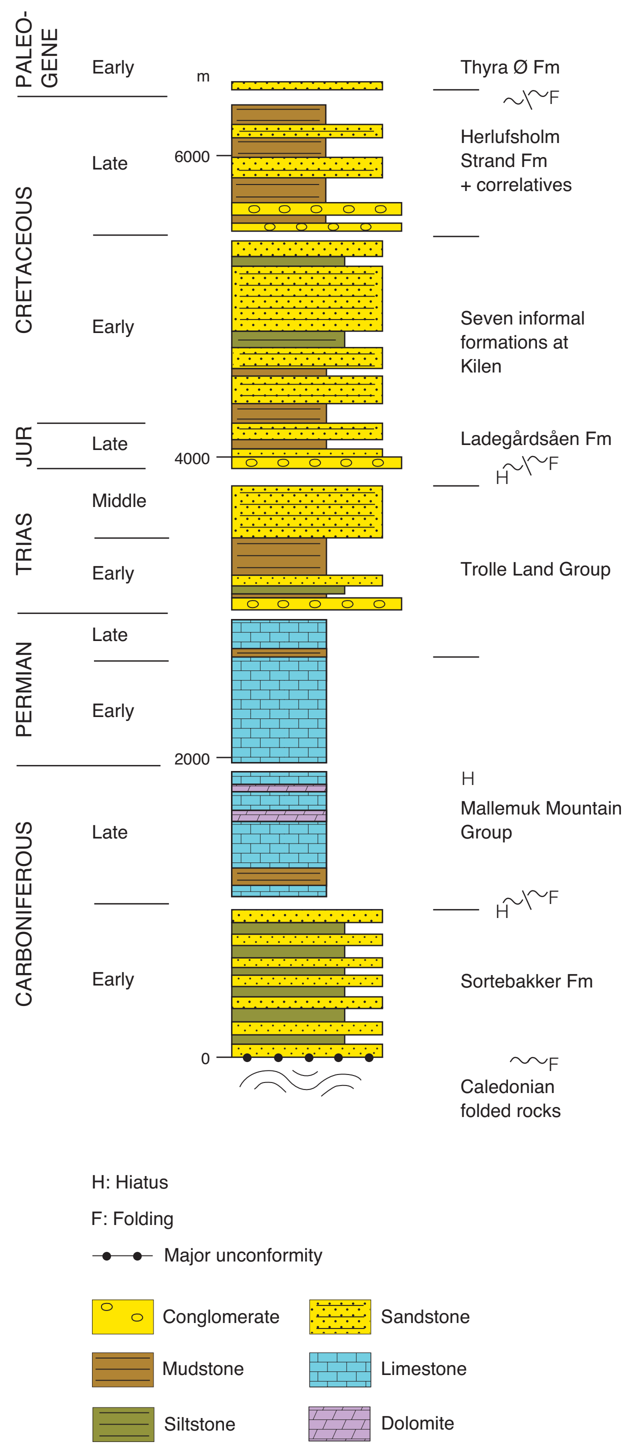


Fig. 38. Composite section of the Wandel Sea Basin successions in eastern North Greenland. The successions occur in several distinct sub-basins. Corresponding units on the map: Sortebakker Formation [20]; Mallemuk Mountain Group [19]; Trolle Land Group [18]; Ladegårdsåen Formation and correlatives [17]; Herlufsholm Strand Formation and correlatives [15]; Thyra Ø Formation [14]. Compiled from Håkansson & Stemmerik (1989), Stemmerik & Håkansson (1989) and Stemmerik *et al.* (2000).

Carboniferous–Tertiary deposits of the Wandel Sea Basin, central and eastern North Greenland

The Wandel Sea Basin deposits were laid down along the northern and north-eastern margin of the Greenland shield (Figs 37, 38). Three main phases of basin formation are recognised, commencing with a widespread Carboniferous to Triassic event of block faulting and regional subsidence (Stemmerik 2000). Later, during the Late Jurassic and Cretaceous, more localised basin formation took place during two separate events in a strike-slip zone formed at the plate boundary between Greenland and Svalbard (Håkansson & Stemmerik 1989, 1995).

Lower Carboniferous fluvial deposits (Sortebakker Formation [**20**]) are restricted to an isolated half-graben in southern Holm Land (*c.* 80°N; Stemmerik & Håkansson 1989, 1991). After mid-Carboniferous regional uplift, rifting started in the late Carboniferous and more than 1100 m of Upper Carboniferous to Lower Permian shallow marine sediments were deposited (Mallemuk Mountain Group [**19**]) (Stemmerik *et al.* 1996, 1998, 2000). The Carboniferous succession is dominated by cyclicly interbedded shelf carbonates (with minor reefs) and siliciclastic rocks. The Lower Permian is mainly represented by shelf carbonates. Renewed subsidence took place during the mid-Permian, and the Upper Permian succession is dominated by alternating shallow marine carbonates and sandstones and deep-water shales. A low-angle unconformity separates these deposits from the overlying Lower and Middle Triassic shelf sandstones and shales (Trolle Land Group [**18**]) in eastern Peary Land.

Sedimentation resumed in the Late Jurassic, and during the Late Jurassic and Early Cretaceous shelf sandstones and shales (Ladegårdsåen Formation [**17**]) were deposited in a series of small isolated sub-basins (Håkansson *et al.* 1991). Following a new episode of strike-slip movements, renewed sedimentation took place in six minor pull-apart basins during the Late Cretaceous. Each basin is characterised by high sedimentation rates, a restricted lateral extent and its location along strike-slip fault zones (Håkansson & Pedersen 1982; Birkelund & Håkansson 1983). Depositional environments range from deltaic to fully marine.

At Kap Washington, on the north coast of Greenland, *c.* 5 km of extrusive volcanic rocks and volcanogenic sediments (Kap Washington Group [**16**]) of peralkaline affinity are preserved (Fig. 37; Brown *et al.* 1987). They are of earliest Paleocene age (64 ± 3 Ma, Estrada *et al.* 2001), and their extrusion may be associated with intrusion of a dense swarm of alkali dolerite dykes in North

Greenland (see Fig. 20). The volcanic rocks are preserved below a major, southward-dipping thrust which transported folded Lower Palaeozoic rocks northwards over the volcanic successions (see Fig. 31).

All pre-Upper Cretaceous deposits in eastern North Greenland were subjected to compressional deformation during the so-called 'Kronprins Christian Land orogeny' (Håkansson *et al.* 1991). Subsequently to this deformation event a thin succession of upper Paleocene to lower Eocene fluviatile and marine sandstones (Thyra Ø Formation [**14**]) accumulated, which are the youngest deposits of the Wandel Sea Basin succession (Håkansson *et al.* 1991; Lyck & Stemmerik 2000).

