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Lithostratigraphy of the Cretaceous–Paleocene Nuussuaq Group, Nuussuaq Basin, West Greenland

Gregers Dam, Gunver Krarup Pedersen, Martin Sønderholm, Helle H. Midtgaard, Lotte Melchior Larsen, Henrik Nøhr-Hansen and Asger Ken Pedersen

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Lithostratigraphy, Nuussuaq Group, Cretaceous, Paleocene, West Greenland, Nuussuaq Basin.

Cover illustration
Sedimentary succession of the Nuussuaq Group at Paatuut on the south coast of Nuussuaq, one of the classical localities for sedimentological and palaeontological studies. The photograph shows deep incision of the Paleocene Quikavsak Formation into the Upper Cretaceous Atane Formation. The conspicuous red coloration is due to self-combustion of carbonaceous sediments. The upper part of the succession comprises volcanic rocks of the West Greenland Basalt Group. The height of the mountains is *c.* 2000 m. Photo: Martin Sønderholm.

Frontispiece: facing page
View down into the narrow Paatuutkløften gorge on the southern coast of Nuussuaq, where coarse-grained, pale sandstones of the Paleocene Quikavsak Formation fill a major incised valley cut into interbedded mudstones and sandstones of the Cretaceous Atane Formation. Sea-fog often invades the coastal valleys but typically dissipates during the day. Photo: Finn Dalhoff.

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Contents

Abstract

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The Nuussuaq Basin is the only exposed Cretaceous–Paleocene sedimentary basin in West Greenland and is one of a complex of linked rift basins stretching from the Labrador Sea to northern Baffin Bay. These basins developed along West Greenland as a result of the opening of the Labrador Sea in Late Mesozoic to Early Cenozoic times. The Nuussuaq Basin is exposed in West Greenland between 69°N and 72°N on Disko, Nuussuaq, Upernivik Ø, Qeqertarsuaq, Itsaku and Svartenhuk Halvø and has also been recorded in a number of shallow and deep wells in the region. The sediments are assigned to the more than 6 km thick Nuussuaq Group (new) which underlies the Palaeogene plateau basalts of the West Greenland Basalt Group. The sediment thickness is best estimated from seismic data; in the western part of the area, seismic and magnetic data suggest that the succession is at least 6 km and possibly as much as 10 km thick. The exposed Albian–Paleocene part of the succession testifies to two main episodes of regional rifting and basin development: an Early Cretaceous and a Late Cretaceous – Early Paleocene episode prior to the start of sea-floor spreading in mid-Paleocene time. This exposed section includes fan delta, fluviodeltaic, shelfal and deep marine deposits.

The Nuussuaq Group is divided into ten formations, most of which have previously been only briefly described, with the exception of their macrofossil content. In ascending stratigraphic order, the formations are: the Kome Formation, the Slibestensfjeldet Formation (new), the Upernivik Næs Formation, the Atane Formation (including four new members – the Skansen, Ravn Kløft, Kingittoq and Qilakitsoq Members – and one new bed, the Itivnera Bed), the Itilli Formation (new, including four new members: the Anariartorfik, Umiivik, Kussinerujuk and Aaffarsuaq Members), the Kangilia Formation (including the revised Annertuneq Conglomerate Member and the new Oyster–Ammonite Conglomerate Bed), the Quikavsak Formation (new, including three new members: the Tupaasat, Nuuk Qiterleq and Paatuutkløften Members), the Agatdal Formation, the Eqalulik Formation (new, including the Abraham Member), and the Atanikerluk Formation (new, including five members: the Naujât, Akunneq (new), Pingu (new), Umiussat and Assoq (new) Members).

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Preface

The onshore Cretaceous–Paleocene sedimentary succession of the Nuussuaq Basin in West Greenland has been studied since the mid-1850s, mainly because of its extremely well-preserved macroplant and invertebrate fossils and the presence of coal. The early work suggested major age differences between the various lithological units, but as knowledge increased as a result of the investigations carried out from the late 1930s to the late 1960s, the time gaps gradually diminished. During this period, several more or less informal stratigraphic schemes evolved and were even used differently by different authors, causing confusion concerning the actual definition, the vertical and lateral extent, and the age of the lithological units. This confusion was not helped by the fact that spelling conventions regarding Greenlandic place names changed considerably over time. No formal lithostratigraphy in the Nuussuaq Basin was defined, although Troelsen (1956) in his overview on stratigraphic units in Greenland treated the units he described as formal.

In the early 1990s, focus was again directed towards the region as an analogue for the offshore basins of West Greenland. The Danish State, and later the Greenland Government, provided substantial funding for studies that could counter the general assessment of the region as being only gas-prone. Both extensive acquisition of seismic data and substantial onshore field studies were initiated in the Nuussuaq Basin during this period under the auspices of the Geological Survey of Greenland (from 1995 the Geological Survey of Denmark and Greenland, GEUS). During the following years, the Nuussuaq Basin evolved from being an analogue for the offshore areas to being an exploration target in itself due to the finds of widespread oil seeps in the basin resulting in the drilling of the first onshore exploration well in Greenland in1996. This culminated in 2007 when petroleum exploration offshore Disko took a major leap forward with the granting of seven new exploration licenses. It is therefore evident that a formal description of the thick and varied succession onshore is strongly needed in order to create a common reference for geoscientists working in the region.

The authors have contributed to various extents in the completion of the manuscript. Gregers Dam, Gunver Krarup Pedersen and Martin Sønderholm have had dual roles as authors and compilers. They have provided original data on most of the formations, have written the introductory chapters and have supplied the majority of the figures. They have been responsible for the manuscript in all stages and have revised the manuscript in accordance with the comments from the referees. Helle H. Midtgaard has provided sedimentological logs and original observations on the Kome, Slibestensfjeldet and Upernivik Næs Formations and on the Ravn Kløft Member of the Atane Formation. Henrik Nøhr-Hansen has examined numerous palynological slides and has provided data on the ages of most of the formations. Lotte Melchior Larsen and Asger Ken Pedersen have made it possible to correlate the siliciclastic sediments of the Atanikerluk Formation to the co-eval magmatic rocks, and have documented the areal extent of sedimentary and volcanic rocks on maps and vertical sections.

