Fig. 15. Late Archaean gneisses with dark amphibolite bands, affected by early and middle Proterozoic orogenic events, and subsequently reworked in the Caledonian orogeny. South of inner Nordvestfjord/ Kangersik Kiatteq, Scoresby Sund region (71°30′N), central East Greenland. The profile height is *c.* 1000 m.

et al. 1994). Archaean orthogneisses [74] have been documented at only one locality (76°40′N) in North-East Greenland (Steiger *et al.* 1976) but their relationships with the surrounding Proterozoic gneisses are uncertain.

Archaean – early Proterozoic basement beneath the Inland Ice

Little is known about the geology of the area now covered by Greenland's central ice cap – the Inland Ice. However, in 1993 one and a half metres of bedrock was retrieved from beneath the highest part of the ice cap (> 3000 m) at the GISP 2 ice core locality (72°35′N, 38°27′W). The rock is a leucogranite, and SHRIMP U-Pb zircon data on a few poorly preserved zircons indicate that it is of Archaean origin, but strongly disturbed by one or more later tectonometamorphic events, most likely during the early Proterozoic (A.P. Nutman, personal communication 1995). These results have been confirmed by Sm-Nd, Rb-Sr and Pb-Pb isotope data (Weis *et al.* 1997).

Proterozoic to Phanerozoic geological development after formation of the Precambrian shield

The Greenland Precambrian shield is composed mainly of crystalline gneisses and plutonic rocks older than 1600 Ma. Younger rock units, middle Proterozoic 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.

Early–middle Proterozoic 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] (Fig. 16a) which is found 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. Strongly

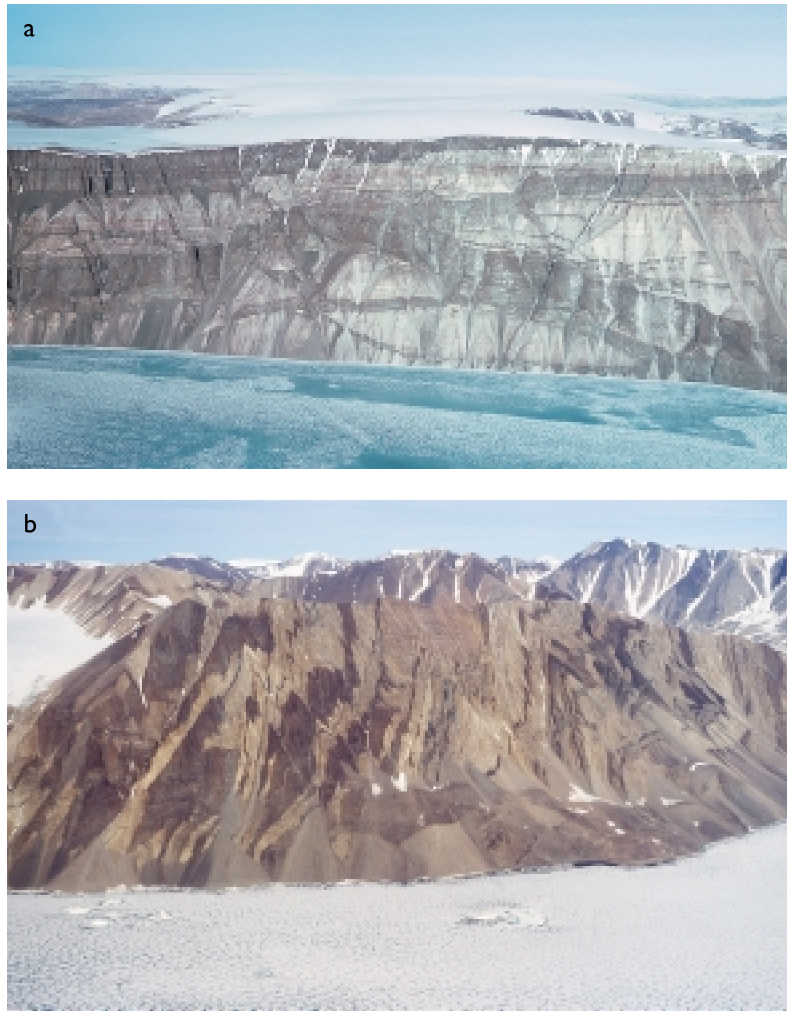


Fig. 16. Lower to middle Proterozoic Independence Fjord Group sandstones. **a**: Undeformed succession cut by *c.* 1230 Ma Midsommersø Dolerite intrusions on the south side of Independence Fjord (*c.* 82°N), eastern North Greenland. Profile height is *c.* 800 m. **b**: Folded and metamorphosed sandstones and dolerites 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.

deformed representatives are found within the Caledonian fold belt in Kronprins Christian Land and areas to the south (Fig. 16b). Radiometric dating by Larsen & Graff-Petersen (1980) indicated a middle Proterozoic age (about 1380 Ma) for the diagenesis, but more recent SHRIMP U-Pb dates from intercalated volcanics in similar sandstones occurring within the Caledonian fold belt suggest that some of the sandstones were deposited before 1740 Ma ago (Kalsbeek *et al.* 1999). The new data post-date compilation of the map, where a middle Proterozoic age is indicated for the Independence Fjord Group.

The succession has been studied primarily in the type area around Independence Fjord in North Greenland, where deposition took place in an intracratonic sag basin. The Independence Fjord Group 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 (Collinson 1980; Sønderholm & Jepsen 1991). The rhythmic sedimentary pattern forms the basis for the present lithostratigraphy. The development of extensive lacustrine conditions suggests that sedimentation was controlled by basin-wide changes in subsidence rates (Collinson 1983).

The Independence Fjord Group sandstones are everywhere cut by numerous mafic sheets, sills and dykes, the 'Midsommersø Dolerites' (Kalsbeek & Jepsen 1983), for which ages around 1250 Ma have been obtained. The dolerites are not shown on the map, but are depicted with other important dyke swarms on Fig. 18.

Zig-Zag Dal Basalt Formation, North Greenland

This middle Proterozoic formation [30] consisting of up to 1350 m of well-preserved tholeiitic flood basalts is among the oldest well-preserved basalt successions known; the main outcrops are south of Independence Fjord in eastern North Greenland. A petrological and geochemical investigation of the basalts has been carried out by Kalsbeek & Jepsen (1984). The Zig-Zag Dal Basalt Formation conformably overlies the Independence Fjord Group and is itself disconformably overlain by the Hagen Fjord Group (see Fig. 22). South of Independence Fjord the basalt succession outcrops over an area of 10 000 km^2, but the local occurrence of similar basalts in eastern Peary Land indicates that the formation once covered a very large part of North Greenland. The basalts are probably related to the same igneous event that produced the Midsommersø Dolerites, and an age of *c.* 1250 Ma is therefore likely.

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 highest 'Porphyritic Unit' (up to 750 m) together comprise 30 flows of mainly aa-type subaerial lavas. The present distribution pattern of the flows shows a maximum thickness of the succession in the centre of the area of outcrop 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.

In Kronprins Christian Land basalts belonging to the Zig-Zag Dal Basalt Formation have not been recognised with certainty. However, deformed dolerites, which probably correlate with the Midsommersø Dolerites, are very common. North-west of Hovgaard Ø (*c.* 80°15′N) within the same region, basalts are present interbedded with the Independence Fjord Group; an age of 1740 Ma has been obtained on zircons from associated rhyolitic rocks (Kalsbeek *et al.* 1999).

Gardar Province, South Greenland

The middle Proterozoic Gardar Province (Upton & Emeleus 1987; Kalsbeek *et al.* 1990) 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. 18).

The Gardar sediments [12] and volcanics [11] of the Eriksfjord Formation rest uncomformably on Ketilidian granites. The Eriksfjord Formation comprises *c.* 1800 m sediments and 1600 m volcanic rocks. The sediments, 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).

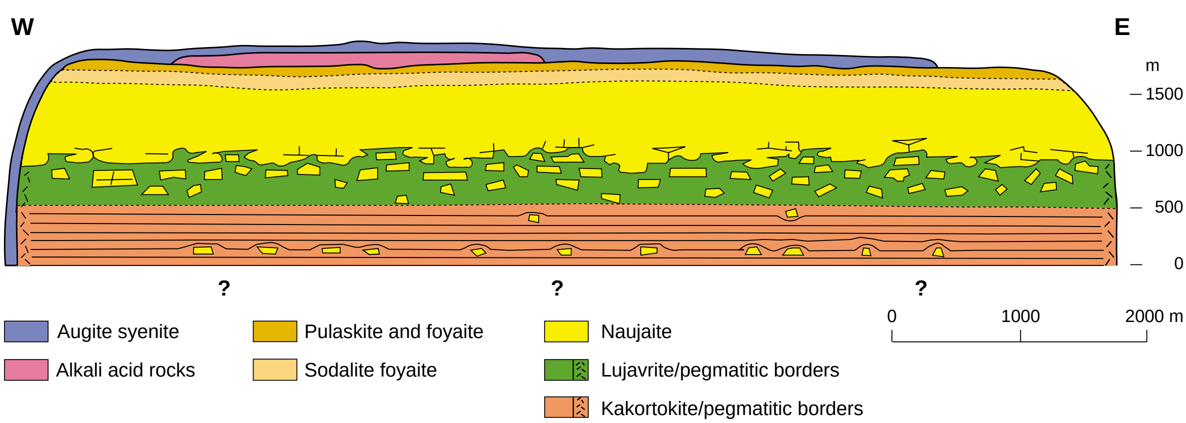


Fig. 17. Diagrammatic cross-section of the Ilímaussaq intrusion west of Narsaq in South Greenland. The intrusion has an outcrop area of 17 × 8 km and has been dated at 1143 ± 21 Ma (see review by Kalsbeek *et al.* 1990). Slightly modified from Andersen *et al.* (1981).

The Gardar intrusive complexes [56] range in age from *c*. 1300 to *c*. 1120 Ma and have been divided into three age groups (Kalsbeek *et al*. 1990). These 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. 17); 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 both 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. 18).

Middle Proterozoic orogenic units reworked in the East Greenland Caledonian fold belt

A middle Proterozoic 'Grenvillian' event has been recorded in the crystalline rocks of the Caledonian fold belt between Scoresby Sund (70°N) and Grandjean Fjord (76°N). A thick sequence of middle Proterozoic metasediments, the Krummedal supracrustal sequence [46], rests on early Proterozoic and Archaean basement gneisses. During a tectonometamorphic event around 950 Ma ago the supracrustal rocks and the underlying basement rocks were apparently reworked to form a migmatite and paragneiss complex [52] containing granite and augen granite intrusions [55]. Zircon and Rb-Sr whole-rock studies indicated some of the granites are *c*. 1000 Ma old (Steiger *et al*. 1979; Rex & Gledhill 1981), and SHRIMP studies on zircons from a major granite body (74°19′N) yielding an age of *c*. 930 Ma have recently confirmed the Grenvillian age (Jepsen & Kalsbeek 1998).

Supracrustal rocks

The Krummedal supracrustal sequence [46] consists of a 2500–8000 m thick suite of pelitic, semipelitic, and quartzitic rocks generally metamorphosed within the amphibolite facies (Henriksen & Higgins 1969; Higgins 1974, 1988; Figs 19, 20). Lateral and vertical lithological variations are considerable and correlation between various local successions has not been possible. Contacts with the underlying late Archaean [74] and early Proterozoic gneisses [70] are generally conformable, but rare discordances may reflect preservation of an original unconformity (Higgins *et al*. 1981). The 'Smallefjord sequence' [46], which 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 later than *c*. 1100 Ma and high-grade metamorphism during a Grenvillian event at *c*. 950 Ma (Strachan *et al*. 1995; Kalsbeek *et al*. 1998b).