Late Palaeozoic and Mesozoic rift basins in East Greenland

A series of Carboniferous–Mesozoic sedimentary basins developed in East Greenland following initial post-Caledonian Devonian deposition. The basins formed as N–S-trending coast-parallel depocentres which reflect prolonged subsidence. Important phases of block faulting and rifting took place during the Early and Late Carboniferous, Late Permian, Late Jurassic and Cretaceous, presaging the opening of the North Atlantic in the late Paleocene (Surlyk 1990, 2003; Stemmerik *et al.* 1993; Surlyk & Ineson 2003). There is a marked difference in post-Carboniferous structural style and depositional history between the basins south and north of Kong Oscar Fjord (*c.* 72°N). The Jameson Land Basin to the south developed as a Late Permian – Mesozoic sag basin, while the region to the north was characterised by continued block faulting and rifting (Fig. 39).

Initial rifting took place during the latest Devonian to earliest Carboniferous, when fluvial sandstones and shales were deposited in narrow half-grabens [**38**] (Stemmerik *et al.* 1991). A pronounced hiatus marked by non-deposition and erosion occurred during the mid-Carboniferous, and active deposition did not resume until the Late Carboniferous when up to 3000 m of fluvial and lacustrine sediments were deposited in active half-grabens [**38**]. Deposition ceased sometime during the latest Carboniferous or earliest Permian. During the Early Permian a new episode of regional uplift and erosion took place.

Late Permian – Early Cretaceous deposits of the Jameson Land Basin (70–72°N)

The Jameson Land Basin contains a stratigraphically complete succession of Upper Permian to earliest Cretaceous sediments (Fig. 40). Sediment infill was derived

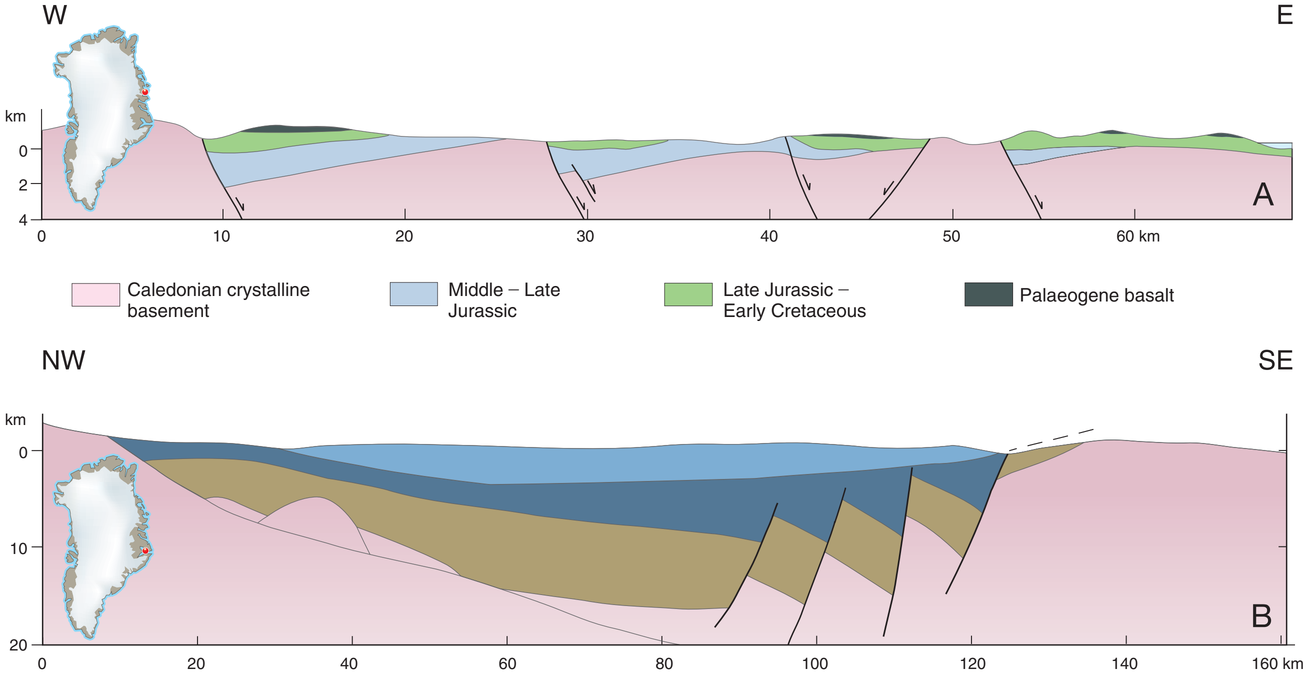


Fig. 39. Upper Palaeozoic – Mesozoic basins in East Greenland. **A**: Northern development at Wollaston Forland (*c.* 74°30′N). **B**: Southern development at Jameson Land (*c.* 71°N). Note the different scales of the two profiles. From Christiansen *et al.* (1991) and Surlyk (1991).