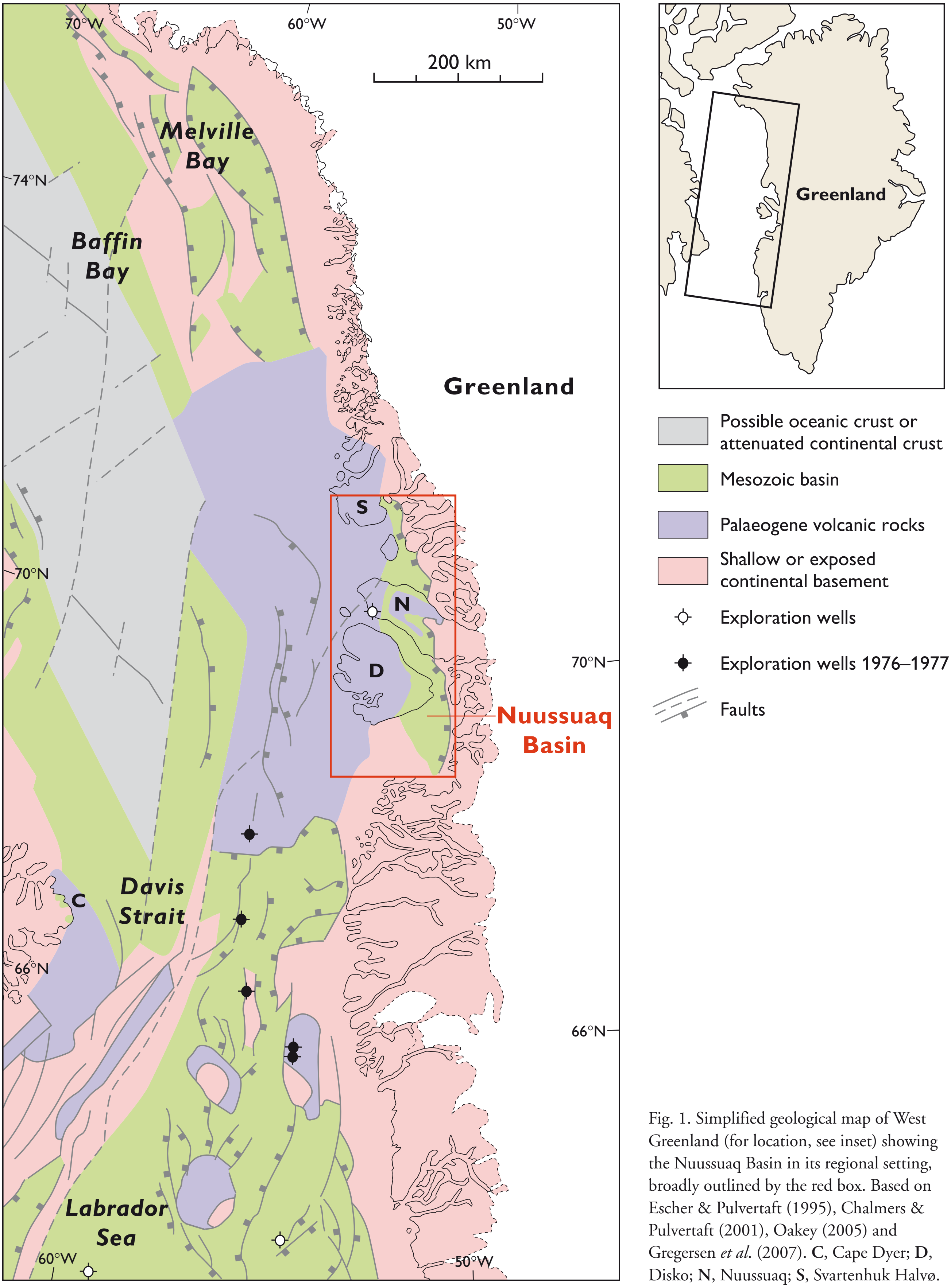


Fig. 1. Simplified geological map of West Greenland (for location, see inset) showing the Nuussuaq Basin in its regional setting, broadly outlined by the red box. Based on Escher & Pulvertaft (1995), Chalmers & Pulvertaft (2001), Oakey (2005) and Gregersen *et al.* (2007). **C**, Cape Dyer; **D**, Disko; **N**, Nuussuaq; **S**, Svartenhuk Halvø.

Introduction

The Nuussuaq Basin belongs to a complex of basins that were formed in the Early Cretaceous, extending from the Labrador Sea in the south to Melville Bay in the north (Fig. 1; Chalmers & Pulvertaft 2001). Due to local uplift during the Neogene, it is the only one of these basins that extends into the onshore area in West Greenland where Upper Cretaceous – Paleocene sediments overlain by volcanic rocks can be studied in the Disko – Nuussuaq – Svartenhuk Halvø area. The Nuussuaq Basin has therefore been used for many years as an analogue for the basins offshore southern and central West Greenland, the primary target for petroleum exploration.

The former lithostratigraphy of the Nuussuaq Basin was established by researchers working with the classic flora and fauna of the Nuussuaq Basin, and definition of lithostratigraphical units was therefore to a large extent governed by fossil finds. This resulted in an incomplete lithostratigraphical scheme comprising some ill-defined units which were not true lithostratigraphic units.

During the last two decades, the sedimentology, biostratigraphy, sequence stratigraphy and organic geo-

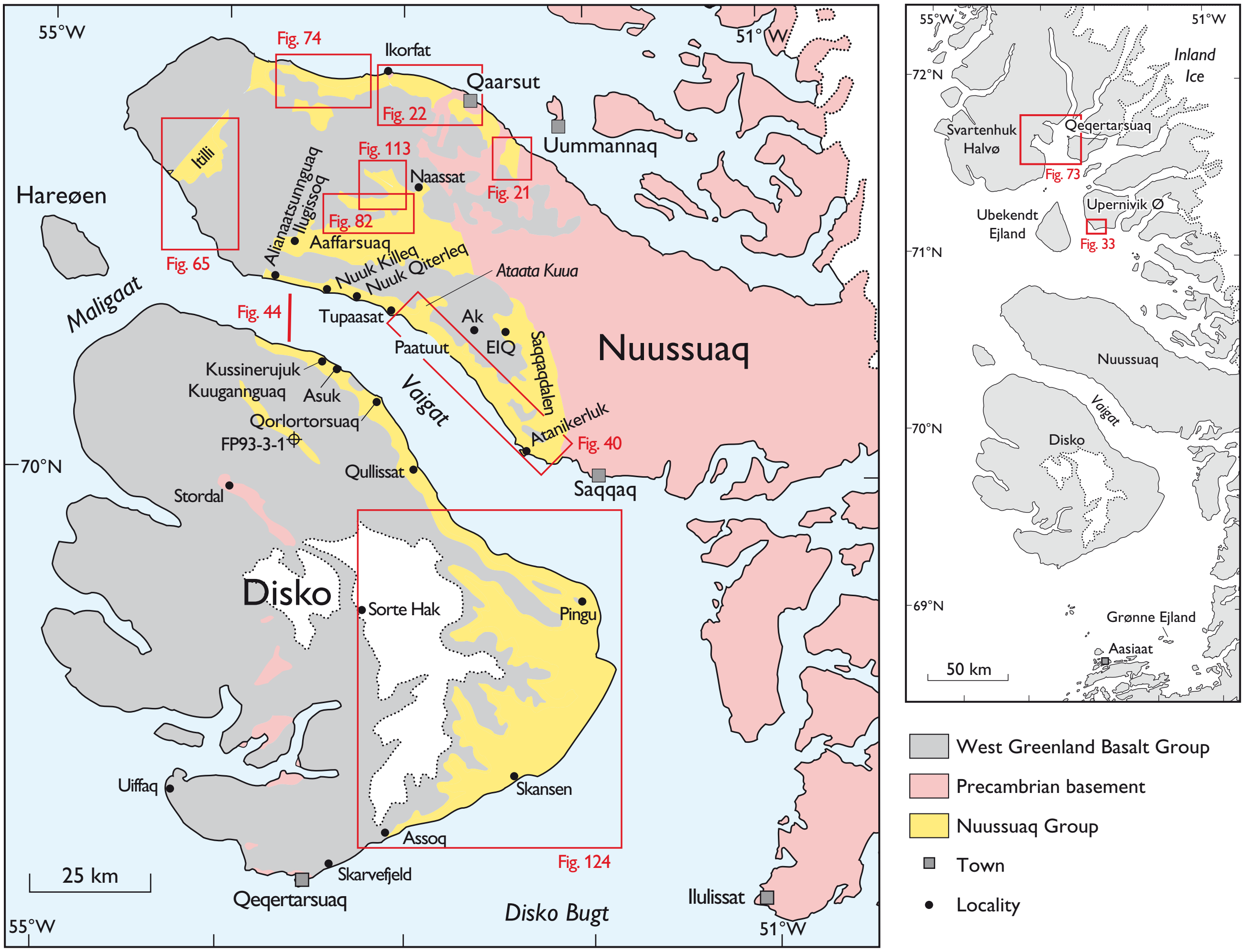


Fig. 2. Map of Disko and Nuussuaq showing the main localities and place names used in this paper. Frames and figure numbers indicate coverage of detailed maps and a seismic section. The pre-Quaternary geology is simplified from Escher (1971). The detailed maps of Upernivik Næs (Fig. 33) and Svartenhuk Halvø – Qeqertarsuaq (Fig. 73) are located on the regional map on the right. **Ak**, Akuliarusinnguaq; **EIQ**, Eqip Inaarsuata Qaqqaa.