Migmatites and granites

The middle Proterozoic supracrustal units in the southern part of the East Greenland Caledonian fold belt have been strongly migmatised and transformed into paragneisses [52], and intruded by sheets of augen granites up to 1000 m thick as well as other granite bodies [55]. In the Scoresby Sund region these rock units have

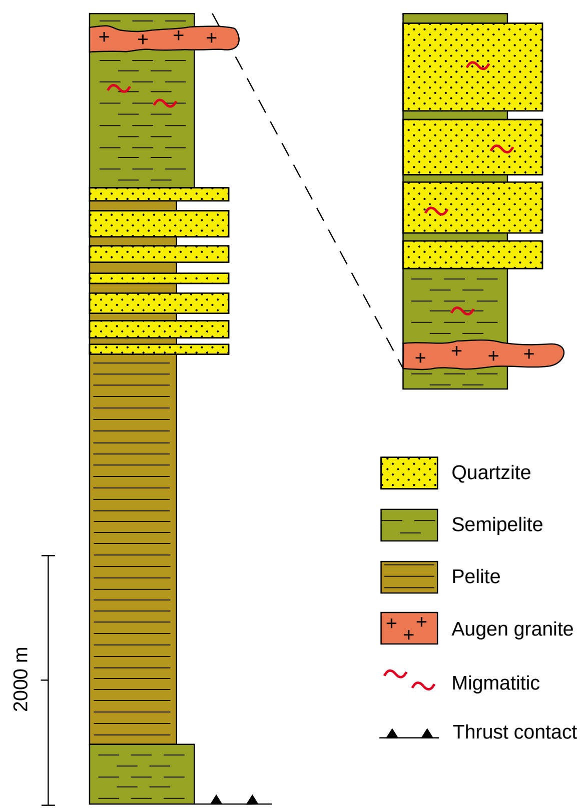


Fig. 19. Sections of the middle Proterozoic Krummedal supracrustal sequence, north of inner Nordvestfjord/Kangersik Kiatteq (71°30′N), Scoresby Sund region, central East Greenland. Based on Higgins (1974).

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 early Archaean Amîtsoq gneisses, Godthåbsfjord region, southern West Greenland. 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 early Archaean in the Godthåbsfjord area to Tertiary 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 isotopic 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 earlier believed to belong to a single swarm may have significantly different ages. The diagrams on the opposite page illustrate the history of dyke emplacent 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 early Archaean gneisses, but are cut by late Archaean granitoid rocks; this permits distinction between early and late Archaean 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.

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

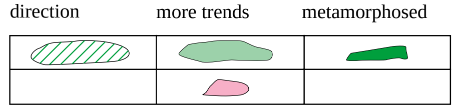


Fig. 18. **Above** and **facing**. Diagrammatic representation of the major suites of mafic dykes and sills in Greenland. Compiled by J.C. Escher and F. Kalsbeek 1997.

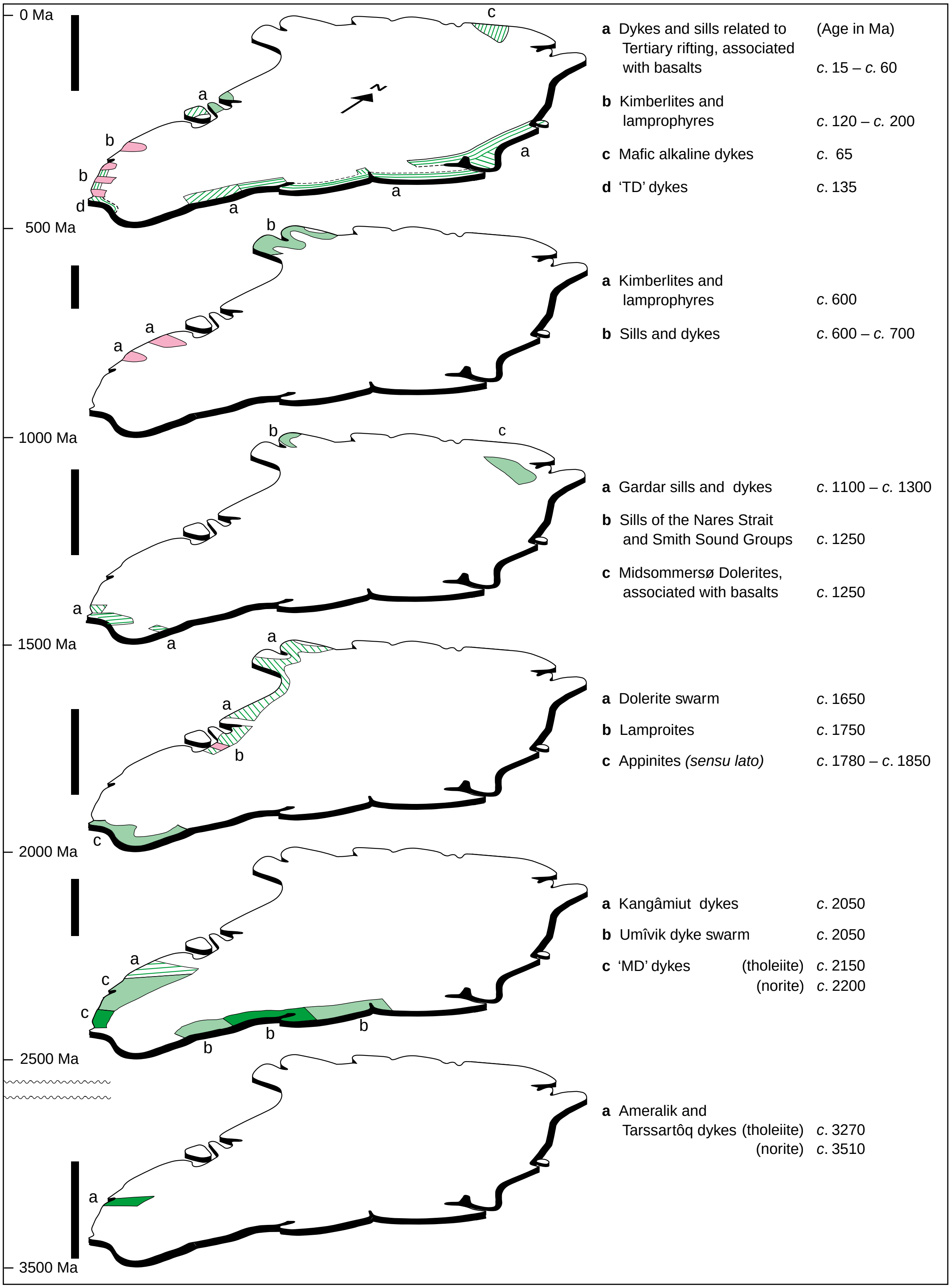

0 Ma
500 Ma
1000 Ma
1500 Ma
2000 Ma
2500 Ma
3500 Ma
N
a Dykes and sills related to Tertiary rifting, associated with basalts | (Age in Ma) c. 15 – c. 60
b Kimberlites and lamprophyres | c. 120 – c. 200
c Mafic alkaline dykes | c. 65
d 'TD' dykes | c. 135
a Kimberlites and lamprophyres | c. 600
b Sills and dykes | c. 600 – c. 700
a Gardar sills and dykes | c. 1100 – c. 1300
b Sills of the Nares Strait and Smith Sound Groups | c. 1250
c Midsommersø Dolerites, associated with basalts | c. 1250
a Dolerite swarm | c. 1650
b Lamproites | c. 1750
c Appinites (sensu lato) | c. 1780 – c. 1850
a Kangâmiut dykes | c. 2050
b Umîvik dyke swarm | c. 2050
c 'MD' dykes (tholeiite) c. 2150 (norite) c. 2200
a Ameralik and Tarssartôq dykes (tholeiite) c. 3270 (norite) c. 3510

Fig. 20. Krummedal supracrustal sequence comprising rusty garnetiferous gneissic schists and siliceous gneisses, inner Nordvestfjord/Kangersik Kiatteq (71°30′N), Scoresby Sund region, central East Greenland. Profile height is *c*. 1500 m.

been deformed into major recumbent folds of nappe dimensions (Chadwick 1975) during a Grenvillian or younger orogeny; isotopic age determinations show that the later deformed augen granites and correlative granites were injected around 1000 Ma ago (Steiger *et al*. 1979; Rex & Gledhill 1981).

Middle–late Proterozoic sedimentary basin in North-West Greenland and Ellesmere Island

Thule Supergroup

The Thule Basin in North-West Greenland is one of several middle–late Proterozoic depocentres fringing the northern margin of the Canadian–Greenland shield. The basin fill consists of undeformed sediments and basaltic rocks assigned to the Thule Supergroup (Dawes *et al*. 1982; Dawes 1997). The rocks are widely exposed in the region between Inglefield Land (79°N) and Thule Air Base/Pituffik (76°N) in Greenland and also crop out in the coastal regions of Ellesmere Island in Canada. The lower part of the basin fill shows many similarities with the Independence Fjord Group and overlying volcanic rocks in eastern North Greenland [31–30]. The Thule Supergroup has a cumulative thickness of at least 6 km and comprises continental to shallow marine sediments, basaltic volcanic rocks and a conspicuous number of doleritic sills; it accumulated between *c*. 1270 Ma and *c*. 650 Ma ago (for discussion, see Dawes 1997; Samuelsson *et al*. 1999). The sediments rest with profound unconformity on peneplaned Archaean – early Proterozoic crystalline basement throughout the region.

The Thule Supergroup is divided into a lower part comprising three groups [5] and an upper part of two groups [3, 4]. 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 late Middle Proterozoic to earliest Late Proterozoic age for the entire succession (Samuelsson *et al*. 1999). The lower part comprises: (1) the Smith Sound Group of shallow marine sandstones and shales with stromatolitic carbonates; (2) the Nares Strait Group which at the base consists of inner shelf mudstones and fluvial sandstones, succeeded by terrestrial basaltic extrusive rocks and volcaniclastic sediments overlain by shallow marine sandstones; (3) the Baffin Bay Group of multicoloured sandstones and conglomerates, 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 and siltstones with some carbonate-rich units in the upper part, and (5) the Narssârssuk Group [3], representing deposition in a low energy environment, with a cyclic carbonate-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 graben on the south-eastern margin of the Thule Basin (Fig. 21).