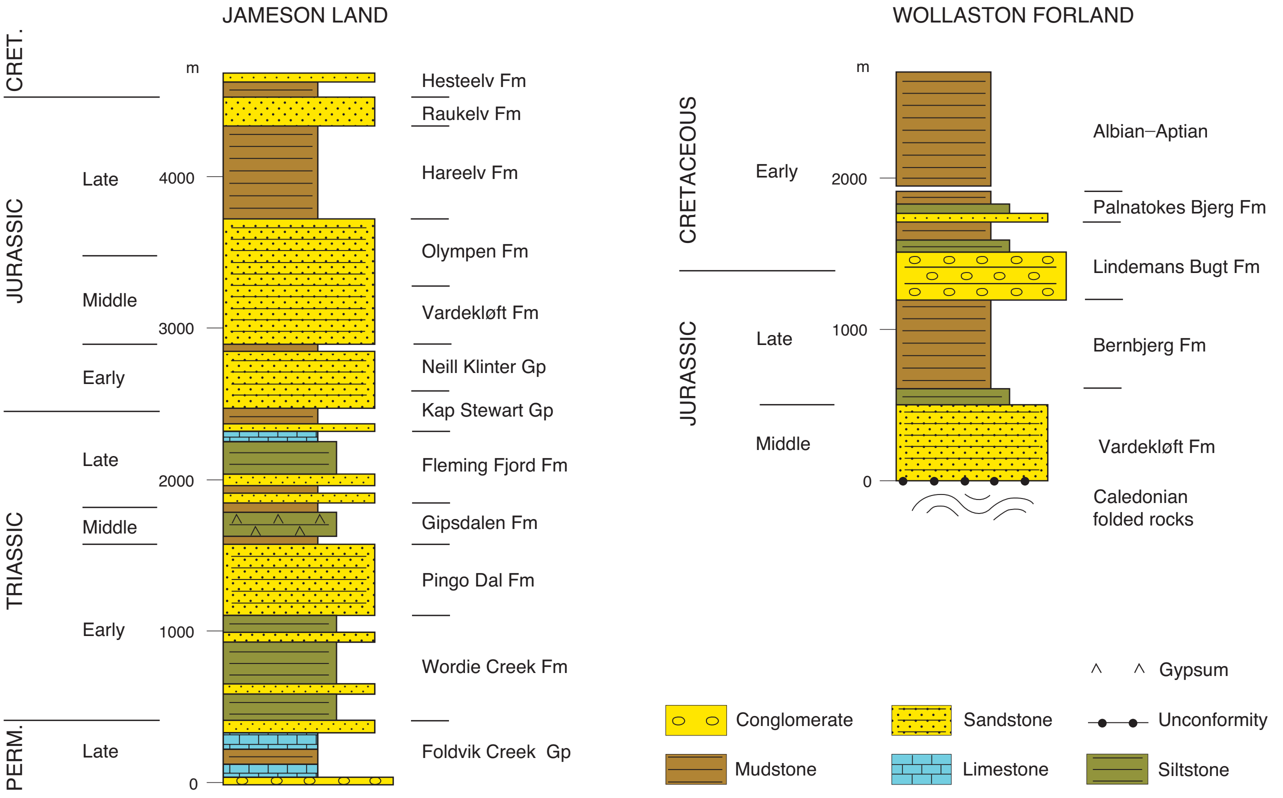


Fig. 40. Schematic sections of the southern (Jameson Land) and northern (Wollaston Forland) developments in the Late Permian and Mesozoic rift margin basins of East Greenland. Corresponding units on the map: Foldvik Creek Group and Wordie Creek Formation [37]; Pingo Dal, Gipsdalen and Fleming Fjord Formations [36]; Kap Stewart Group and Neill Klinter Group [35]; Vardekløft, Olympen, Hareelv and Bernbjerg Formations and correlatives [34]; Raukelv, Hesteelv, Lindemans Bugt and Palnatokes Bjerg Formations and Aptian–Albian sediments [33]. Compiled from: Surlyk & Clemmensen (1975); Clemmensen (1980b); Surlyk *et al.* (1981, 1986); Surlyk (1990, 1991); Stemmerik *et al.* (1993); Dam & Surlyk (1998). A revised provisional lithostratigraphy of the uppermost Triassic – Jurassic has been proposed by Surlyk (2003).

from both the east and west during most of the basin history. The first marine incursion into the area since the Early Palaeozoic took place during the Late Permian and earliest Triassic with deposition of more than 900 m of shallow marine sediments [37] (Surlyk *et al.* 1986). The Permian deposits include alluvial fan conglomerates to marginal marine carbonates and evaporites in the lower part, and carbonate platform to basinal shale deposits in the upper part. The latest Permian and Triassic deposits were dominated by marine sandstones and shales. The next stage in basin development began with deposition of *c.* 1400 m of alluvial conglomerates and lacustrine dolomite and shale during the Triassic [36] (Clemmensen 1980a, b).

This Late Palaeozoic – Mesozoic extensional basin in East Greenland contains a succession from uppermost Triassic to Lower Cretaceous, recording at first thermal subsidence, then onset and culmination of rifting, and finally waning of rifting (Surlyk 2003). A major lacustrine basin [35] covered most of Jameson Land during the latest Triassic – earliest Jurassic (Dam & Surlyk 1993, 1998). Renewed marine incursions took place during the Early Jurassic (Dam & Surlyk 1998), and during the remaining part of the Jurassic and earliest Cretaceous shelf conditions persisted in the basin (Surlyk 1990). During Middle and Late Jurassic time the basin infill mainly comprised shallow-water sandstones in the northern half of the basin while deeper water shales occur in the southern part [34]. Latest Jurassic and earliest Cretaceous deposits [33] are restricted to the southernmost part of the basin and are dominated by shallow marine sandstones (Surlyk 1991). A revised stratigraphy of the uppermost Triassic to Jurassic has been proposed by Surlyk (2003).

Late Permian – Cretaceous deposits in North-East Greenland (72–76°N)

The sedimentary succession is stratigraphically less complete in this part of East Greenland due to continuous block faulting during the Mesozoic (Surlyk 1990; Stemmerik *et al.* 1993). Major hiatuses occur at around the Permian–Triassic boundary and in the Triassic and Early Jurassic.

The Upper Permian and Lower Triassic sediments [**37**, **36**] resemble those in Jameson Land; continental Middle Triassic deposits are restricted to the southernmost part of the region. The Middle to Upper Jurassic sediments [**34**] also resemble those in Jameson Land (Fig. 40), but were deposited in a separate basin (Surlyk 1977). Renewed rifting disrupted the northern part of the region into a series of 10–40 km wide half-grabens during the latest Jurassic and earliest Cretaceous (Surlyk 1978). These were infilled with more than 3000 m of syn-sedimentary marine breccias and conglomerates that pass laterally into sandstones and shales. The younger Cretaceous sediments (upper part of [**33**]) were deposited in a less active rift setting and are dominated by sandy shales with minor conglomerates.

Cretaceous–Palaeogene deposits

Central West Greenland

Cretaceous–Palaeogene sedimentary rocks [**8**] crop out in the Disko–Svartenhuk Halvø region (69–72°N) of West Greenland, where they are overlain by Palaeogene basalts (Pedersen *et al.* 2006). The sediments were laid down in the Nuussuaq Basin and are referred to as the Nuussuaq Group. Although now bounded to the east by an extensional fault system, the sediments may originally have extended both east and south of their present area of outcrop (Chalmers *et al.* 1999). A single seismic reflection line acquired on the south coast of Nuussuaq *c.* 25 km west of locality 2 in Fig. 41 suggests that there are at least 6 km, and perhaps as much as 8 km, of Mesozoic sedimentary rocks below sea level at this locality (Christiansen *et al.* 1995; Chalmers *et al.* 1999), but the age and character of the deepest deposits are not known. The following notes are drawn largely from a new comprehensive description of the entire succession of exposed and drilled sedimentary rocks in the basin (Dam *et al.* 2009).

The oldest sedimentary rocks exposed in the Nuussuaq Basin belong to the Kome Formation of Albian age (column and locality 4 in Fig. 41). These were deposited during a syn-rift phase and crop out on north-east Nuussuaq where they lie directly on weathered Precambrian basement. The coarse sandstones, mudstones and sparse coal of the Kome Formation reflect an environment dominated by fluvial channels, flood plains and fan deltas amid basement highs. The Slibestensfjeldet Formation that overlies the Kome Formation on north-eastern Nuussuaq is up to 240 m thick and was deposited in an extensive lake.

In latest Albian to Early Campanian time the south-eastern part of the Nuussuaq Basin was the site of a major fluvio-deltaic system that fanned out to the west and north-west from a point somewhere east of the island of Disko/Qeqertarsuaq, reaching deeper water at a shelf edge situated approximately at the position of the N–S-trending fault system crossing Disko and Nuussuaq that is shown in the inset map in Fig. 41. The deposits of this system constitute the Atane Formation which is at least 3000 m thick in the Vaigat area, although the thickest exposed sections are only up to 800 m thick. In the south-east, sandstones alternating with mudstones, coal seams and heteroliths represent the deposits of a braided river plain while farther north-west (e.g. at locality 2 in Fig. 41) the formation consists of stacked, typical deltaic, coarsening-upward successions (Fig. 42).