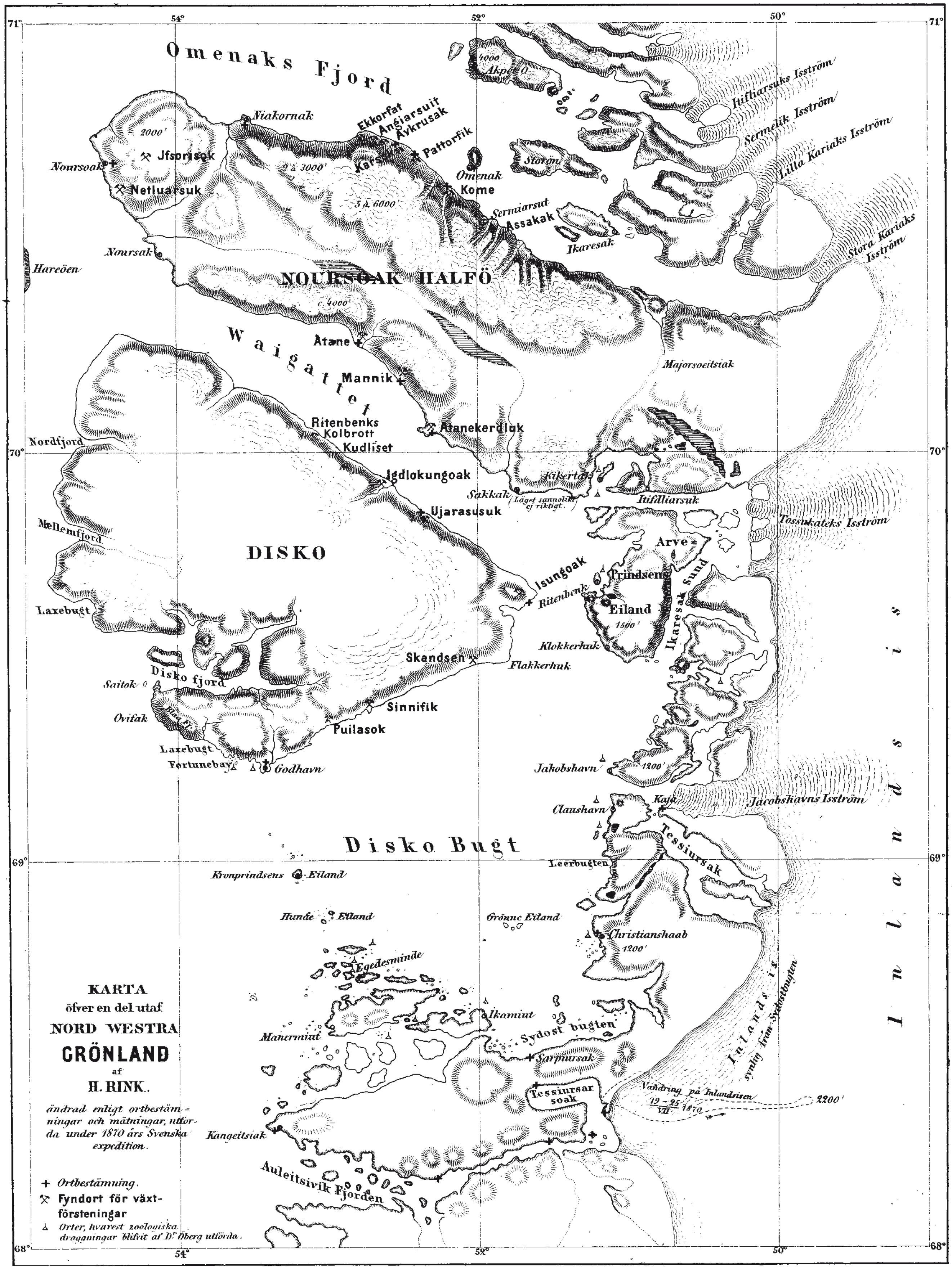


Fig. 3. Topographical map by Rink (1857) reproduced by Nordenskiöld (1871), showing the location of Kome, Atane and other named features given lithostratigraphic significance by Nordenskiöld.

chemistry of the Nuussuaq Basin have been studied in detail by the Survey and the University of Copenhagen, and it is now possible to establish a modern, formal, lithostratigraphic framework for all the sedimentary units in the Nuussuaq Basin. As now defined, the individual Cretaceous – Early Paleocene formations are, to a large extent, genetic units bounded by unconformities. The new framework has been established with the least possible alteration of the earlier defined units in order to avoid confusion and to promote the overall understanding of the basin. Therefore, the naming of units does not in all cases conform to the rules set out by the North American Commission on Stratigraphic Nomenclature (1983). Some of the old informal units were named according to their content of fossils or lithology; a few of these units have been retained due to the large collections of fossils originating from them.

The place names used herein are all in modern Greenlandic orthography. However, previously defined lithostratigraphic units using older spelling have not been renamed. A complete list of place names used is given in both new and old orthography in the Appendix; their location is shown on Fig. 2.

Previous work

The period before 1938 – the pioneers on the fossil floras

The Cretaceous–Paleocene sediments of West Greenland have been known as far back as the time when the Norsemen in Greenland visited this area and named a headland 'Eysunes' from the Norse word 'eisa' (meaning glowing embers); this refers to the spontaneous combustion of organic-rich mudstones and coal that has taken place after landslides at several localities along Vaigat, the strait between Disko and Nuussuaq (Fig. 2; Rosenkrantz 1967; Henderson 1969).

Following re-colonisation in 1721, the coal seams along Vaigat again attracted much attention, and by the time the region had its first inspector in 1782 the Disko Bugt colonies had become self-sufficient in coal, as mentioned in Paul Egede's 'Efterretninger om Grönland' (Steenstrup 1874). The early geological and geographical investigations of this region were reported by Giesecke (1806–13, in: Steenstrup 1910), Rink (1853, 1857; Fig. 3), Nordenskiöld (1871, 1872) and Brown (1875). An account of the later investigations up to 1968 can be found in Rosenkrantz (1970).

For many years it was plant fossils found in the limnic part of the succession that attracted the attention of geologists from all over the world. Brongniart (1831 p. 351) described the first species from Kome on northern Nuussuaq. In the following years, collections of plant fossils were made at several localities in the region, mainly from eastern Disko and Atanikerluk, which were described by Heer (1868). These descriptions aroused so much interest that a British expedition led by E. Whymper and R. Brown was sent out to collect new material in 1867 (Heer 1870). The expedition of A.E. Nordenskiöld in 1870 provided a much larger collection, and for the first time Upper Cretaceous strata were recognised (Heer 1874a, b). Collections from an expedition in 1871 led by E.G.R. Nauckhoff were described by Heer (1880). Important new collections were made by K.J.V. Steenstrup during his expeditions in 1871–72 and 1878–80, and members of Steenstrup's expeditions discovered a number of new plant fossil localities on Disko, Nuussuaq, Upernivik Ø and Svartenhuk Halvø (Fig. 4). Steenstrup brought his collection back to Copenhagen in 1880 and it was described by Heer (1882, 1883a, b). Heer (1883b) concluded from his studies, which now included more than 600 species (e.g. Fig. 5), that the plant fossils could be divided into three Cretaceous floras (the Kome, Atane and Patoot floras) and one flora of Tertiary age (the Upper Atanikerdluk flora).

Later work on plant fossils from this area includes that of Seward (1924, 1926), Miner (1932a, b; 1935), Seward & Conway (1935, 1939), Koch (1963, 1964, 1972a, b), and Boyd (1990, 1992, 1993, 1994, 1998a, b, c, 2000). The plant fossils from Upernivik Næs, described as being part of the Atane flora by Heer (1883b), were recognised as a separate flora (Upernivik Næs flora) by Koch (1964) and referred to as the Upernivik flora by Boyd (1998a, b, c, 2000).