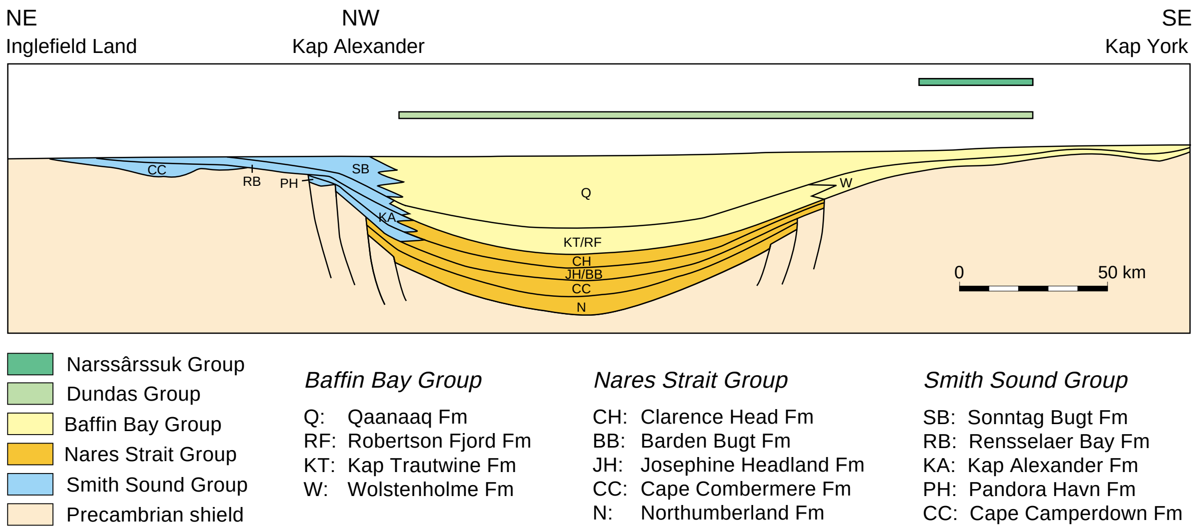


Fig. 21. A cross-section through the Thule Basin, North-West Greenland, with the lower Thule Supergroup as basin fill, showing the relationships of groups and their formations. The spatial relationship of the Dundas and Narssârssuk Groups superimposed on this middle Proterozoic evolutionary stage is shown by the **green bars**. Vertical exaggeration × 25. Slightly modified from Dawes (1997).

Late Proterozoic sedimentary basins in North, North-East and East Greenland

Hagen Fjord Group, North Greenland

Deposits in a late Proterozoic basin 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, overlie sandstones of the lower Proterozoic Independence Fjord Group and basalts of the middle Proterozoic Zig-Zag Dal Basalt Formation (1250 Ma old; Sønderholm & Jepsen 1991; Clemmensen & Jepsen 1992). The easternmost occurrences of the succession are found in Caledonian thrust sheets with substantial westward displacement in Kronprins Christian Land, indicating that the basin originally had a wider eastwards extent (Figs 22, 23).

The Hagen Fjord Group [27] is an up to 1000 m thick succession of siliciclastic and carbonate sediments

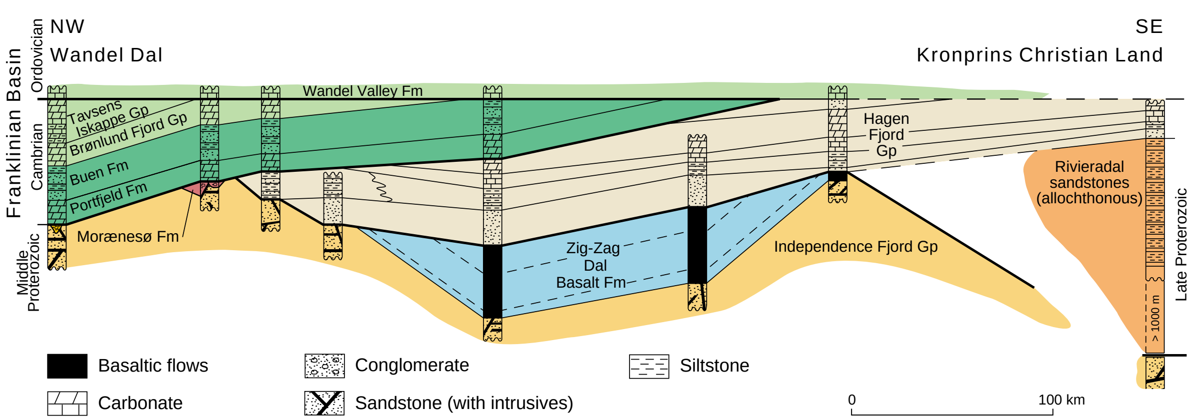


Fig. 22. Schematic cross-section of the Proterozoic–Ordovician succession in eastern North Greenland between Wandel Dal (*c.* 82°N) and Kronprins Christian Land (*c.* 80°N). It shows the relationships between the middle Proterozoic Zig-Zag Dal Basalt Formation, the late Proterozoic Hagen Fjord Group 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).

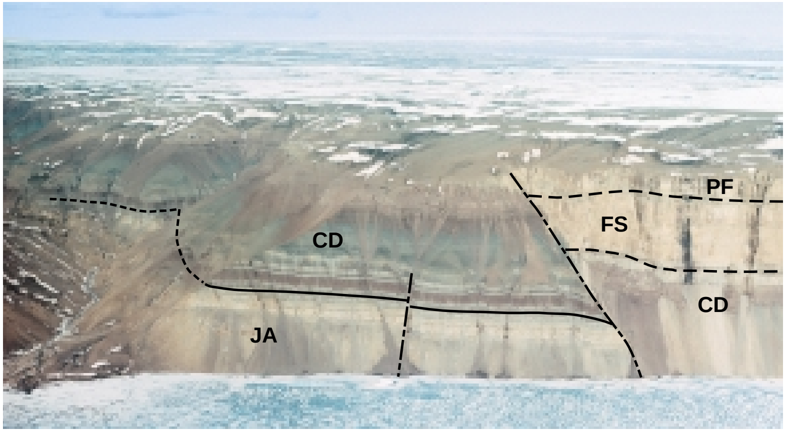


Fig. 23. Hagen Fjord Group on the north-west side of Hagen Fjord, eastern North Greenland. A lower light coloured sandstone (Jyske Ås Formation, **JA**, 400 m) is overlain by a multicoloured sandstone-siltstone association (Campanuladal and Kap Bernhard Formations, **CD**, 450 m), with a light coloured 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.

deposited on a shallow water shelf. In the lower part it comprises mainly sandstones which are overlain by a sandstone-siltstone association. The upper part is characterised by limestones and dolomites with abundant stromatolites, and these are capped by a sandstone unit. The age of the group is not well constrained, but indirect and direct microfossil evidence points to a Sturtian to Vendian age. A thin succession of correlative sediments occurs in Dronning Louise Land at *c.* 77°N (Strachan *et al.* 1992).

The Rivieradal sandstones [29] are confined to allochthonous Caledonian thrust sheets in the Kronprins Christian Land area, and are in part equivalent to the Hagen Fjord Group (Clemmensen & Jepsen 1992). This succession is 7500–10 000 m thick and comprises conglomerates, sandstones, turbiditic sandstones and mudstones. It probably accumulated in a major half-graben basin, the bounding western fault being reactivated as a thrust during the Caledonian orogeny.

A succession of diamictites and sandstones up to 200 m thick, believed to be late Precambrian (Varangian) 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 in age (Collinson *et al.* 1989; Sønderholm & Jepsen 1991).

Eleonore Bay Supergroup, East and North-East Greenland

The Eleonore Bay Supergroup comprises an up to 16 km succession of shallow water sediments which accumulated in a major sedimentary basin extending between latitudes 71°40′ and 76°00′N in East and North-East Greenland (Sønderholm & Tirsgaard 1993). Exposures occur only within the present Caledonian fold belt, and in general the sediments are moderately deformed and weakly to moderately metamorphosed. The contact with the underlying basement is structural, variously described as an extensional detachment (Hartz & Andresen 1995; Andresen *et al.* 1998) or dominated by thrusting (Soper & Higgins 1993; Higgins & Soper 1994). Sedimentation is constrained to the interval between *c.* 950 Ma and 610 Ma by Grenvillian ages on underlying basement rocks and the Varangian age of the overlying Tillite Group. Acritarchs from the three youngest groups of the Eleonore Bay Supergroup indicate a Sturtian age (Vidal 1976, 1979).

The lower part of the Eleonore Bay Supergroup (Fig. 24) 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 (Caby & Bertrand-Sarfati 1988; Smith & Robertson 1999). 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. 25) reflect deposition in marine shelf environments (Tirsgaard & Sønderholm 1997). 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). The latest stage of basin fill is represented mainly 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 with a sheltered inner lagoon behind an inner shallow barrier shoal (Frederiksen & Craig 1998).

Tillite Group, East Greenland

The Tillite Group [42] consists of a 700–800 m thick succession of Vendian age (610–570 Ma) and includes two glacigene diamictite formations (Hambrey & Spencer 1987). It crops out in East Greenland between latitudes 71°40′ and 74°N where it overlies the Eleonore Bay Supergroup, 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.

Isolated occurrences of diamictites comparable with units in the Tillite Group overlie crystalline basement complexes in the Scoresby Sund region (Henriksen 1986; Moncrieff 1989), and are shown on the map by a special symbol [41].

Sediments 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 is uncertain, 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°N), overlying Archaean crystalline basement rocks. A thin sequence of weakly metamorphosed marbles and chloritic schists, often highly sheared adjacent to the thrust, overlies tillitic rocks [28] preserved in erosional depressions in the gneiss surface (Phillips & Friderichsen 1981). If the tillites can be correlated with the Varangian tillites of the fjord zone as suggested by Moncrieff (1989), then the overlying marbles and schists are probably of early Palaeozoic age.

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

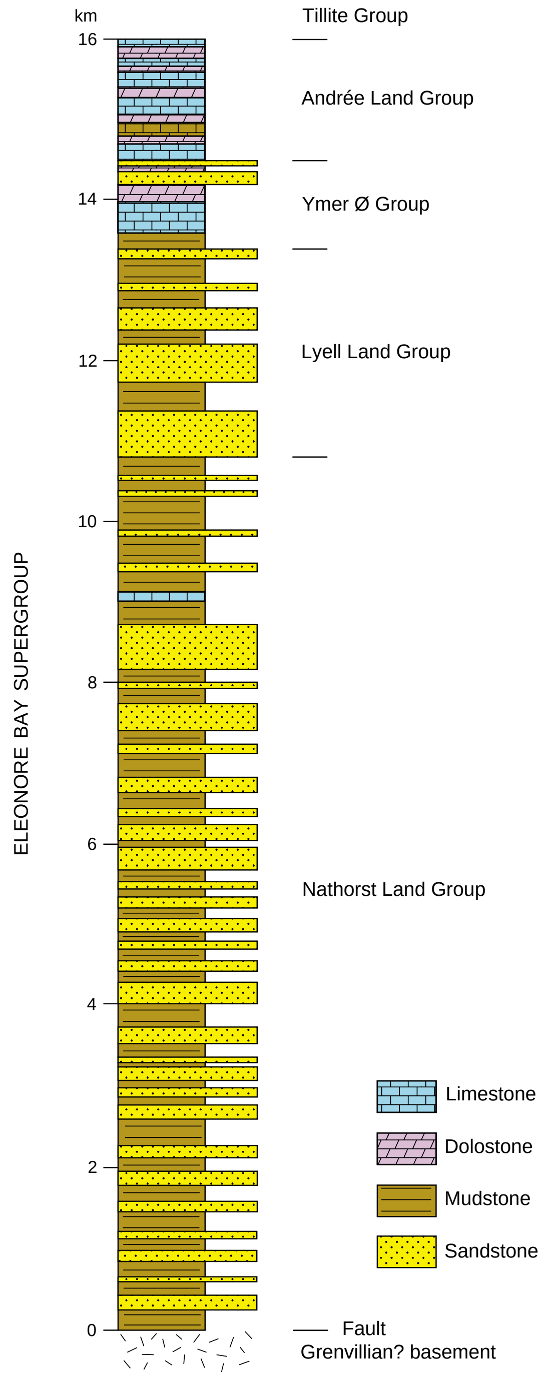


Fig. 24. Schematic composite section of the late Proterozoic Eleonore Bay Supergroup, central fjord zone (72°–74°N), North-East Greenland. Units on the map: Nathorst Land Group [44]; Lyell Land, Ymer Ø and Andrée Land Groups [43]; Tillite Group [42]. Based on Sønderholm & Tirsgaard (1993).