The coeval deep marine sedimentary rocks on western Nuussuaq and eastern Svartenhuk Halvø are referred to the Itilli Formation which comprises slope mudstone, turbidite sandstone and conglomerate units (Dam & Sønderholm 1994). On Svartenhuk Halvø the formation is dominated by mudstone intercalated with thin beds of sandstone interpreted as distal turbidites (Dam 1997). The slope deposits of the Itilli Formation were also penetrated in the GRO#3 exploration well on western Nuussuaq (locality 1, Fig. 41) that terminated drilling at 3 km depth. The thickness of the Itilli Formation is estimated to be at least 2000 m on western Nuussuaq and at least 1000 m in eastern Svartenhuk Halvø (Dam *et al.* 2009).

In the Early Campanian the region again became tectonically unstable (Dam *et al.* 2000). Phases of block-faulting and uplift were followed by incision of both submarine and subaerial canyons into the underlying deposits (Fig. 42). Conglomerates, turbiditic and fluvial sands and mudstones of Maastrichtian to Danian age (Kangilia, Quikavsak and Agatdal Formations) were deposited mainly in valleys and submarine canyons and consequently vary considerably in thickness (Dam & Sønderholm 1994, 1998; Dam 2002; Dam *et al.* 1998, 2009). The Kangilia Formation varies in thickness from 440 m where it is thickest (locality 3, Fig. 41) to only 75 m on central Nuussuaq. The Quikavsak and Agatdal

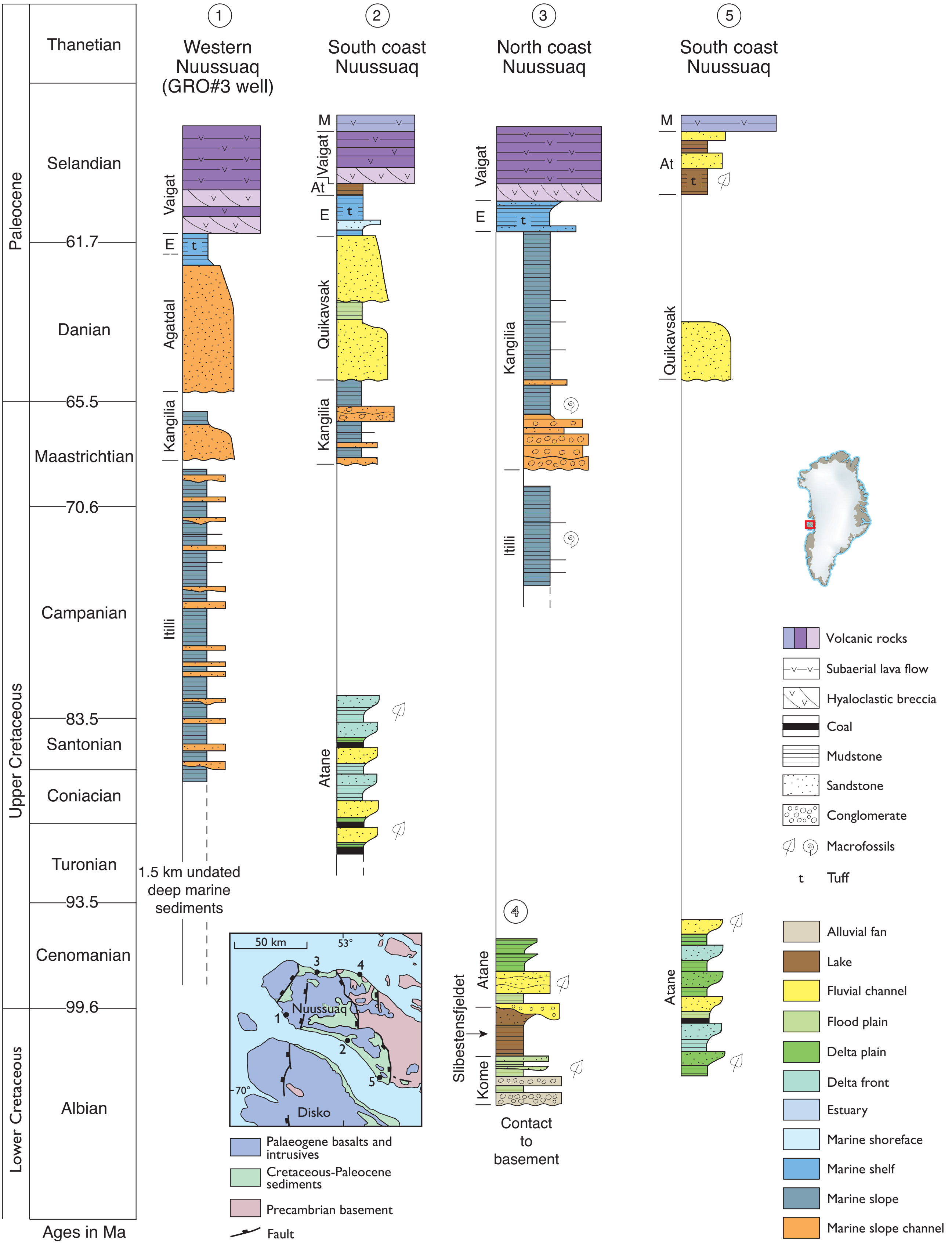
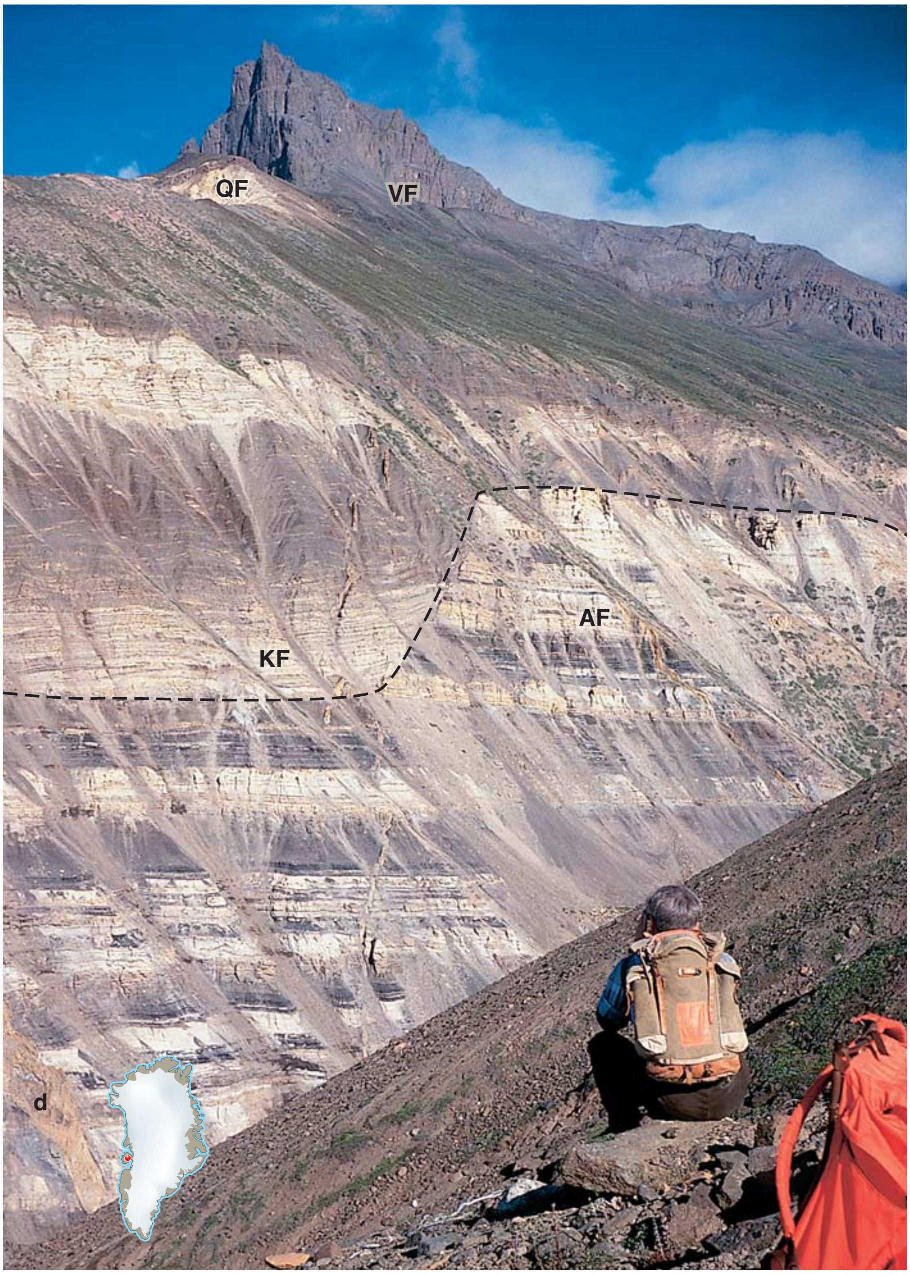