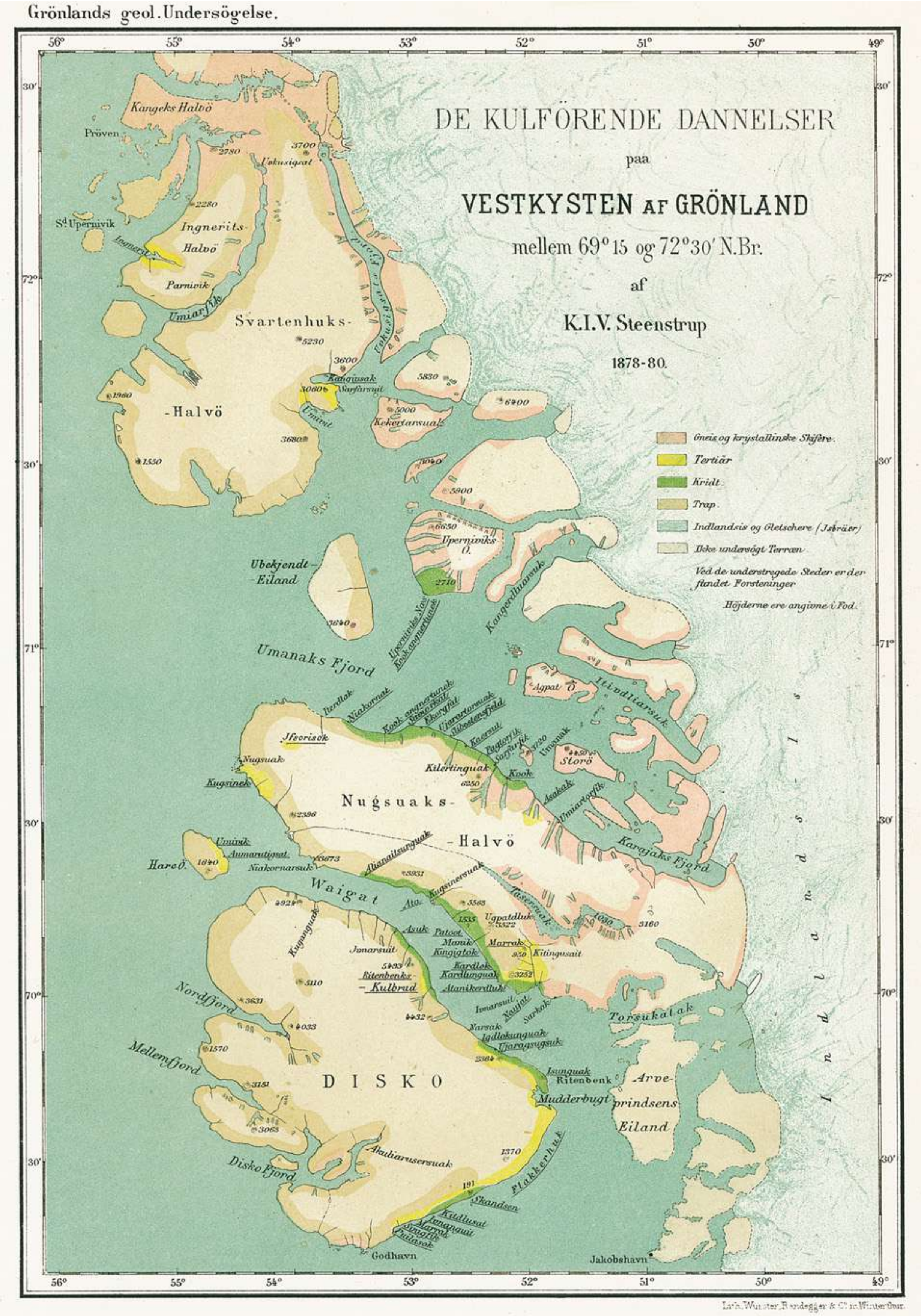


Fig. 4. The first geological map of the Nuussuaq Basin published by Steenstrup (1883b). Note that only the coastal areas were known as all travel was by boat. Steenstrup made several long journeys in an umiaq, a traditional open rowing boat of seal-skin with a crew of women.

Fig. 5. Plant fossils from the Atane Formation at Atanikerluk illustrated in *Flora Fossilis Arctica* by Heer (1883b).

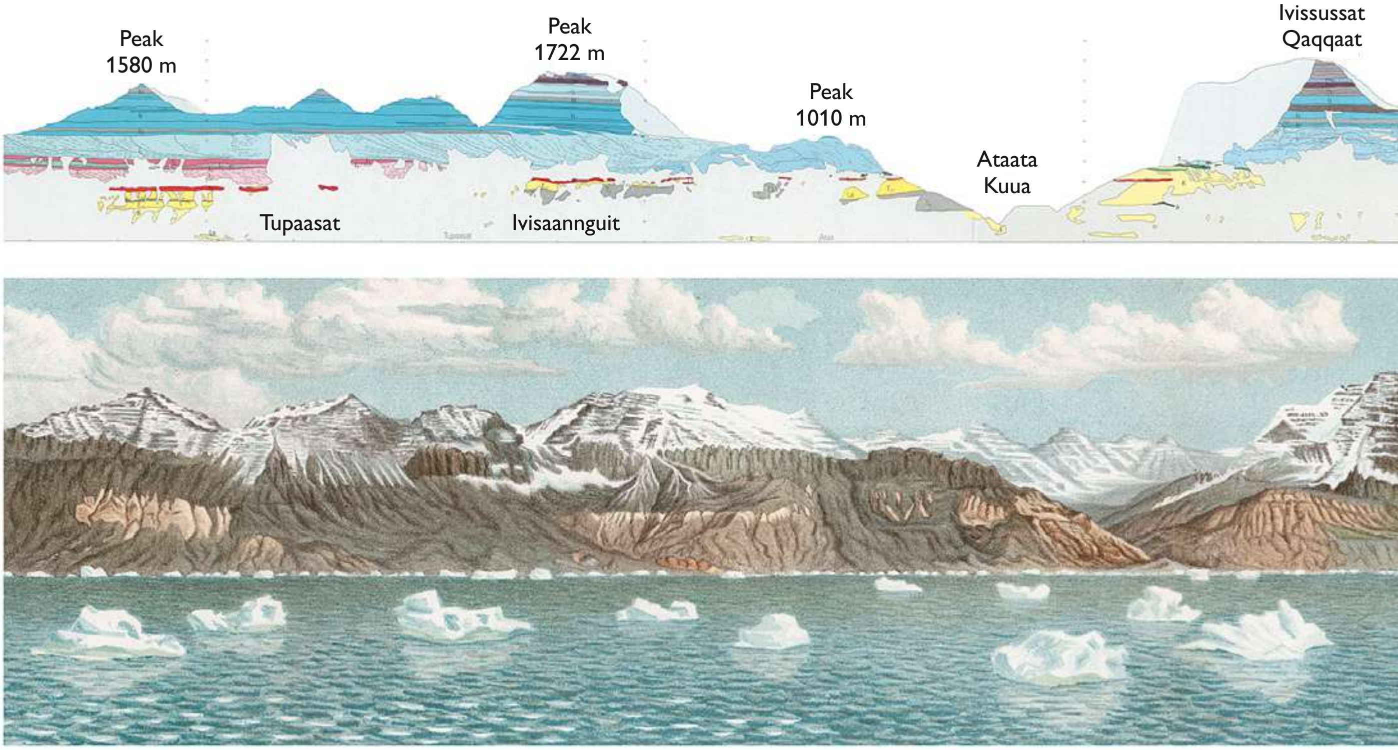


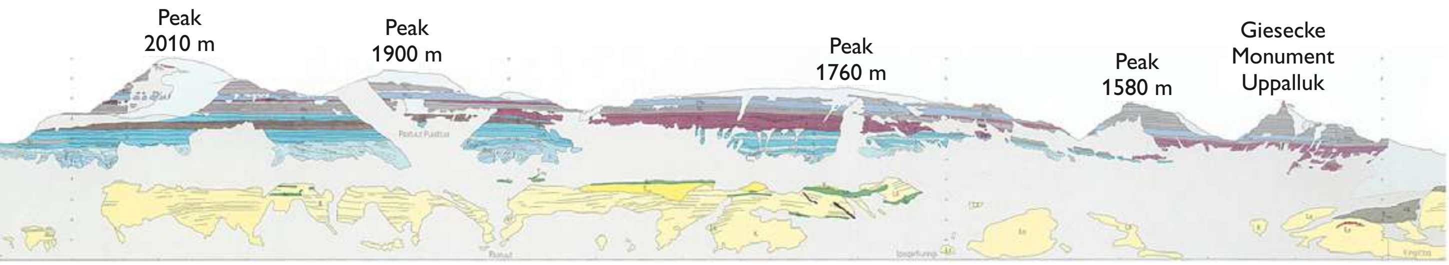
Fig. 6. The south coast of Nuussuaq around the Ataata Kuua river delta (the large valley in the centre of the profile) which is the type area of the Nuussuaq Group. **Upper panel**: Part of modern section measured by multimodel photogrammetry using oblique aerial photographs (from A.K. Pedersen *et al.* 1993). **Lower panel**: Part of a long section painted by Harald Moltke, who accompanied K.J.V. Steenstrup on his journey in 1898 (from Steenstrup 1900). The 33 km long profile extends a little more to the west than the map in Fig. 40. The profile shows many of the characteristic features of the Nuussuaq Basin: Cretaceous sediments including the Atane Formation, up to 800 m (pale yellow); Paleocene incised valleys, marine and lacustrine mudstones (grey), and hyaloclastic foreset-bedded breccias overlain by subaerial lava flows above *c.* 800 m (red, blue, purple and grey, hyaloclastite breccias in pale colours, lava flows in deep colours). Outcrops of the Quikavsak Formation, including the type section, are shown in bright yellow below the summit Point 1580 m (upper panel).