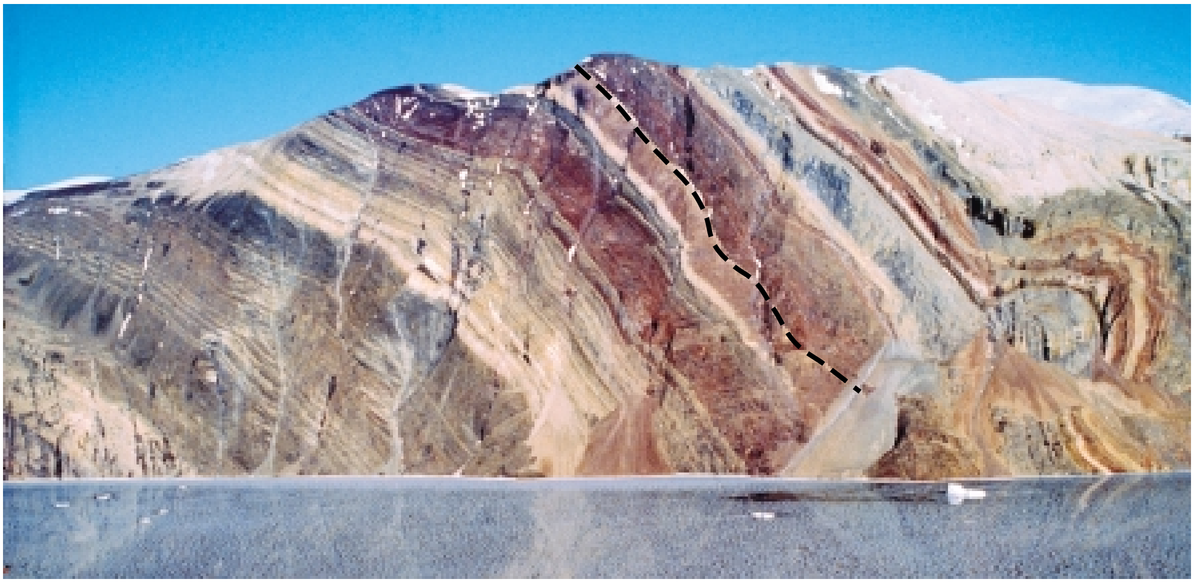


Fig. 25. Part of the upper Eleonore Bay Supergroup, west side of Ymer Ø (*c*. 73°N), North-East Greenland. Succession is approximately 2 km in thickness and includes from left to right: Lyell Land Group (apart from the two lowest formations) and to the right of the black dashed line Ymer Ø Group (the lowest five of seven formations). Photo: M. Sønderholm.

Caledonian thrust units of metasediments and gneisses. The Eleonore Sø series comprises low-grade metamorphic sandstones, shales and carbonates associated with volcanic rocks (tuffs and pillow lavas). These are overlain unconformably by a thick quartzite unit which preserves abundant *Skolithos*, and is therefore latest Precambrian to earliest Cambrian in age; the underlying series must thus be older. Recent SHRIMP studies on zircons from a quartz porphyry intruding the Eleonore Sø series indicate an emplacement age of *c*. 1900 Ma (F. Kalsbeek, personal communication 1998).

Carbonatite complexes in Archaean gneisses of West Greenland

Two carbonatite complexes occur in the Precambrian gneisses of West Greenland. The oldest is the c. 600 Ma old Sarfartôq carbonatite complex [61] found south of Søndre Strømfjord at 66°30′N (Secher & Larsen 1980; Larsen & Rex 1992). It is an intrusive conical body with a core of carbonatite sheets and a marginal zone of hematised gneiss with carbonatite dykes. The intrusion is surrounded by a 20 km radius coeval kimberlite cone sheet swarm (see Fig. 18). The younger complex is the 173 Ma old (middle Jurassic) Qaqarssuk carbonatite complex [59], found east of Maniitsoq/Sukkertoppen at 65°23′N, which has a steep ring-dyke structure (Knudsen 1991).

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 or earliest Cambrian and continued until at least 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).

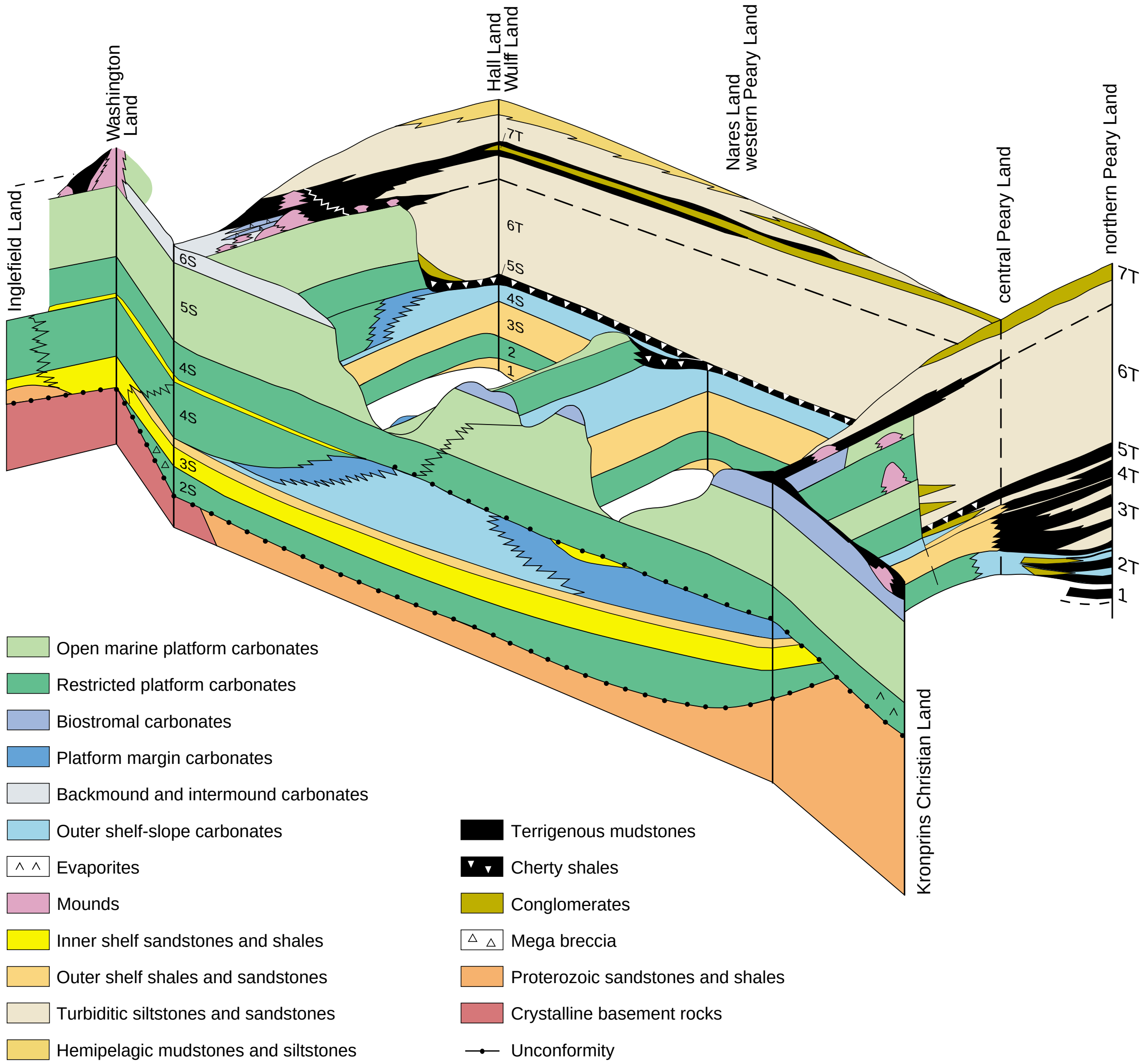


Fig. 26. Block diagram illustrating relationships between shelf, slope and trough sequences in the Lower Palaeozoic Franklinian Basin of North Greenland. The schematic fence diagram covers a region of *c*. 700 km east–west and *c*. 200 km north–south. Shelf stages (**S**) and trough stages (**T**) are divided into time intervals. **1**: late Proterozoic? – 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).

Throughout the Early Palaeozoic, the basin in Greenland was divided into a southern shelf and slope area and a northern 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. 26). 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 terminology is employed (Trettin 1991, 1998).

Cambrian–Silurian in North Greenland

The oldest shelf deposits of Early Cambrian age 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).

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).

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 carbonates (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, whereafter 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. 27) 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 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. 28; 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). 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 down-flexing 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. They 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, whereas current directions in Ellesmere Island demonstrate an

Fig. 27. 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.

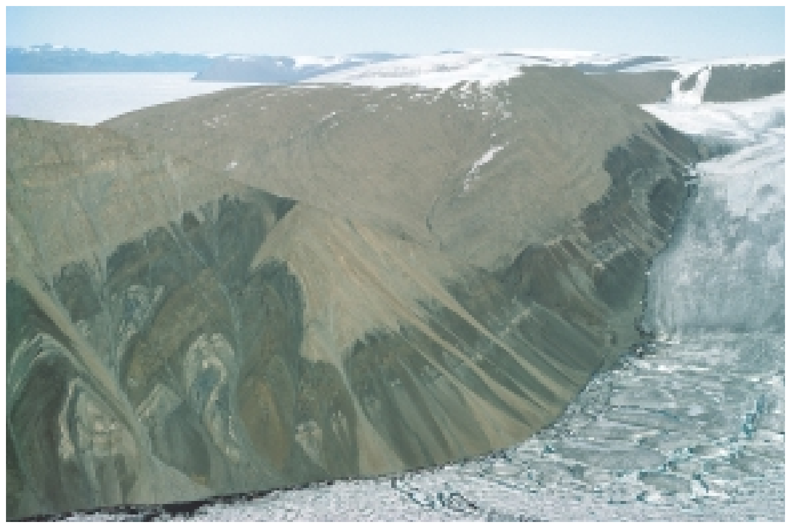


Fig. 28. Middle Ordovician – Lower Silurian sediments in the deep-water sequence of the Franklinian Basin (Amundsen Land Group dark unit; Merqujôq Formation light coloured unit). The sediments were folded into south-facing tight folds during the Ellesmerian orogeny. North-east cape of Victoria Fjord, central North Greenland, view towards the east. Profile height is *c.* 400 m.