Fig. 41. Lithostratigraphic sections in the Nuussuaq Basin, Disko–Nuussuaq region, central West Greenland (from Dam *et al.* 2009). The names of the formations are shown to the left of the simplified logs which indicate the main lithologies and depositional environments. **M**: Maligât Formation (belongs to the overlying West Greenland Basalt Group); **At**: Atanikerluk Formation; **E**: Eqalulik Formation. Locations of the sections are shown in the index map.

Fig. 42. Major submarine canyon incised in Middle Turonian to Late? Santonian sediments (Atane Formation, **AF**) and infilled with Late Maastrichtian and Early Danian turbidites (Kangilia Formation, **KF**). Thickness of the well-exposed part of the section is approximately 250 m. Note the coarsening-upwards cyclicity in the Atane Formation sediments. Pale sandstones of the Danian Quikavsak Formation (**QF**) can be seen high up on the ridge. The highest rocks exposed are hyaloclastic breccias of the Vaigat Formation (**VF**); a dyke is marked **d**. Summit of the ridge is 920 m a.s.l. Locality: Ataata Kuua (locality 2 in Fig. 41).



Formations are time-equivalents, the former being fluvial–estuarine and the latter marine. The thickness of the entirely channelised Quikavsak Formation varies from zero to 180 m, while the Agatdal Formation is 18–65 m thick on central Nuussuaq but *c.* 250 m thick in the GRO#3 well. On central Nuussuaq some units in the Agatdal Formation are extremely rich in redeposited marine fossils, mainly gastropods and bivalves.

The marine mudstones of the Eqalulik Formation that overlie the formations mentioned before are locally interspersed with volcaniclastic sandstones and tuffs, thus recording the earliest evidence of volcanic activity within the sedimentary section of the Nuussuaq Basin. The thickness of the Eqalulik Formation varies from 12 m to more than 200 m.

The youngest deposits (Atanikerluk Formation) in the Nuussuaq Basin were deposited in lakes in the eastern part of the basin when basalts in the form of hyaloclastite ‘deltas’ overlain by subaerial lava flows prograded from the west and dammed up a large body of standing water fed by fluvial run-off (G.K. Pedersen *et al.* 1998; A.K. Pedersen *et al.* 2007). The deposits that filled the lakes are arranged in two coarsening-upward successions beginning with lacustrine mudstones and passing up into lacustrine–fluvial sandstones. The cumulative thickness of the deposits is *c.* 500 m, the thickest single section (*c.* 400 m) occurring on eastern Disko.

Southern East Greenland

A *c.* 1 km thick Cretaceous to Palaeogene sedimentary succession [**50**] occurs in East Greenland in the Kangerlussuaq Basin north-west of Nansen Fjord (68°17′N). The sediments onlap crystalline basement to the east and north, but elsewhere the base of the succession is not seen. The sedimentary rocks belong to the Kangerdlugssuaq and Blosseville Groups (Soper *et al.* 1976; Nielsen *et al.* 1981). The oldest exposed deposits are fluvial and estuarine sandstones of Late Aptian – Early Albian age. They are overlain by Upper Cretaceous offshore marine mudstones interbedded with thin turbiditic sandstones. In the early Paleocene sediment input increased and submarine fan sandstones were deposited along the northern basin margin whereas mudstone deposition continued within the basin. The offshore marine succession is unconformably overlain by fluvial sheet sandstones and conglomerates of latest Paleocene age (M. Larsen *et al.* 1999, 2001, 2006). The succession records a basin history of mid-Cretaceous transgression and Late Cretaceous – early Paleocene highstand followed by extensive uplift and basin-wide erosion in the mid-Paleocene. The uplift was quickly followed by renewed subsidence and the onset of extensive volcanism.

Tertiary volcanics, intrusions and post-basaltic sedimentary rocks

The Palaeogene lava regions of both West and East Greenland represent major eruption sites at the edges of the continent, from which lavas spilled over Mesozoic – early Paleocene sedimentary basins and lapped onto the Precambrian basement of the continental interior. The volcanic products were formed during the initial phase of continental break-up and initiation of sea-floor spreading in the early Palaeogene.

Palaeogene basalts, central West Greenland

Palaeogene volcanic rocks crop out in central West Greenland between latitudes *c.* 69° and 73°N. They are noted for the presence of native iron-bearing basalts and large volumes of high-temperature picrites and olivine basalts (Clarke & Pedersen 1976; L.M. Larsen & Pedersen 2009). The composite stratigraphic thickness of the succession varies between 4 and 10 km, with the smallest thickness on Disko and a maximum on Ubekendt Ejland/Illorsuit (71°N).