In spite of the fact that this part of Greenland had been visited by a large number of expeditions with geological objectives, knowledge of the marine strata was rather poor until the Nûgssuaq Expeditions from 1938 to 1968, probably because the marine fossils were overshadowed by the very well-preserved plant fossils. Some marine fossils were collected in the latter part of the 19th century by G.F. Pfaff, C.F.V. Henriksen and Greenlanders from Niaqornat, and important collections were made by K.J.V. Steenstrup during his expeditions in 1871–72 and 1878–80. Additional sampling was carried out by D. White and C. Schuchert in 1897 and by J.P.J. Ravn and A. Heim in 1909.

Steenstrup (1874) recognised the presence of marine strata within the Atane Formation of Nordenskiöld (1871) along the south coast of Nuussuaq (Figs 4, 6). The collection of marine fossils made by Steenstrup in 1871–72 in this area was examined by Schlüter (1874 pp. 30–31), who concluded that the marine strata in West Greenland must be of Late Cretaceous age. This conclusion was supported by de Loriol (1883) who studied Steenstrup's 1879 collection of marine faunas from the north coast of Nuussuaq and from Paatuut and Ataa on the south coast.

The collection of *Scaphites* from Niaqornat, which was augmented considerably by Greenlanders who accompanied Steenstrup on his expeditions of 1878–80, was examined by V. Madsen (1897) who referred the dominant species to the European Senonian *Scaphites römeri* d'Orb.

In 1897, a geological expedition under the auspices of the United States National Museum in connection with the Peary Arctic Expedition collected fossils from the Cretaceous and Tertiary localities on Nuussuaq. Stanton (in: White & Schuchert 1898) was of the opinion that the collection of marine fossils from the north coast of Nuussuaq included a number of characteristic Late Cretaceous types that could be equated to the Senonian



of Europe, but he left the possibility open that some of the faunas from the south coast of Nuussuaq could be Tertiary in age.

Ravn (1918) arrived at the same conclusion as Schlüter, de Loriol and Stanton concerning the age of the marine strata in West Greenland, namely that they are Senonian (Late Cretaceous). His study was based on old material stored in the Mineralogical Museum in Copenhagen and collected by Pfaff, Henriksen and Steenstrup together with material collected in 1909 by Ravn, and to a lesser extent by Heim, from Disko and Nuussuaq (Heim 1910; Ravn 1911). The work of Ravn (1918) was at that time the most thorough study of the marine fossils and many species were illustrated for the first time. According to Ravn (1918 p. 330) the occurrence of American Upper Cretaceous species in the Greenland fauna suggested that a marine connection between West Greenland and the central part of Canada and the United States possibly existed in Late Cretaceous time, particularly as no affinities with the American Coastal Plain Cretaceous fauna or the Cretaceous of East Greenland were evident. Relying solely on Ravn's results, Teichert (1939 p. 155) came to a similar conclusion, and in an accompanying map Teichert showed the transgression of the Late Cretaceous sea to West Greenland to be from the north-west. Frebold (1934) described an Early Senonian fauna from East Greenland and also made some remarks on the Senonian fauna from West Greenland.

The pioneering stratigraphic papers by Heer (1868, 1870, 1874a, b, 1880, 1882, 1883a, b), Nordenskiöld (1871, 1872), and Steenstrup (1883b) resulted in the establishment of three pre-volcanic lithostratigraphic units (the Kome, Atane and Upper Atanikerdluk Formations) and four biostratigraphic units (the Kome, Atane, Patoot and Upper Atanikerdluk floras). The first geological map of the region also derives from this period (Fig. 4; Steenstrup 1883b).

The Nûgssuaq Expeditions 1938–1968

In 1938, the Danish Nûgssuaq Expeditions ushered in a new epoch in the study of the Cretaceous–Tertiary sediments in West Greenland. One of the many objectives of these expeditions was the study of the marine strata on Nuussuaq and in other parts of the basalt region of West Greenland (Rosenkrantz 1970) and to obtain a more precise age for the limnic beds and their famous floras.

In 1938 and 1939, the two Nûgssuaq Expeditions led by A. Rosenkrantz and supported by the Carlsberg Foundation and the Royal Greenland Trade Department (Den Kongelige Grønlandske Handel) carried out studies in the Nuussuaq Basin. This work was continued after the Second World War under the auspices of the newly established Geological Survey of Greenland

Fig. 7. Members of the Nûgssuaq Expedition in 1949. Back row (from left): Johansi, Abraham Løvstrøm, Sonja Alfred Hansen, Andreas Tobiassen, Maggie Graff-Petersen. Front row (from left): Alfred Rosenkrantz, Kristian Schou, Bruno Thomsen, Christian Poulsen, Søren Floris and Eske Koch. Many of those in the photo accompanied Rosenkrantz on several expeditions. Rosenkrantz acknowledged the assistance of the hunters from Niaqornat, and Sonja Hansen's discovery of the most fossiliferous lithology when he established the Andreas, Sonja and Abraham Members of his Agatdal Formation.

(Grønlands Geologiske Undersøgelse, GGU). From 1948 to 1968, 16 expeditions to the area (14 led by A. Rosenkrantz and two by S. Floris and K. Raunsgaard Pedersen) had to a greater or lesser degree been involved in the study of the marine strata. A summary of the expeditions and their results was given by Rosenkrantz (1970). More than 47 individuals participated in the work on the marine deposits during this 30-year period, some of whom are seen in Fig. 7.

These expeditions represented the first attempt to study systematically the marine Cretaceous–Tertiary sediments in West Greenland. A new biostratigraphy was erected (Rosenkrantz 1970 fig. 2) and it is thanks to the efforts of the members of the Nûgssuaq Expeditions that large collections of marine fossils were brought back to the Geological Museum in Copenhagen. The fossils from these outstanding collections have since been described by many other workers:

Ammonites and belemnites: Birkelund (1956, 1965)
Corals: Floris (1967, 1972)
Coccoliths: Perch-Nielsen (1973), Jürgensen & Mikkelsen (1974)
Crustaceans: Collins & Wienberg Rasmussen (1992)
Fish: Bendix-Almgreen (1969)
Foraminifera: H.J. Hansen (1970)
Gastropods and bivalves: Yen (1958), Kollmann & Peel (1983), Petersen & Vedelsby (2000)
Leaves and fruits: Koch (1959, 1963, 1964)
Ostracods: Szczechura (1971)
Palynomorphs: K.R. Pedersen (1968)
Wood: Mathiesen (1961)

The gastropods were the subject of special study by Rosenkrantz, but at the time of his death in 1974 only a fraction of the material had been published. A catalogue comprising the gastropod material left unpublished at Rosenkrantz's death was published by Kollmann & Peel (1983) and represents the culmination of many years of work by Rosenkrantz and the technicians and artists under his direction. A catalogue of 115 bivalve taxa from the Rosenkrantz collection has been published by Petersen & Vedelsby (2000). The gastropod family *Psedolividae* has been revised by Pacaud & Schnetler (1999). However, large parts of the collection including echinoderms, serpulids, bryozoans, nautiloids, cirripeds, brachiopods and insects are still unpublished.

Aspects of the stratigraphy of the Cretaceous–Tertiary sediments in the Disko – Nuussuaq – Svartenhuk Halvø area were published in a number of papers between 1959 and 1976, in particular by Koch (1959, 1963, 1964), Koch & Pedersen (1960), Rosenkrantz & Pulvertaft (1969), H.J. Hansen (1970), Rosenkrantz (1970) and Henderson *et al.* (1976). Some elements of the stratigraphy presented in these papers are well established, especially the biostratigraphy of the marine Cretaceous based on ammonites collected *in situ* (Birkelund 1965) and the lithostratigraphy of the non-marine Paleocene in southern Nuussuaq (Koch 1959). However, other stratigraphic interpretations were based on very general descriptions and a number of undocumented statements and correlations. A shortcoming of the work on the sediments during the Nûgssuaq Expeditions was the lack of a formal correlative, regional framework for the marine and non-marine Cretaceous strata.