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 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). On the geological map it is represented by two divisions: middle Proterozoic crystalline rocks [52] and a late Proterozoic to Late Silurian complex of undifferentiated metasedimentary and

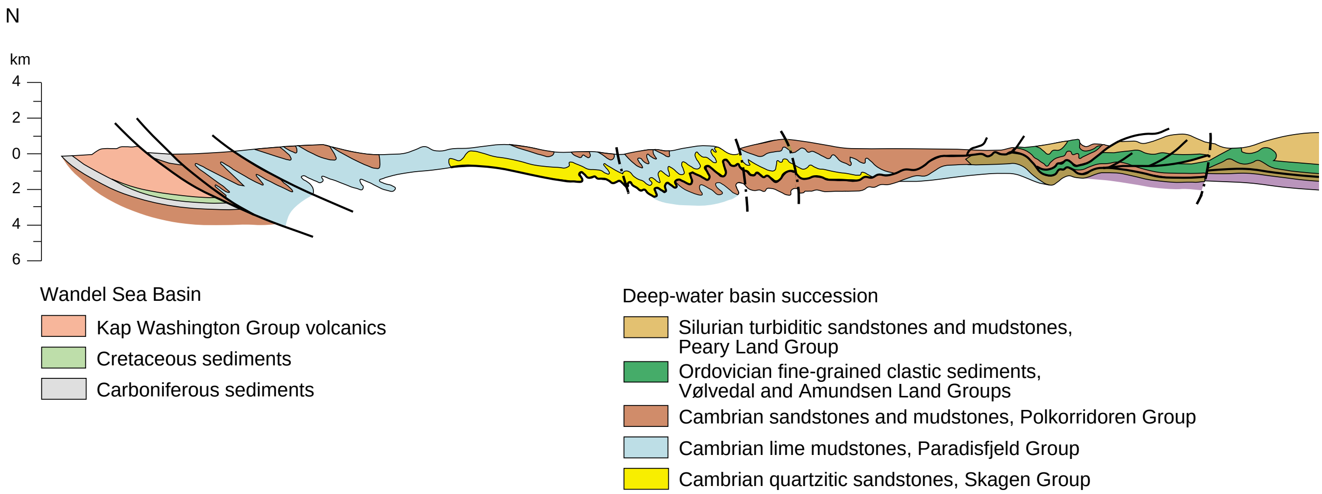


Fig. 29. N–S structural cross-section through the North Greenland (Ellesmerian) fold belt and its southern foreland in North Greenland (*c.* 39°W, westernmost Peary Land). Compiled from Soper & Higgins (1990) and Henriksen (1992).

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 later supracrustal complexes include varied 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.

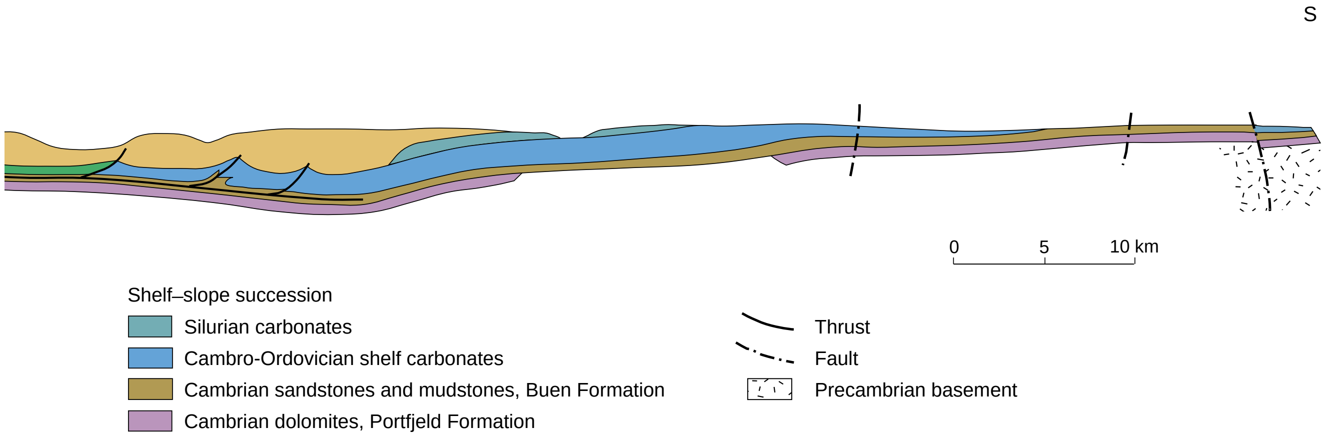
Ellesmerian orogeny in North Greenland and Ellesmere Island

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. 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. 29). 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.

Lower Palaeozoic of East Greenland

Cambrian–Ordovician sediments in the Caledonian fold belt

Cambrian–Ordovician rocks [40] make up an approximately 4000 m thick succession within the East Greenland Caledonian fold belt between latitudes 71°40′ and 74°30′N (Haller 1971; Peel 1982; Henriksen 1985). The sediments 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. 30); uppermost Ordovician to Silurian sediments are not known in East Greenland.

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 (Chazyan) 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). The 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.

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). 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 base-

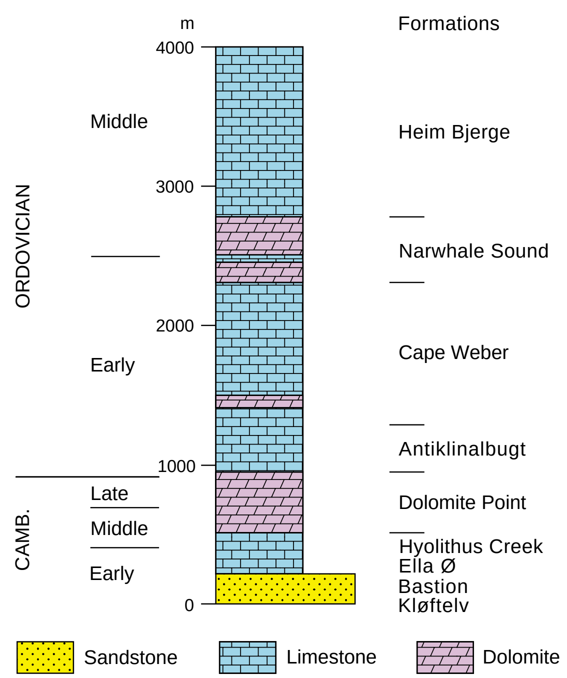


Fig. 30. Schematic lithostratigraphic composite section of the Cambro-Ordovician sediments in East Greenland (*c.* 71°30′–74°30′N). Unit [40] on the map.

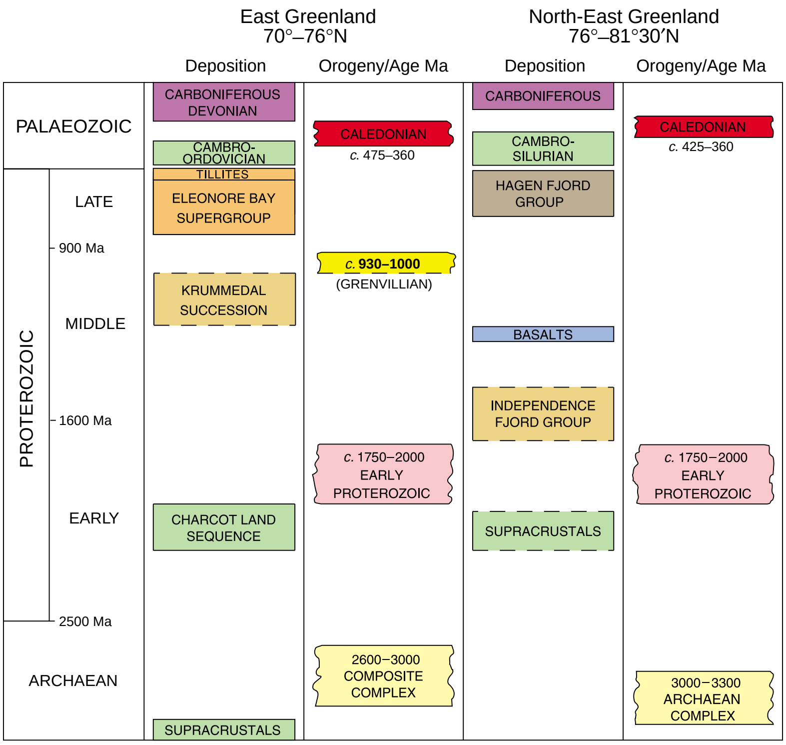


Fig. 31. Schematic chronological diagram showing pre-Caledonian and Caledonian elements occurring in the East Greenland Caledonian fold belt. **Colours** are approximately the same as those used for the units on the map.

ment rocks [74, 70, 52], overlain by middle and upper Proterozoic [46–43] and lower Palaeozoic [74] sediments (Fig. 31). The deep-seated infrastructural levels are characterised by superimposed fold phases of several different ages, whereas the high level suprastructural levels exhibit relatively simple open folds of Caledonian age. Large-scale westward-directed nappes and thrust sheets interleave different levels of the Caledonian fold belt with one another and override the margin of the Greenland shield. Extensional structures characterise some of the late tectonic phases (Strachan 1994; Hartz & Andresen 1995; Andresen *et al.* 1998). The southern and central parts of the fold belt in East Greenland reveal mainly deep-seated infracrustal basement (Fig. 32), whereas in the northernmost part of the fold belt in Kronprins Christian Land high level thin-skinned structures are preserved. Reviews of the East Greenland Caledonides have been presented by Haller (1971), Henriksen & Higgins (1976), Higgins & Phillips (1979), Henriksen (1985), Hurst *et al.* (1985) and Jepsen *et al.* (1994).

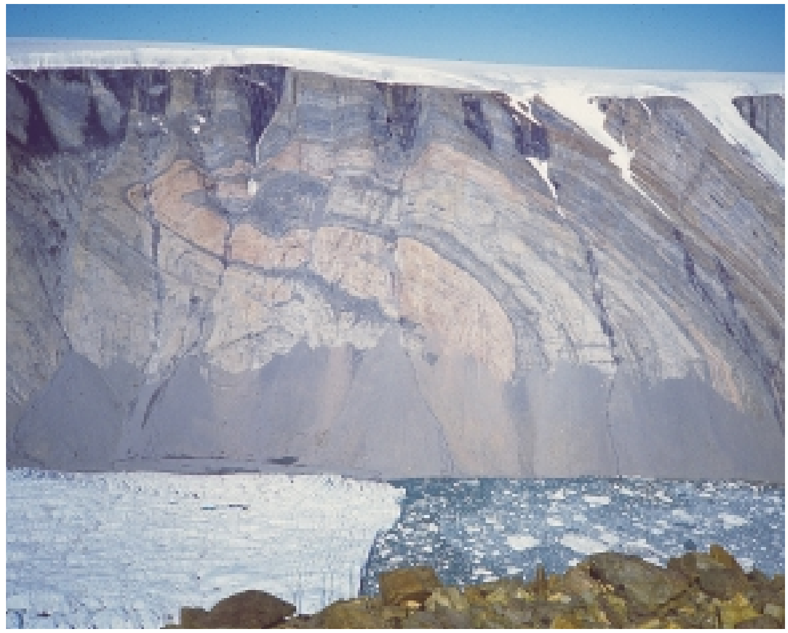
Caledonian intrusions and plutonic rocks

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 late Proterozoic Eleonore Bay Supergroup sediments and the adjacent metamorphic complexes (Jepsen & Kalsbeek 1998; Fig. 33), whereas in southern areas plutonic bodies are widespread within the crystalline complexes. Granodiorites and granites are the most abundant types and these have yielded intrusive ages from 475 Ma to *c.* 375 Ma. Most ages occur in the range 445–400 Ma (Hansen & Tembusch 1979; Steiger *et al.* 1979; Rex & Gledhill 1981). The Caledonian granites in the northernmost part of their region of occurrence (75°–76°N) were emplaced about 400–430 Ma ago and these contain a large proportion of crustally derived components (Hansen *et al.* 1994).

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 fold 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. 32. Major isoclinal fold in reactivated Lower Proterozoic 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.