Eruption of the basalts began in a submarine environment, and the earliest basalts, which occur to the west (Fig. 41), consist of hyaloclastite breccias. When the growing volcanic pile became emergent, thin subaerial pahoehoe lava flows started to form. They flowed eastwards into a deep marine embayment where they became transformed into hyaloclastite breccias that prograded eastwards in large-scale Gilbert-type deltas with foresets up to 700 m high (Pedersen *et al.* 1993). Blocking of the outlet caused the marine embayment to be transformed into a lake, which was ultimately filled in with volcanic rocks (A.K. Pedersen *et al.* 1996; G.K. Pedersen *et al.* 1998) so that subsequent lava flows lapped onto Precambrian crystalline basement highs in the east.

The lower part of the succession (Vaigat Formation) consists almost entirely of tholeiitic picrites and olivine-phyric to aphyric magnesian basalts [7] (Pedersen 1985a). The upper part of the succession (Maligât Formation) consists of tholeiitic, plagioclase-phyric basalts [**6**] which formed thick plateau lava flows of aa-type. Both the Vaigat and Maligât Formations contain sediment-contaminated units of magnesian andesite and, in the Maligât Formation, also dacite and rhyolite, mostly as tuffs (e.g. Pedersen 1985b). Some of the sediment-contaminated rocks in both formations contain graphite and native iron, formed by reaction with coal and organic-rich mudstones. The succession is mostly flat lying, but is cut by coast-parallel faults in the western part where the lavas dip at up to 40° westwards.

On Svartenhuk Halvø the upper part of the succession is named the Svartenhuk Formation, which is the stratigraphic equivalent to the Maligât Formation (J.G. Larsen & Pulvertaft 2000). This area is characterised by extensional faulting and tilting, which together with flexure zones locally give rise to dips of up to 60° to the south-west.

The major part of the volcanic pile was erupted in a short time span 62–60 Ma ago. On western Nuussuaq and Svartenhuk Halvø there is a younger group of lavas dated at *c.* 55 Ma (recognised after the map was printed) which also occurs on Ubekendt Ejland (Storey *et al.* 1998).

Palaeogene basalts, East Greenland

Early Palaeogene volcanic rocks crop out in East Greenland between latitudes 68° and *c*. 75°N. South of Scoresby Sund/Kangertittivaq (*c*. 70°N) plateau basalts cover an extensive region of *c*. 65 000 km^2, resting on Mesozoic–Paleocene sediments in the east and south, and on Caledonian and Precambrian gneisses in the west (Nielsen *et al*. 1981; L.M. Larsen *et al*. 1989). North of Scoresby Sund Palaeogene basic sills and dykes are widespread in the Mesozoic strata, and a further sequence of plateau basalts is found between latitudes 73° and 75°N.

Blosseville Kyst region (68–70°N)

The earliest Palaeogene volcanics are 61–58 Ma old (Storey *et al*. 2007). They comprise a *c*. 1.8–2.5 km thick succession of tholeiitic basalts with subordinate picrite [**49**], which occurs in the southernmost part of the volcanic province between 68° and 68°30′N (Nielsen *et al*. 1981). The basalts are aphyric or olivine-pyroxene-phyric, and the succession consists of intercalated subaerial flows, hyaloclastites, tuffs and sediments. It is interpreted as the infill of a shallow, partly marine, basin with a source area to the south, along the present coast or on the shelf.

The main part of the region 68–70°N is made up of a thick succession of 56.1–55.0 Ma old tholeiitic plateau basalts [**48**] formed by 5–50 m thick subaerial flows of plagioclase-phyric to aphyric basalt (L.M. Larsen *et al*. 1989, 1999; Pedersen *et al*. 1997; Storey *et al*. 2007). The succession is at least 5.5 km thick in the central Blosseville Kyst area and thins inland and to the north to 2–3 km (Fig. 43). Four formations can be followed over almost the whole area and represent two major volcanic episodes. Eruptions took place over the entire area, but accumulation was largest in the coastal areas where the lava pile sagged during deposition. The subsidence accelerated with time, suggesting increased focusing of the magmas into a developing rift zone beyond the present coast.

Along the present coast the lava flows dip seawards at 10–50° due to later flexing and faulting (Nielsen & Brooks 1981; Pedersen *et al*. 1997). Intense injection of coast-parallel dykes occurred in several episodes (Nielsen 1978; L.M. Larsen *et al*. 1989).

Younger alkali basalt lavas cap the plateau basalts in some small inland areas; one of these occurrences is of Miocene age (13–14 Ma; Storey *et al*. 1996).

Hold with Hope to Shannon region (73–75°N)

A succession of *c*. 600–800 m of plateau basalts [**32**] occurs in the Hold with Hope to Shannon region in a block-faulted area. The succession is divided into a lower part of uniform tholeiitic lavas and an upper part with variable tholeiitic and alkali basaltic lavas (Upton *et al*. 1984, 1995; Watt 1994). Between the two there are local occurrences of intervolcanic conglomerates. The basalts on Shannon and the Pendulum Øer, north-east of Wol-

Fig. 43. Major unconformity between Precambrian gneisses deformed during the Caledonian orogeny [**52**] and Palaeogene plateau basalts [**32**]. The basalt section shown is approximately 800 m thick. North of Gåsefjord/Nertiit Kangersivat (*c*. 70°N), Scoresby Sund region, central East Greenland. Photo: W.S. Watt.

laston Forland, mainly occur as voluminous sills. The reduced magnitude of volcanic activity in this northerly area, compared to the region south of Scoresby Sund, suggests that it was peripheral to the main volcanic activity in the East Greenland Tertiary volcanic province.

Small areas of basalts with alkaline chemistry occur in the nunatak region (74°N) where they overlie Caledonian and older crystalline rocks (Katz 1952; Brooks *et al.* 1979; Bernstein *et al.* 2000).

Palaeogene intrusions, East Greenland

Numerous intrusions are exposed along about 1000 km of the coastal region of East Greenland between latitudes 66°30′ and 74°N, in addition to the many dykes and sills (see Fig. 20); approximately 20 of these intrusions are shown on the map, separated into felsic [53] and intermediate and mafic [57] types (Fig. 44). They reflect episodes of alkaline magmatism linked to the continental break up of the North Atlantic (Nielsen 1987), and range in age from late Paleocene to Oligocene. The oldest intrusions occur in the south, and have ages between 57 and 47 Ma. Felsic intrusions in the south are 35–37 Ma old, whereas the more northerly intrusions (72–74°N) have ages in the range 48–25 Ma (Tegner *et al.* 1998, 2008; Brooks *et al.* 2004).