A lithostratigraphy for the marine Danian beds of northern and central Nuussuaq was established by Rosenkrantz (in: Koch 1963) and Rosenkrantz (1970). The Paleocene Kangilia and the Agatdal Formations were subdivided into members by Rosenkrantz (1970), but these subdivisions are not entirely satisfactory, and Rosenkrantz's correlation of the marine Paleocene across Nuussuaq at member level was not documented.

As regards the marine Cretaceous, the situation was rather better thanks largely to the comprehensive work of Birkelund (1965). She demonstrated that the marine Cretaceous spanned the upper Turonian – Maastrichtian interval, and that the oldest marine strata are to be found on Svartenhuk Halvø.

Two map sheets in GGU's 1:500 000 map series covering the central part of West Greenland were compiled during this period (A. Escher 1971; J.C. Escher 1985).

The early hydrocarbon and coal-related studies 1968–1982

In the late 1960s, the hydrocarbon potential of the basins offshore Labrador and West Greenland was recognised. In the early 1970s, petroleum exploration started with the acquisition of a large number of seismic surveys and culminated with the drilling of five exploration wells offshore West Greenland in 1976 and 1977 (Fig. 1; Rolle 1985). In acknowledgement of the need for geological information, GGU and the petroleum industry studied the sedimentology, biostratigraphy and organic geochemistry of the onshore Cretaceous–Tertiary successions. However, these studies came to an abrupt end when all five wells drilled offshore were declared to be dry and the industry left West Greenland. The most important results of these studies were published by Henderson (1969, 1973, 1976), Sharma (1973), Elder (1975), Schiener (1975, 1976), J.M. Hansen (1976), Henderson *et al.* (1976, 1981), Schiener & Floris (1977) and Schiener & Leythaeuser (1978).

During this phase of the work, the first overall facies pattern was established and a palaeogeographic reconstruction for the mid-Cretaceous was presented (Schiener 1975, 1977), but neither a basin model nor systematic biostratigraphy or lithostratigraphy were published, despite the great efforts of both GGU and the petroleum industry. However, unpublished reports by Ehman *et al.* (1976), Croxton (1976, 1978a, b) and Ehman (1977) and an unpublished thesis by J.M. Hansen (1980b) presented new stratigraphic divisions and correlations based on palynology. The reports of Ehman *et al.* and Croxton dealt with the entire sedimentary succession of the region, but only in rather general terms. In contrast, J.M. Hansen focussed on the marine Paleocene and presented a more detailed stratigraphic analysis. A sedimentological paper on the Lower Cretaceous fluviodeltaic sediments at Kuuk, on the north coast of Nuussuaq was published by Pulvertaft (1979). Three 1:100 000 map sheets were compiled during this period (Rosenkrantz *et al.* 1974, 1976; Pulvertaft 1987).

The first seismic lines in the Nuussuaq Basin were also acquired during this period (Sharma 1973; Elder 1975). According to the interpretations of these authors, the thickest succession of sediments is found along the north coast of Nuussuaq, where it amounts to 4 km, of which 3 km are below sea level. Along southern Nuussuaq, the total thickness of sediments was estimated to be about 3 km, of which 2 km were interpreted to occur below sea level.

Following the abandonment of the coal mine at Qullissat on the north-east coast of Disko in 1972, a major study on the coals on Nuussuaq was initiated by GGU in 1978 with support from the Danish Ministry of Commerce. The aim of the project was to produce detailed geological and technical information on the coal-bearing strata on the south coast of Nuussuaq, requisite information for a decision whether or not to invest in detailed exploration programmes (Shekhar *et al.* 1982). Three stratigraphic boreholes were drilled and a total of 828 m of core was taken. More than 12 km of outcrop section was measured and numerous coal samples were analysed. Unfortunately, the results were disappointing and did not warrant further investigation; the results were never considered in more detail and were only documented in an internal project report (Shekhar *et al.* 1982). Although the study provided a lot of new information on the coals and the sedimentary succession, this information was never synthesised.

Recent investigations

In the 1980s, petroleum geological research at GGU was focussed on North and East Greenland and only limited research was carried out in the Nuussuaq Basin, mainly by geologists from the universities of Copenhagen and Aarhus (Johannessen & Nielsen 1982; G.K. Pedersen 1989; Boyd 1990, 1992, 1993, 1994, 1998a, b, c, 2000). It was not until the start of GGU's Disko Bugt Expeditions (1988–1992; Fig. 8) that extensive studies of the Cretaceous–Tertiary sedimentary and volcanic succession of the Nuussuaq Basin were initiated together with

Fig. 8. Members of the Disko Bugt Expeditions in 1992. Studies on the sediments of the Nuussuaq Basin were carried out from a base in Uummannaq. Participants (left to right): Ib Olsen, Søren Saxtorph, Gregers Dam, Eskild Schack Pedersen, Helle H. Midtgaard, Christian J. Bjerrum, Lotte Melchior Larsen, Asger Ken Pedersen, Stig Schack Pedersen, Martin Sønderholm, Christian Schack Pedersen, Gunver Krarup Pedersen and Flemming Getreuer Christiansen.

studies on the adjacent Precambrian terrain and studies relevant for mineral exploration in the region (Kalsbeek & Christiansen 1992, and references therein).

During the first years of the Disko Bugt Expeditions, most of the research on sediments dealt with the mid-Cretaceous deltaic deposits of the Atane Formation and the synvolcanic lacustrine deposits. It was carried out mainly by the University of Copenhagen and resulted in a number of case studies on sedimentology and palynostratigraphy (see below).

The introduction of multimodel photogrammetry during this period (A.K. Pedersen & Dueholm 1992) permitted detailed mapping of individual rock units (e.g. A.K. Pedersen *et al.* 1993, 2002). This provided a framework for later correlation of the synvolcanic sediments and interpretation of their palaeogeography (e.g. A.K. Pedersen *et al.* 1996; G.K. Pedersen *et al.* 1998).

From the onset of field studies in the 1960s and the subsequent drilling of the five dry exploration wells in the mid-1970s, the lack of documented oil-prone source rocks in West Greenland had been acknowledged as the main risk in relation to oil exploration in West Greenland. In order to confront this problem, GGU initiated a re-evaluation of the hydrocarbon potential. A systematic analysis of the Nuussuaq Basin was initiated in 1990 as part of the Disko Bugt Expeditions including sedimentological, palynostratigraphical, source rock and diagenetic studies.

At the same time, GGU reassessed some of the seismic data acquired during the early 1970s offshore West Greenland, and it became evident that sedimentary basins which could contain oil and gas were much more extensive than had previously been supposed (Chalmers 1989, 1993). This was further substantiated when seismic traverses across the Labrador Sea acquired in 1977 by Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) were reprocessed and reinterpreted; from the reprocessed lines it could be seen that the continent–ocean boundary lies much farther from the Greenland coast than previously supposed, opening up the possibility that prospective sedimentary basins exist in the deeper parts of Greenland waters (Chalmers 1991; Chalmers *et al.* 1993). This resulted in government-funded acquisition of more than 6000 km of seismic data by GGU in 1990–92 and a speculative survey of nearly 2000 km in 1992, all in offshore West Greenland. In addition, more than 4000 km of seismic data in Melville Bay offshore North-West Greenland were acquired by the industry in 1992. A licensing round was announced in West Greenland in 1993, but no applications were submitted, mainly due to the lack of a documented oil-prone source rock in West Greenland.

The perception of the prospectivity of the area was significantly enhanced, however, by the discovery of bitumen in vugs in basalts near the base of the lava pile in 1992 and in a slim-core well (Marraat-1) in 1993 (Christiansen & Pulvertaft 1994; Dam & Christiansen 1994). Then, in 1994, a 13 km long reflection seismic line acquired on the southern shore of Nuussuaq revealed that the base of the sedimentary basin is at least 5 km below sea level at this locality (Christiansen *et al.* 1995). With these results, attention began to focus on the petroleum potential of the Nuussuaq Basin itself. After the original discoveries, oils and bitumen were found in surface outcrops over a wide area of western Nuussuaq and also on the north side of Disko and on the south-eastern corner of Svartenhuk Halvø (Christiansen *et al.* 1998). Inspired by the early finds, grønArctic Energy Inc., a small

Fig. 9. The GRO#3 exploration well on western Nuussuaq drilled by the Canadian company grønArctic Inc. in 1996. For location, see Fig. 65; the drilled succession is shown in Fig. 67. Photo: Kim Zinck-Jørgensen.