Devonian continental sediments in East Greenland

Following the Caledonian orogeny a period of extensional faulting led to the initiation of a Devonian sedimentary basin in central East Greenland (Larsen & Bengaard 1991; Hartz & Andresen 1995). The Devonian sediments unconformably overlie Ordovician and older rocks, and are preserved in north–south trending graben-like structures.

The basin fill is of Middle and Late Devonian age [39] and consists of more than 8 km of continental siliciclastic sediments with some volcanic intervals. Four lithostratigraphic groups have been established, each corresponding to a tectonostratigraphic stage (Fig. 34). The earliest deposits (Vilddal Group) are interpreted as laid down by gravelly braided rivers and alluvial fans, which gave way to meandering streams and flood plains. The overlying sandstones of the Kap Kolthoff Group were deposited by extensive coalescing braidplain systems (Olsen 1993); this group commonly contains intervals of basic and acid volcanic rocks. During the following stage (Kap Graah Group) sedimentation took place in transverse and longitudinal fluvial systems and was dominated by fine-grained sandstones and siltstones; aeolian deposits occur locally. This was followed by deposition of fluvial sandstones, flood basin sediments and lacustrine siltstones of the Celsius Bjerg Group. The basin fill was disturbed by a series of defor-

Fig. 33. Caledonian granite with large sedimentary xenoliths of the late Proterozoic 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.

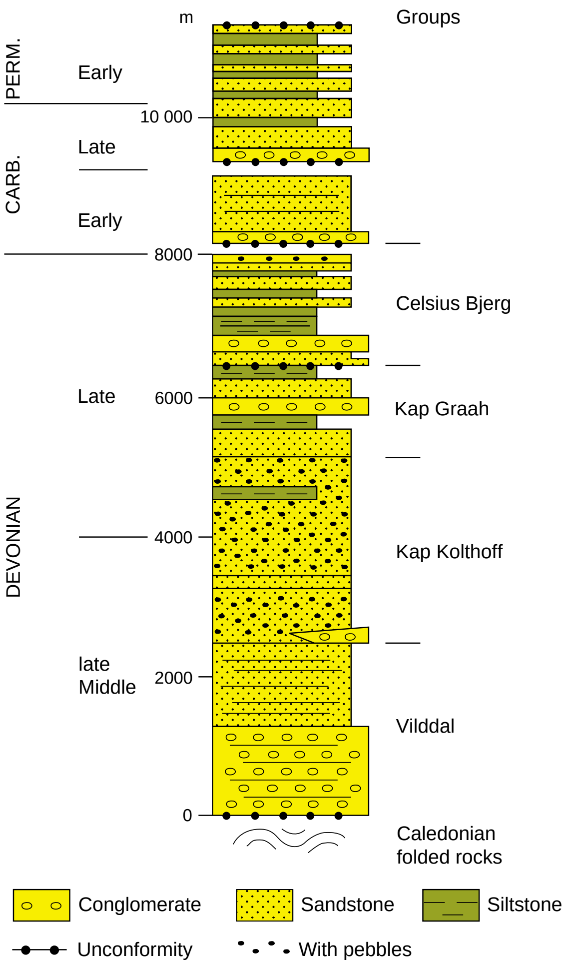


Fig. 34. Schematic, lithostratigraphic composite section of Devonian – Lower Permian continental clastic deposits in central East Greenland (71°–74°30′N), units [39] and [38] on the map. Compiled from Olsen & Larsen (1993) and Stemmerik *et al.* (1993).

mation events both during and after sedimentation (Haller 1971; Olsen & Larsen 1993). New palaeomagnetic and isotopic age data have been interpreted as indicating a Carboniferous age for the younger part of the succession (Hartz *et al.* 1997), but this view is dismissed by Marshall *et al.* (1999).

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 35, 36). Three main phases of basin formation are recognised, commencing with a widespread Carboniferous to Triassic event of block faulting and regional subsidence. Later, during the Late Jurassic and

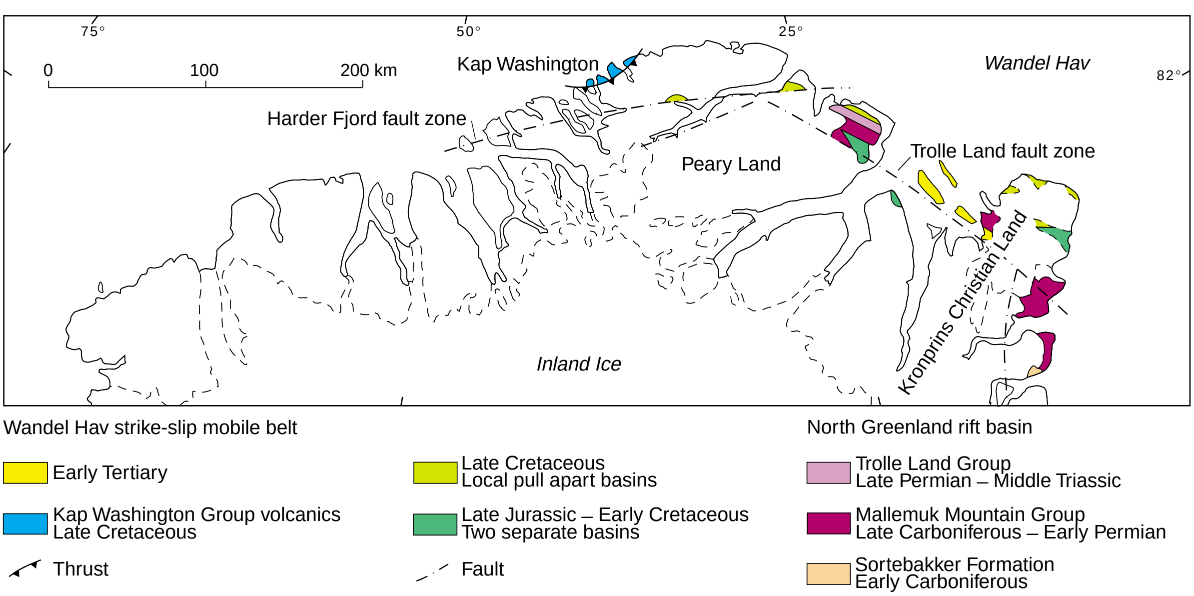


Fig. 35. Distribution of the Wandel Sea Basin sequences in central and eastern North Greenland. Modified from Håkansson *et al.* (1994).

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). The Carboniferous succession is dominated by cyclic 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. 35; Brown *et al.* 1987). They are of latest Cretaceous age, and their extrusion may be associated with intrusion of a dense swarm of alkali dolerite dykes in North Greenland (see Fig. 18). The volcanic rocks are preserved below a major, southward-dipping thrust which transported folded Lower Palaeozoic rocks northwards over the volcanic successions (see Fig. 29).

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). Subsequent to this deformation event a thin succession of upper Paleocene to lower Eocene fluviatile sandstones (Thyra Ø Formation [14]) accumulated, the youngest deposits of the Wandel Sea Basin succession (Håkansson *et al.* 1991).

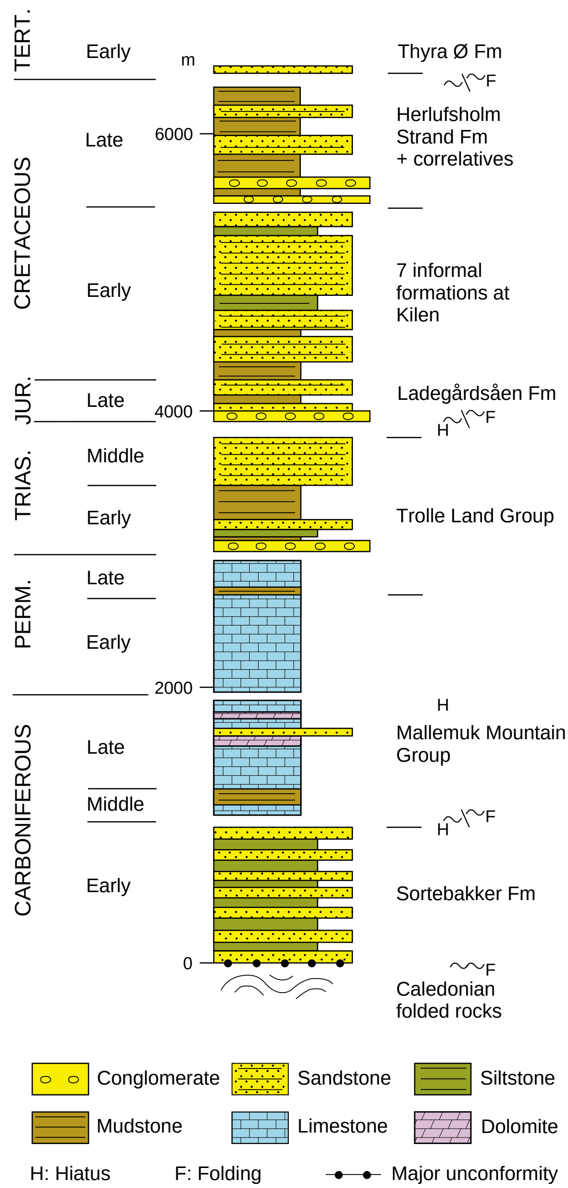


Fig. 36. Composite section of the Wandel Sea Basin successions in eastern North Greenland. The successions occur in several distinct sub-basins. Corresponding units on the map: Sortebakker Fm [20]; Mallemuk Mountain Group [19]; Trolle Land Group [18]; Ladegårdsåen Formation and correlatives [17]; Herlufsholm Strand Formation and correlatives [15]; Thyra Ø Formation [14]. Compiled from Håkansson & Stemmerik (1989) and Stemmerik & Håkansson (1989) .

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; Stemmerik *et al.* 1993). 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. 37).

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 (see Fig. 34), 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. 38). Sediment infill was derived 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 sediments 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 Triasssic [36] (Clemmensen 1980a, b).

A major lacustrine basin [35] covered most of Jameson Land during the latest Triassic – earliest Jurassic (Dam & Surlyk 1993, 1998). Renewed marine incursions took

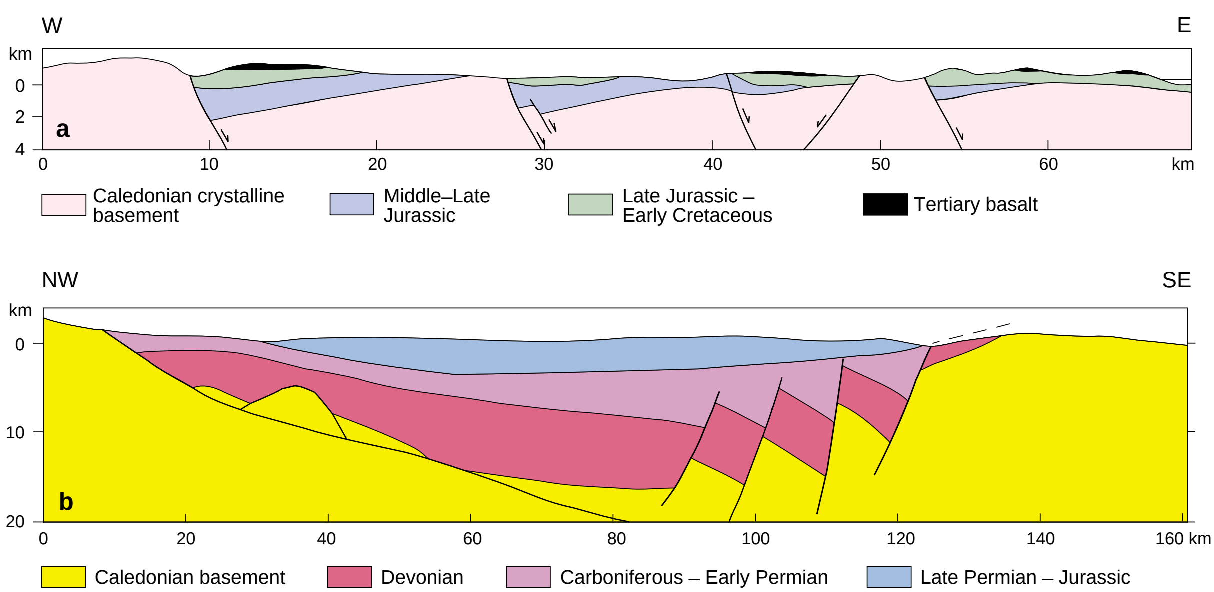


Fig. 37. Upper Palaeozoic – Mesozoic basins in East Greenland. **a**: Northern development at Wollaston Forland (*c.* 74°30′N). **b**: Southern development at Jameson Land (*c.* 71°N). Colours approximately as used on the map. Note the different scales of the two profiles. From Christiansen *et al.* (1991) and Surlyk (1991).