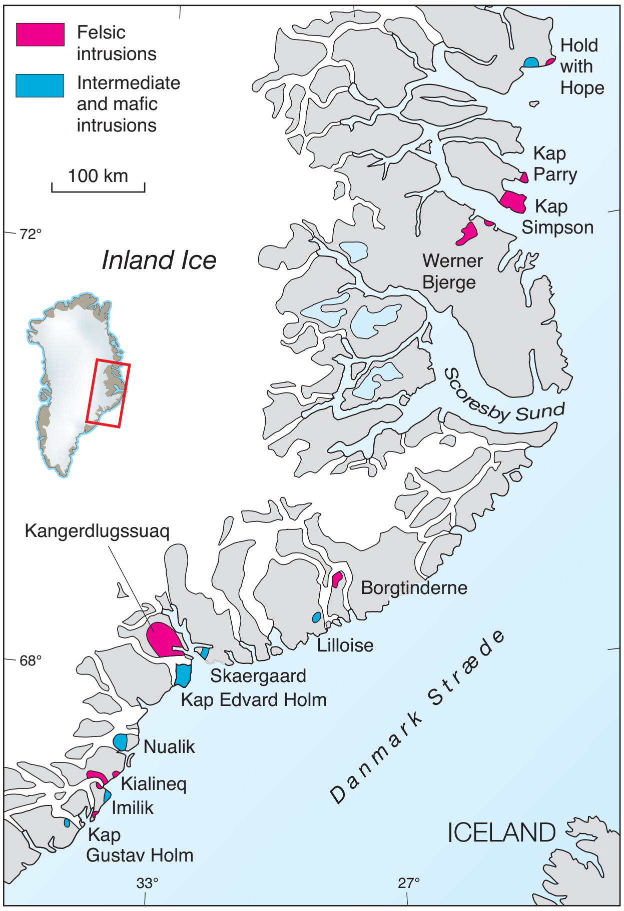


Fig. 44. Major Tertiary intrusive centres in East Greenland (*c.* 66°30′–74°N). Slightly modified from Nielsen (1987).

Petrologically the intrusions can be divided into three groups (Nielsen 1987): (A) alkaline inland intrusions; (B) alkaline dyke swarms and (C) syenitic to granitic complexes and dykes. Most of the numerous intrusions found along the coast belong to the third group; they are central intrusions and intrusive complexes, often with several rock types within the same complex. They range from a few square kilometres to *c.* 850 km^2 in size. The felsic complexes [53] are dominated by alkali granites, quartz syenites, syenites and nepheline syenites. The mafic to intermediate complexes [57] are dominated by tholeiitic gabbros, whereas subordinate rock types locally include monzonite and alkali gabbro. The 55 Ma old Skaergaard intrusion is a classic example of a layered gabbroic intrusion, and has been studied in great detail (Wager & Deer 1939; McBirney 1996a, b; Irvine *et al.* 1998).

Post-basaltic Palaeogene sedimentary rocks, East Greenland

Post-basaltic sedimentary rocks [47] are preserved in two small, down-faulted areas near the Atlantic coast south of Scoresby Sund (Kap Brewster, *c.* 70°10′N and Kap Dalton, *c.* 69°25′N). They comprise a *c.* 100 m thick succession of Palaeogene (Middle Eocene, 48–45 Ma old) fluvial to shallow marine sandstones and siltstones (M. Larsen *et al.* 2005) referred to as the Kap Dalton Group. These post-volcanic deposits have been dated by dinoflagelate cysts and suggest that volcanism in this region came to an end close to the Early-Middle Eocene boundary between 49 and 48 Ma.

The Palaeogene sedimentary rocks preserved onshore are marginal exposures of an extensive and much thicker (5–6 km) Tertiary succession found on the adjacent shelf areas (see p. 75).

Pliocene–Pleistocene sediments, central North Greenland

The late Pliocene – early Pleistocene Kap København Formation [13] is a *c.* 100 m thick succession of unconsolidated sand and silt, which crops out over an area of *c.* 500 km^2 in easternmost Peary Land, North Greenland

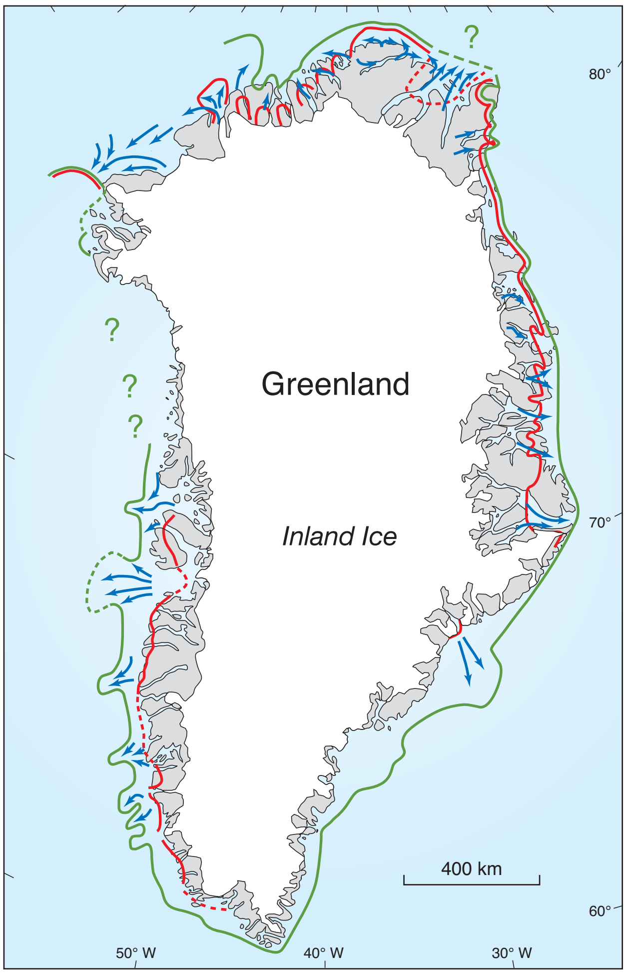


Fig. 45. Former extent of the Greenland Inland Ice during the last glacial maximum. **Green**: *c.* 18 000 years before present; **red**: *c.* 10 000 years ago; **blue arrows**: major glacier outlet streams. Modified from Funder & Hansen (1996).

(Funder & Hjort 1980; Funder 1989). The succession contains well-preserved faunal and floral elements. The base of the succession is not exposed. The lower 25 m comprise marine silt containing high Arctic molluscs, whereas the upper sand-dominated part containing tree trunks reflects nearshore environments. The flora and fauna found in this upper unit point to a much warmer climate than the present. The Kap København Formation shows disturbance caused by overriding glaciers during the Quaternary glaciation, and is overlain by till.

Quaternary glacial sediments and glaciation

During most of the Quaternary Greenland was completely, or almost completely, covered by ice, and glacial deposits are widespread on the present ice-free land areas and on the adjacent shelf (Funder 1989; Funder *et al.* 1998). As the map is a bedrock geology map, Quaternary deposits are only shown in regions where a thick cover of Quaternary superficial deposits conceals the bedrock over large areas (valleys, interior plains and some coastal areas). These areas have been shown on the map as undifferentiated Quaternary.