Canadian company, held a concession in western Nuussuaq from 1994 to 1998. During this period, the company drilled four slim-core wells (GANW#1, GANE#1, GANK#1 and GANT#1) and one conventional exploration well (GRO#3) to a depth of 2996 m (Fig. 9). The wells were drilled in areas where geological information on the sediments beneath the volcanic rocks was completely lacking, and they provided a large volume of new data that also tied the outcrop areas together. Detailed sedimentological, organic geochemical and palynostratigraphical analyses of the wells were carried out by the Survey and were published in numerous reports of the 'Danmarks og Grønlands Geologiske Undersøgelse Rapport' series in 1996–97. Many of the results have later been incorporated into and summarised in other publications.

The positive results from the years 1990–1994 encouraged the Government of Greenland and the Danish State to provide further funding for studies to overcome the disappointing outcome of the 1992 licensing round. More field work was carried out on Disko, Nuussuaq and Svartenhuk Halvø in the period between 1994 and 2002. During the summer of 1995, the Survey acquired more than 3700 km of seismic and gravity data, mainly in the fjords and sounds around Disko and Nuussuaq (Christiansen *et al.* 1996a), and a 1200 m deep stratigraphic slim-core hole (Umiivik-1) was drilled on Svartenhuk Halvø in 1995 (Bate & Christiansen 1996). Additional information was obtained using seismic and magnetic data from the 1970s combined with an aeromagnetic survey flown over the area in 1997 (Rasmussen *et al.* 2001). The most important results from these studies include:

1) Interpretation of seismic and magnetic data, forward modelling of gravity profiles and a reappraisal of all available data on faults in the onshore areas (Chalmers *et al.* 1999).
2) Documentation of several oil types in surface oil seeps and wells and several possible source rock intervals and their possible correlation with Cenomanian–Turonian oils from the Central Western Interior Seaway in North America, or to Upper Jurassic-sourced oils from the Jeanne d'Arc Basin offshore Newfoundland and in the North Sea (Bojesen-Koefoed *et al.* 1999, 2004, 2007; Christiansen *et al.* 2002).
3) Documentation of wet gas in the Umiivik-1 well (Fig. 73), suggesting the presence of a good, but overmature, Turonian source rock for condensate or oil (Dam *et al.* 1998b).
4) Establishment of a new biostratigraphic scheme for the Cretaceous and Paleocene onshore and offshore deposits (Nøhr-Hansen 1996; Nøhr-Hansen *et al.* 2002; Sønderholm *et al.* 2003).
5) Documentation of promising reservoir intervals in the turbidite succession and a quantitative log-interpretation of the upper part of the GRO#3 well (which was not tested prior to casing), suggesting high hydrocarbon saturations in sandstone units (Kristensen & Dam 1997; Dam *et al.* 1998d; Kierkegaard 1998).
6) Completion of the geological mapping of eastern Disko and south-east Nuussuaq (A.K. Pedersen *et al.* 2000, 2001, 2007a, b). Extensive photogrammetrical work forms the basis of five geological profiles through the Nuussuaq Basin (1:20 000). These profiles document the sediments of the Nuussuaq Group and the overlying West Greenland Basalt Group, including the relationships between the early volcanic rocks and the synvolcanic sediments (A.K. Pedersen *et al.* 1993, 2002, 2003, 2005, 2006a, b).

The onshore studies carried out since 1988 have resulted in numerous publications, as summarised below:

Biostratigraphy and palaeontology:
Boyd (1990, 1992, 1993, 1994, 1998a, b, c, 2000), Hjortkjær (1991), Piasecki *et al*. (1992), Koppelhus & Pedersen (1993), Nøhr-Hansen (1993, 1996, 1997a, b, c), Nøhr-Hansen & Dam (1997), Dam *et al*. (1998b, c), Kennedy *et al*. (1999), Lanstorp (1999), Nøhr-Hansen & Sheldon (2000), Nøhr-Hansen *et al*. (2002), Sønderholm *et al*. (2003), G.K. Pedersen & Bromley (2006).

Diagenesis:
Preuss (1996), Stilling (1996), Kierkegaard (1998).

Organic geochemistry:
Christiansen *et al*. (1996b, 1998, 1999, 2000), Bojesen-Koefoed *et al*. (1997, 1999, 2001, 2004, 2007), Nytoft *et al*. (2000), G.K. Pedersen *et al*. (2006).

Sedimentology:
G.K. Pedersen & Jeppesen (1988), G.K. Pedersen (1989), Pulvertaft (1989a, b), Midtgaard (1991), Olsen (1991), Olsen & Pedersen (1991), G.K. Pedersen & Pulvertaft (1992), Dueholm & Olsen (1993), Olsen (1993), Dam & Sønderholm (1994), A.K. Pedersen *et al*. (1996), Midtgaard (1996a, b), Dam & Sønderholm (1998), G.K. Pedersen *et al*. (1998), Dam *et al*. (1998a, 2000), Jensen (2000), Dam & Nøhr-Hansen (2001), Dam (2002), Nielsen (2003).

Structural geology:
Chalmers *et al*. (1999), J.G. Larsen & Pulvertaft (2000), Chalmers & Pulvertaft (2001), Marcussen *et al*. (2002), Bonow (2005), Japsen *et al*. (2005, 2006, 2009), Wilson *et al*. (2006), Bonow *et al*. (2006a, b, 2007).

Well descriptions:
Dam & Christiansen (1994), Christiansen *et al*. (1994a, 1996c, 1997), Bate & Christiansen (1996), Dam (1996a, b, c, 1997), Dahl *et al*. (1997), Kristensen & Dam (1997), Nøhr-Hansen (1997a, b, c), Kierkegaard (1998), Ambirk (2000), Madsen (2000).

Geological setting

As a result of the opening of the Labrador Sea in Late Mesozoic to Early Cenozoic times, a complex of linked rift basins stretching from the Labrador Sea to northern Baffin Bay developed along West Greenland (Fig. 1; Chalmers & Pulvertaft 2001).

Two main episodes of regional rifting and basin development during this time have been documented in the area: an episode of Early Cretaceous rifting, and a Late Cretaceous – Early Paleocene rift episode prior to the start of sea-floor spreading in mid-Paleocene time (Dam & Sønderholm 1998; Dam *et al.* 2000; Chalmers & Pulvertaft 2001; Dam 2002; Sørensen 2006).

The most extensive outcrops of Mesozoic–Palaeogene rocks in the entire Labrador Sea – Davis Strait – Baffin Bay region are those of the Nuussuaq Basin in the Disko – Nuussuaq – Svartenhuk Halvø area in central West Greenland. This basin may be a southern extension of the basin complex in the Melville Bay region (Fig. 1; Whittaker *et al.* 1997); the offshore area between 68° and 73°N is, however, covered by Palaeogene basalts and little is therefore known about the deeper-lying successions in this region. A small outcrop is known from Cape Dyer, eastern Baffin Island (Burden & Langille 1990) and outcrops of Cretaceous–Palaeogene sediments are also seen farther north in Arctic Canada on Bylot Island (Miall *et al.* 1980; Miall 1986; Harrison *et al.* 1999) and on Ellesmere Island (Núñez-Betelu 1994, Núñez-Betelu *et al.* 1994a, b; Harrison *et al.* 1999).

During the Early Paleocene (Danian), the area offshore southern West Greenland was subjected to major uplift and erosion (Bonow *et al.* 2007). Sedimentation resumed in the Late Danian contemporaneously with the major episode of Paleocene volcanism in the Disko–Nuussuaq area and continued into the Holocene with a major hiatus spanning the Oligocene in the north and the mid-Eocene to mid-Miocene in the south (Dalhoff *et al.* 2003).