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 sediment 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 sediments [33] are restricted to the southernmost part of the basin and are dominated by shallow marine sandstones (Surlyk 1991).

Late Permian – Cretaceous sediments 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 sediments are restricted to the southernmost part of the region. The Middle to Upper Jurassic sediments [34] also resemble those in Jameson Land (Fig. 38), 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 breccias and conglomerates that pass upwards 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.

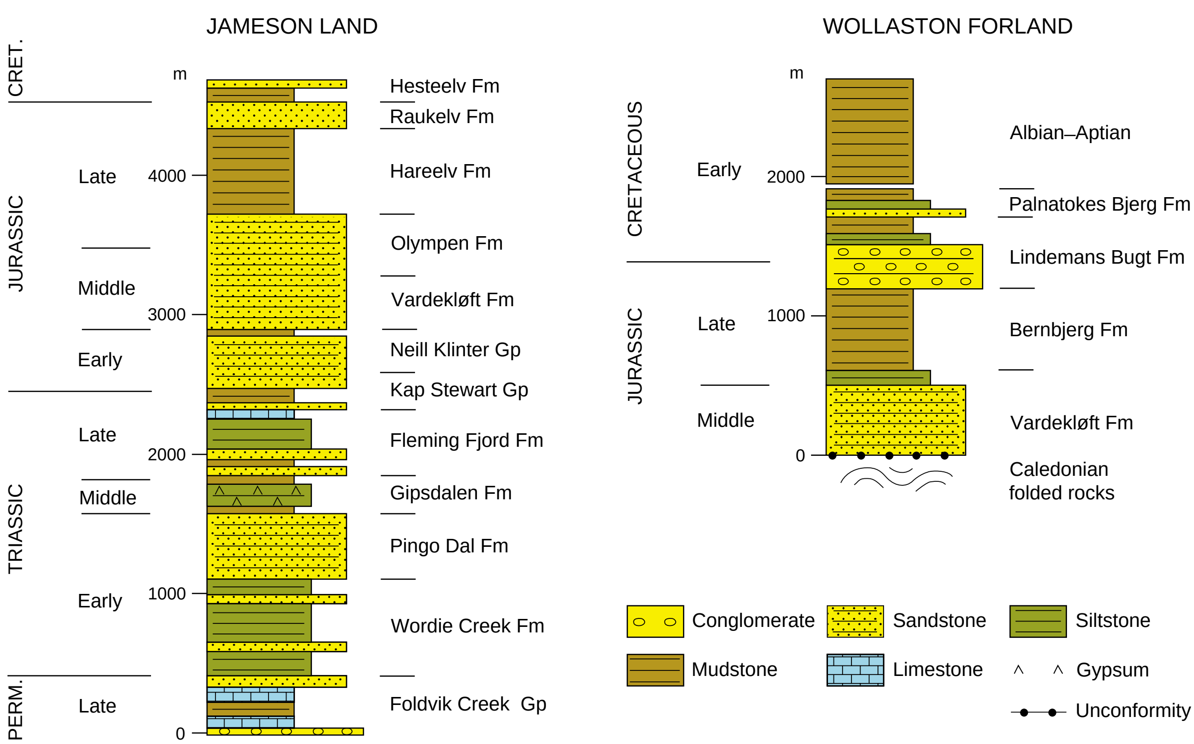


Fig. 38. Schematic sections of the northern (Wollaston Forland) and southern (Jameson Land) developments in the Late Permian and Mesozoic rift margin basins of East Greenland. Corresponding units on the map: Foldvik Creek Group and Wordie Creek Formation [37]; Pingo Dal, Gipsdalen and Fleming Fjord Formations [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 revision of the Jurassic stratigraphy of East Greenland is currently (1999) being undertaken by Finn Surlyk and co-workers.

Cretaceous–Tertiary sediments

Central West Greenland

Cretaceous–Tertiary sediments [8] outcrop in the Disko–Svartenhuk Halvø region (69°–72°N) of West Greenland, where they are overlain by Lower Tertiary basalts (Fig. 39). The sediments were laid down in the Nuussuaq Basin. 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). Recently acquired seismic data indicate that the maximum thickness of sediments in the basin exceeds 8 km (Christiansen *et al.* 1995; Chalmers *et al.* 1999), but the age and character of the deepest sediments are not known.

The lower part of the exposed Cretaceous succession, which is of Albian – early Campanian age, was deposited in a fluvial- and wave-dominated delta environment (Atane Formation; Pedersen & Pulvertaft 1992). The delta fanned out to the west and north-west from a point east of Disko/Qeqertarsuaq island, reaching into deeper-water turbidite-influenced environments in the position of present-day western and northern Nuussuaq and Svartenhuk Halvø. Pre- and syn-rift fluvial sandstones with minor mudstones and coal characterise the southern and eastern parts of the outcrop area. To the north-west these give way to stacked, typical deltaic, coarsening-upwards successions (Fig. 40), each starting with interdistributary bay mudstones and ending with coal, while farther west and north-west dark mudstones and a variety of turbidites were deposited in a purely marine environment (lower part of Itilli succession; Dam & Sønderholm 1994; Dam 1997; Christiansen *et al.* 1998). In central Nuussuaq there is evidence of an early Campanian rift event, and shelf deltaic sedimentation gives way to deposition from catastrophic mass flows.

At some time during the Maastrichtian the region again became tectonically unstable. Phases of block-faulting and uplift were followed by incision of both subaerial valleys and submarine canyons into the underlying sediments (Fig. 40). Conglomerates, turbiditic and fluvial sands and mudstones of late Maastrichtian to middle Paleocene age (Kangilia and Quikavsak Formations) filled the valleys and submarine canyons (Dam & Sønderholm 1994, 1998).

The youngest Paleocene sediments are lacustrine mudstones deposited in lakes that were dammed up by volcanic rocks encroaching from the west (Pedersen *et al.* 1998).

Southern East Greenland

A *c.* 1 km thick Cretaceous to Lower Tertiary sedimentary succession [50] occurs in East Greenland north-east of the fjord Kangerlussuaq (*c.* 68°30′N). The sediments onlap crystalline basement to the east and north, but elsewhere the base of the succession is not seen. The sediments belong to the Kangerdlugssuaq and Blosseville Groups (Soper *et al.* 1976; Nielsen *et al.* 1981).

The oldest exposed sediments 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 ?mid-Paleocene age (M. Larsen *et al.* 1996, 1999).

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 sediments

The early Tertiary 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 Tertiary.

Tertiary basalts, central West Greenland

Tertiary volcanics 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 the large volumes of high-temperature picrites and olivine basalts (Clarke & Pedersen 1976). 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).

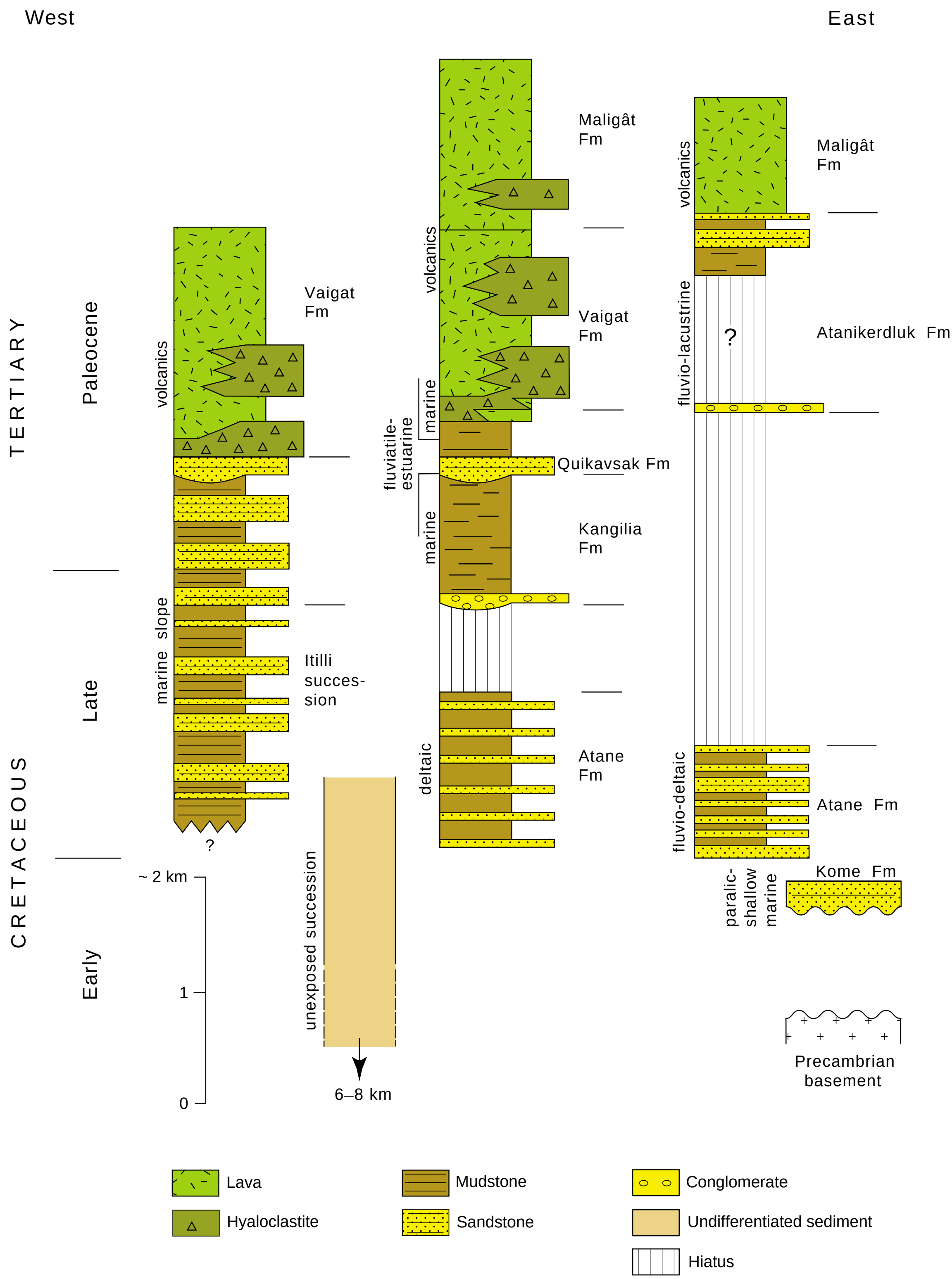


Fig. 39. Lithostratigraphic sections in the Nuussuaq Basin, Disko–Nuussuaq region, central West Greenland. Compiled from Pedersen & Pulvertaft (1992), Piasecki *et al.* (1992), Dam & Sønderholm (1994, 1998) and Christiansen *et al.* (1995).