Recent studies indicate that the glaciation of North-East Greenland had started as early as the mid-Miocene (14–15 Ma ago; Thiede *et al.* 2001). Evidence from the shelf areas shows that an early glaciation of Greenland at the end of the Pliocene (*c.* 2.4 million years ago) was more extensive than any succeeding glaciation, with an ice sheet covering nearly the entire shelf region up to a few hundred kilometres beyond the present coastline (Funder 1989). During this glaciation the land area was subjected to extensive erosion, with much of the eroded material being deposited on the offshore shelves.

The superficial deposits found on the ice-free land areas are dominated by the late Quaternary development of the past *c.* 130 000 years (Saalian/Illinoian–Holocene). The last interglacial period (Eemian/Sangamonian) is recorded in both East and West Greenland. During the late Weichselian/Wisconsinan *c.* 18 000 years ago the maximum extent of the ice around the northern parts of Greenland was close to the present coastline, whereas in parts of West and South-East Greenland the ice advanced onto the shelf area (Funder & Hansen 1996; Fig. 45). In South Greenland, modelling of the thickness of the ice cover over the outer coast during the Last Glacial Maximum shows that the ice must have been at least 1500 m thick (Bennike *et al.* 2002). Recent studies indicate that the Greenland ice sheet during the late Weichselian/Wisconsinan reached out to the middle–outer continental shelf in North-East Greenland, a distance of more than 100–200 km beyond the present coastline (Evans *et al.* 2009).

The retreat of the Inland Ice after the last glacial period began 14 000–10 000 years ago, and continued with oscillations to a maximum stage of withdrawal approximately 6000 years ago when the ice margin was up to 20 km inside its present position. The position of the margin of the Inland Ice where it now abuts against land areas only shows minor fluctuations (Fig. 46). Significant changes are almost restricted to major drainage outlets where the Inland Ice flows into fjords to form calving glaciers; the most active glaciers in Greenland have velocities of up to 22 m per 24 hours.

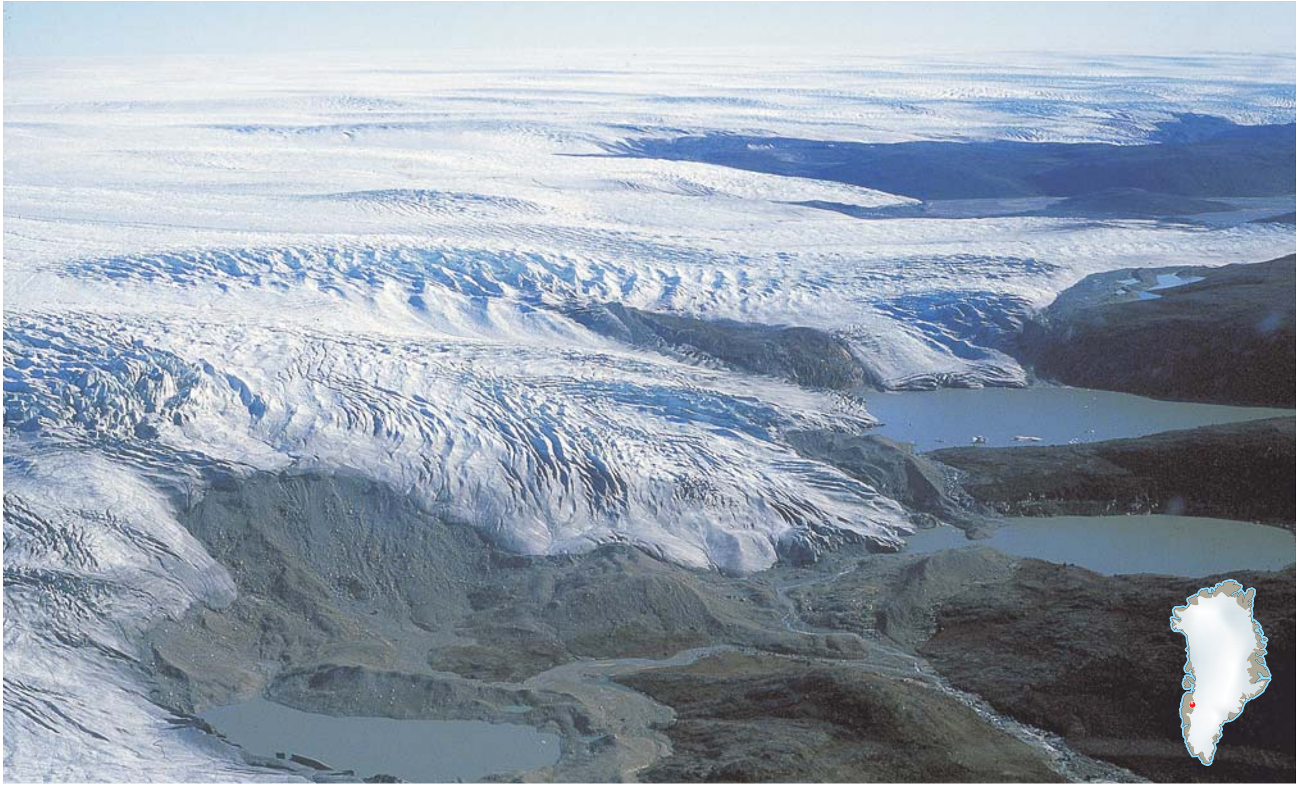


Fig. 46. Characteristic front of the Inland Ice abutting the ice-free land area, with moraines and small lakes. The distance from the bottom of the picture to the land area in the background is approximately 5 km. The locality is about 75 km north-north-east of Søndre Strømfjord airport, southern West Greenland, at *c.* 67°30´N. View is towards south. Photo: H. Højmark Thomsen.

Glaciology

The present ice cover of Greenland is a relic of the Pleistocene ice ages. It consists of the large continental ice sheet (the Inland Ice), and local ice caps and glaciers (Weidick 1995).

The Inland Ice has an area of *c.* 1 707 000 km^2 and reaches an altitude of 3230 m with a maximum thickness of 3420 m. The local ice caps and glaciers cover areas of *c.* 49 000 km^2 (Weng 1995). The volume of the Inland Ice has been estimated at 2 600 000 km^3, based on ice thickness measurements by airborne radio-echo sounding; a rough estimate of the volume of local ice caps and glaciers is 20 000 km^3. On the map, surface contours, isopachs of ice thickness and contours of the bedrock below the Inland Ice are shown.

Mean annual air temperatures on the Inland Ice range from –30°C over a large region in its central and northern parts to about –5°C in its south-western marginal areas. The temperature of the ice ranges between –32° and 0°C; with increasing depth, the temperature generally increases due to geothermal heat flux and internal heating caused by deformation. In some locations, the temperature at the base of the ice sheet may reach its melting point.

Mass balance

The mass balance (budget) of the Inland Ice is the difference between accumulation (of snow in the interior region mainly) and ablation by melting and calving of icebergs in the marginal areas.

The accumulation of snow decreases from south to north from more than 2000 mm water equivalent/year in coastal areas in the south-west to 100 mm water equiv-