Fig. 40. Valley incised in Cenomanian sediments (Atane Formation) and infilled with upper Maastrichtian turbidites (Kangilia Formation). Thickness of well-exposed part of the section is approximately 250 m. Note the coarsening-upwards cyclicity in the deltaic Atane Formation sediments. Pale sandstone of the Quikavsak Formation can be seen high up on the ridge. The highest rocks exposed are hyaloclastite breccias in the Vaigat Formation. Summit of ridge is at 920 m. Locality: Ataata Kuua, south-west side of Nuussuaq, central West Greenland.

Eruption of the basalts began in a submarine environment, and the earliest basalts, which occur to the west (Fig. 39), 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 which 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 completely filled in with volcanic rocks (Pedersen *et al.* 1996, 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 areas where the lavas dip at up to 40° westwards.

The major part of the volcanic pile was erupted in a short time span 61–59 Ma ago. In western Nuussuaq there is a younger group of lavas dated at 52.5 Ma (first recognised after the map was printed) which probably also occurs on Ubekendt Ejland and the Svartenhuk Halvø peninsula (Storey *et al.* 1998).

Tertiary basalts, East Greenland

Early Tertiary 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–Tertiary sediments in the east and south, and on Caledonian and Precambrian gneisses in the west (Nielsen *et al.* 1981; Larsen *et al.* 1989). North of Scoresby Sund lower Tertiary basic sills and dykes are widespread in the Mesozoic sediments, and a further sequence of plateau basalts is found between latitudes 73° and 75°N.

Blosseville Kyst region (68°–70°N)

The earliest Tertiary volcanics are 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 tholeiitic plateau basalts [48] which form 5–50 m thick subaerial flows of plagioclase-phyric to aphyric basalt (L.M. Larsen *et al.* 1989, 1999; Pedersen *et al.* 1997). 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. 41). Four formations can be followed over almost the whole area, representing two major volcanic episodes. Eruptions took place over the whole 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; 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).

Fig. 41. A major unconformity between Caledonian deformed Precambrian gneisses [52] and Lower Tertiary 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.

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

A succession of *c*. 1100–1200 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 Wollaston 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 lay 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).

Tertiary intrusions, East Greenland

Numerous Tertiary 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. 18); approximately 20 of these intrusions are shown on the map, separated into felsic [53] and intermediate and mafic [57] types (Fig. 42). 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 (Tegner *et al*. 1998), whereas the more northerly intrusions (72°–74°N) are all younger, with ages in the range 48–28 Ma.

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. In size they range from a few square kilometres to *c*. 850 km^2. 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 (Wagner & Deer 1939; McBirney 1996a, b; Irvine *et al*. 1998).

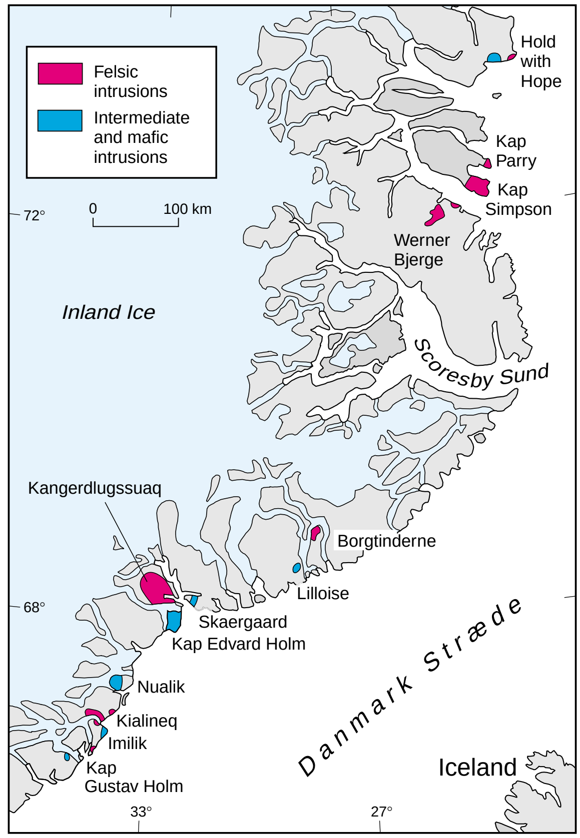


Fig. 42. Major Tertiary intrusive centres in East Greenland (*c*. 66°30′–74°N). Slightly modified from Nielsen (1987).

Post-basaltic Tertiary sediments, East Greenland

Post-basaltic sediments [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 an 80–130 m thick succession of Lower Tertiary (lower Eocene and lower Oligocene) marine sandstones and siltstones with conglomerates (Soper & Costa 1976). At one of the localities these deposits are overlain by a *c*. 75 m thick succession of probably Upper Tertiary (Miocene) marine conglomerates and sandstones (Birkenmajer 1972).

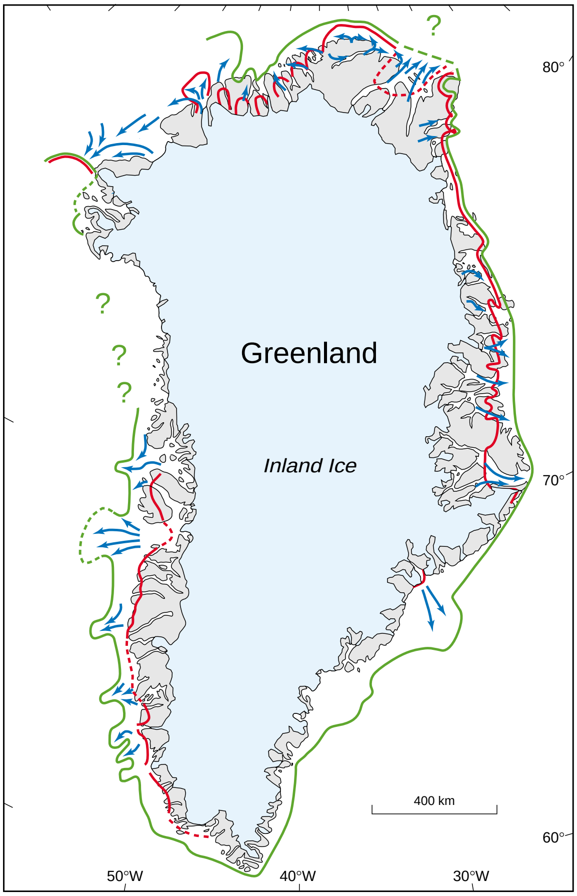


Fig. 43. Former extent of the Greenland Inland Ice during the last glacial maximum. **Green**: *c.* 18 000 years before present; **red**: *c.* 10 000 years ago; **blue arrows**: major glacier outlet streams. Modified from Funder & Hansen (1996).

The Tertiary sediments preserved onshore are marginal exposures of an extensive and much thicker (5–6 km) Tertiary succession found on the adjacent shelf areas (see p. 58).

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 outcrops over an area of *c.* 500 km^2 in easternmost Peary Land, North Greenland (Funder & Hjort 1980; Funder 1989). The sequence contains well-preserved faunal and floral elements.

The base of the succession is not exposed. The lower 25 m comprises 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 disturbances caused by overriding glaciers during the Quaternary glaciation, and is overlain by till.

Quaternary glacial sediments

During most of the Quaternary Greenland was completely, or almost completely, covered by ice, and surficial 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 onset of glaciation may have occurred as early as the late Miocene (*c.* 7 Ma ago) (Larsen *et al.* 1994a, b). 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 the 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. 43).

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 10 km inside its present position. The position of the margin of the Inland Ice where it abuts against land

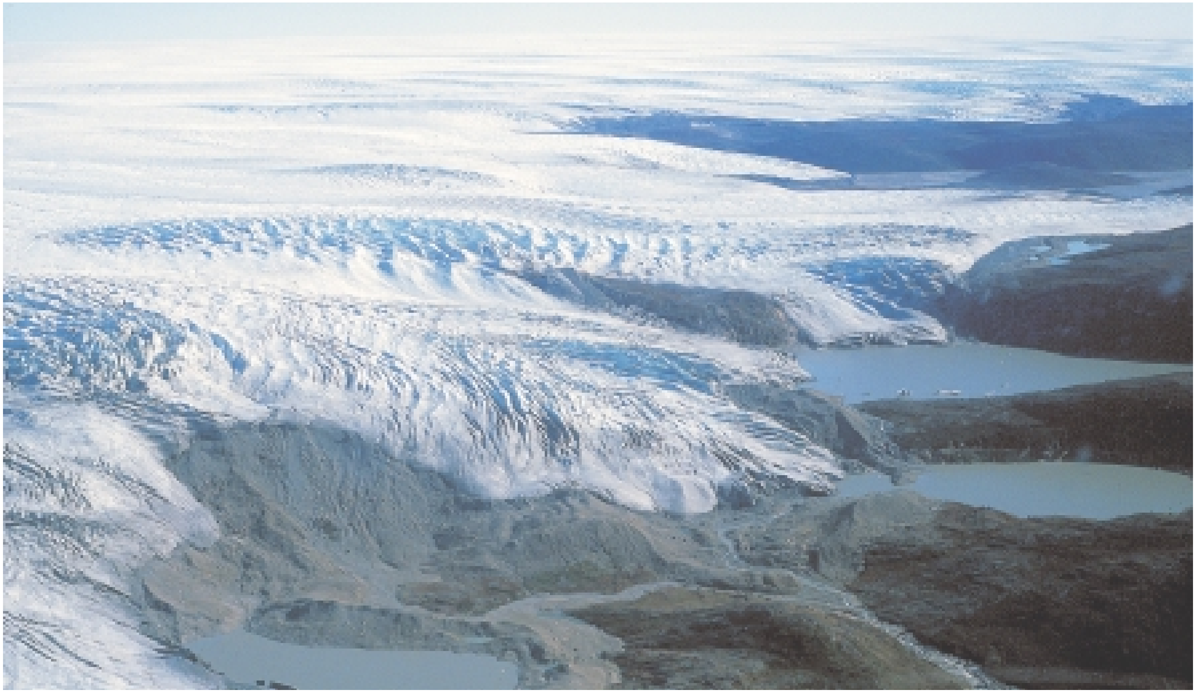


Fig. 44. Characteristic front of the Inland Ice abutting the ice-free land area, with moraines and small lakes. The distance from the bottom of the picture to the land area in the background is approximately 5 km. The locality is about 75 km north-north-east of Søndre Strømfjord airport, southern West Greenland, at c. 67°30′N. View is towards south. Photo: H. Højmark Thomsen.

areas at present shows only minor fluctuations (Fig. 44). Significant movements 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 in 24 hours.

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 the central and northern parts to about –5°C in south-western marginal areas. The temperature of the ice ranges between –32° and 0°C; with increasing depth, temperatures generally increase due to geothermal heat flux and internal heating caused by ice deformation. In some locations, the temperature at the base of the ice sheet may reach melting point.