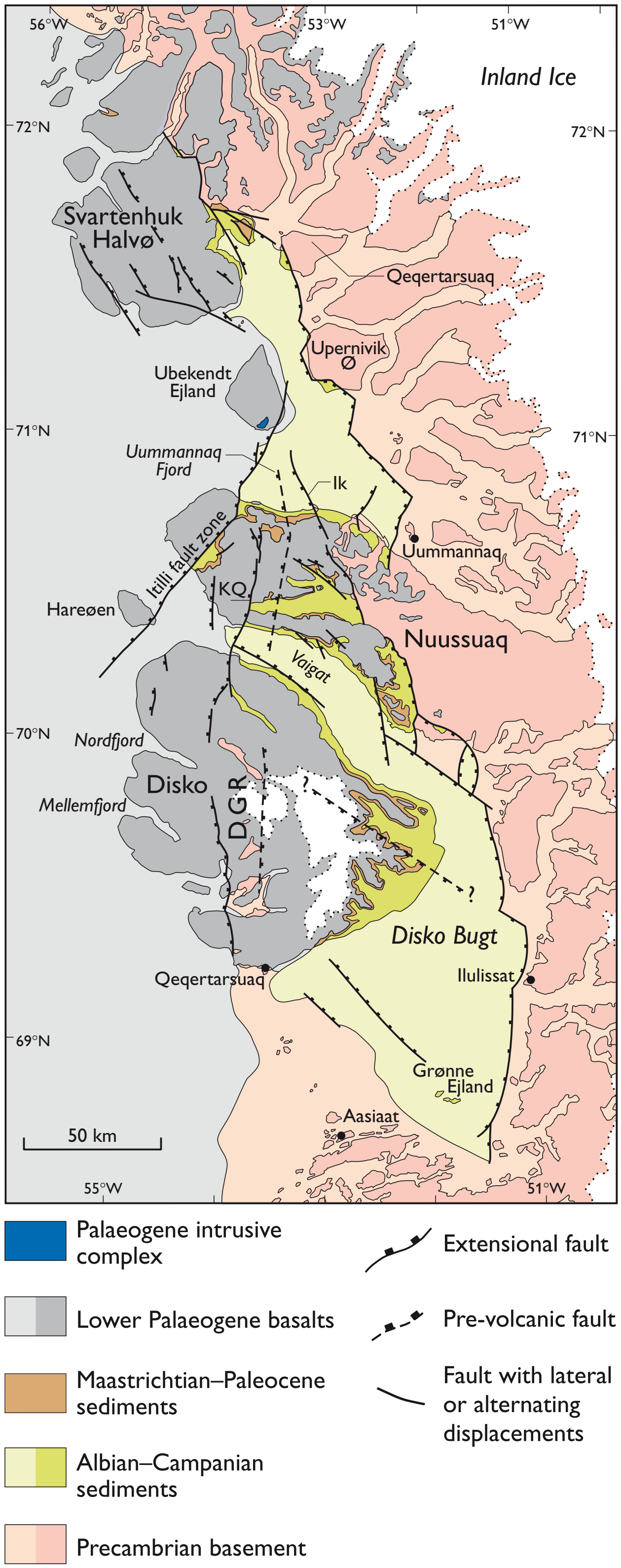
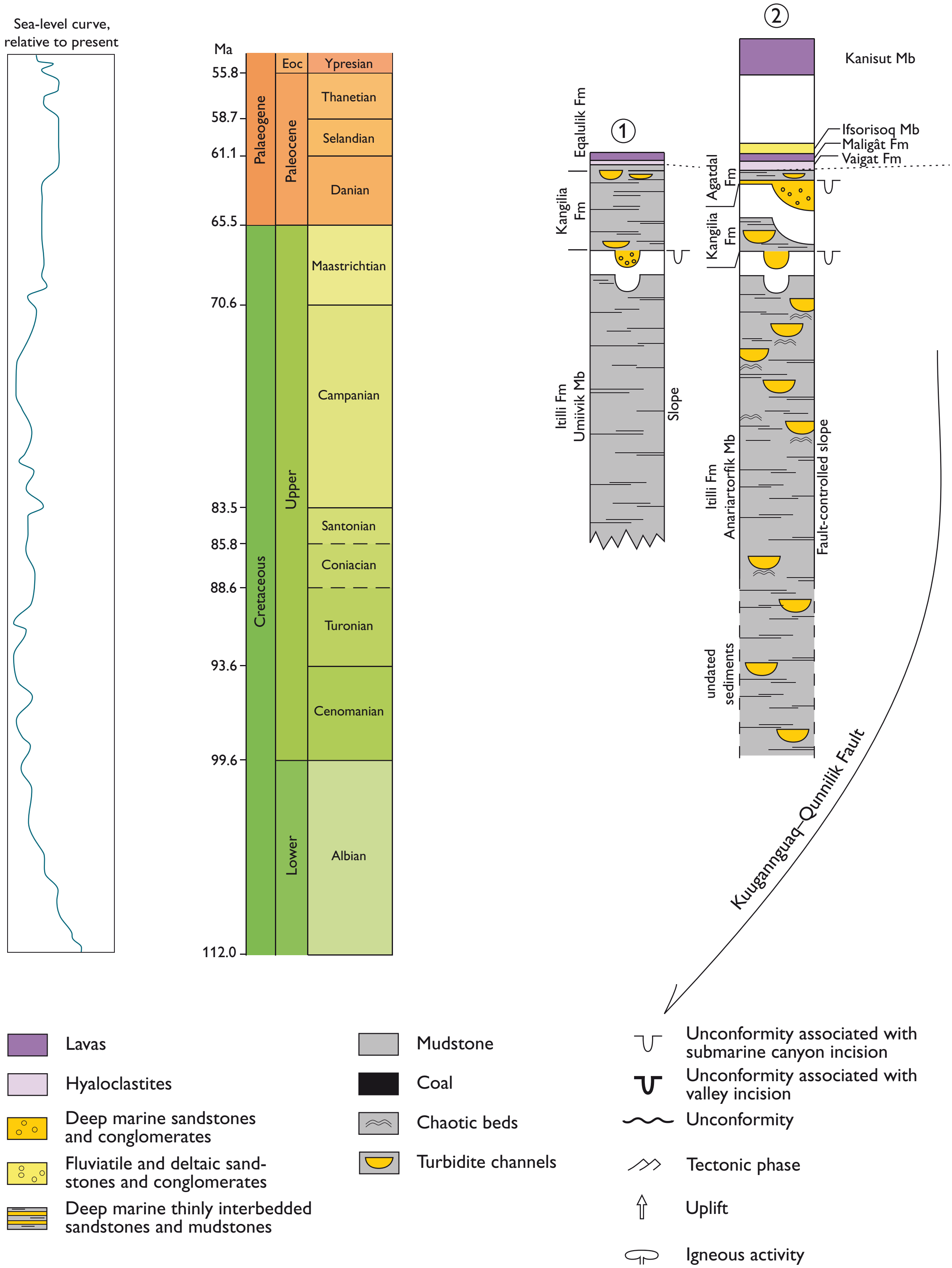


Fig. 10. Simplified geological map of the Nuussuaq Basin (after Chalmers *et al.* 1999). **Ik**, Ikorfat fault zone; **KQ**, Kuugannguaq–Qunnilik Fault; **DGR**, Disko Gneiss Ridge. The offshore geology is indicated by paler shades.



Sea-level curve, relative to present
Ma
55.8
58.7
61.1
65.5
70.6
83.5
85.8
88.6
93.6
99.6
112.0
Palaeogene
Cretaceous
Eoc
Paleocene
Upper
Lower
Ypresian
Thanetian
Selandian
Danian
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
1
2
Eqalulik Fm
Kangilia Fm
Itilli Fm
Umiivik Mb
Slope
Kanisut Mb
Ifsorisoq Mb
Maligât Fm
Vaigat Fm
Agatdal Fm
Kangilia Fm
Itilli Fm
Anariartorfik Mb
Fault-controlled slope
undated sediments
Kuugannguaq–Qunnilik Fault
Lavas
Hyaloclastites
Deep marine sandstones and conglomerates
Fluviatile and deltaic sandstones and conglomerates
Deep marine thinly interbedded sandstones and mudstones
Mudstone
Coal
Chaotic beds
Turbidite channels
Unconformity associated with submarine canyon incision
Unconformity associated with valley incision
Unconformity
Tectonic phase
Uplift
Igneous activity

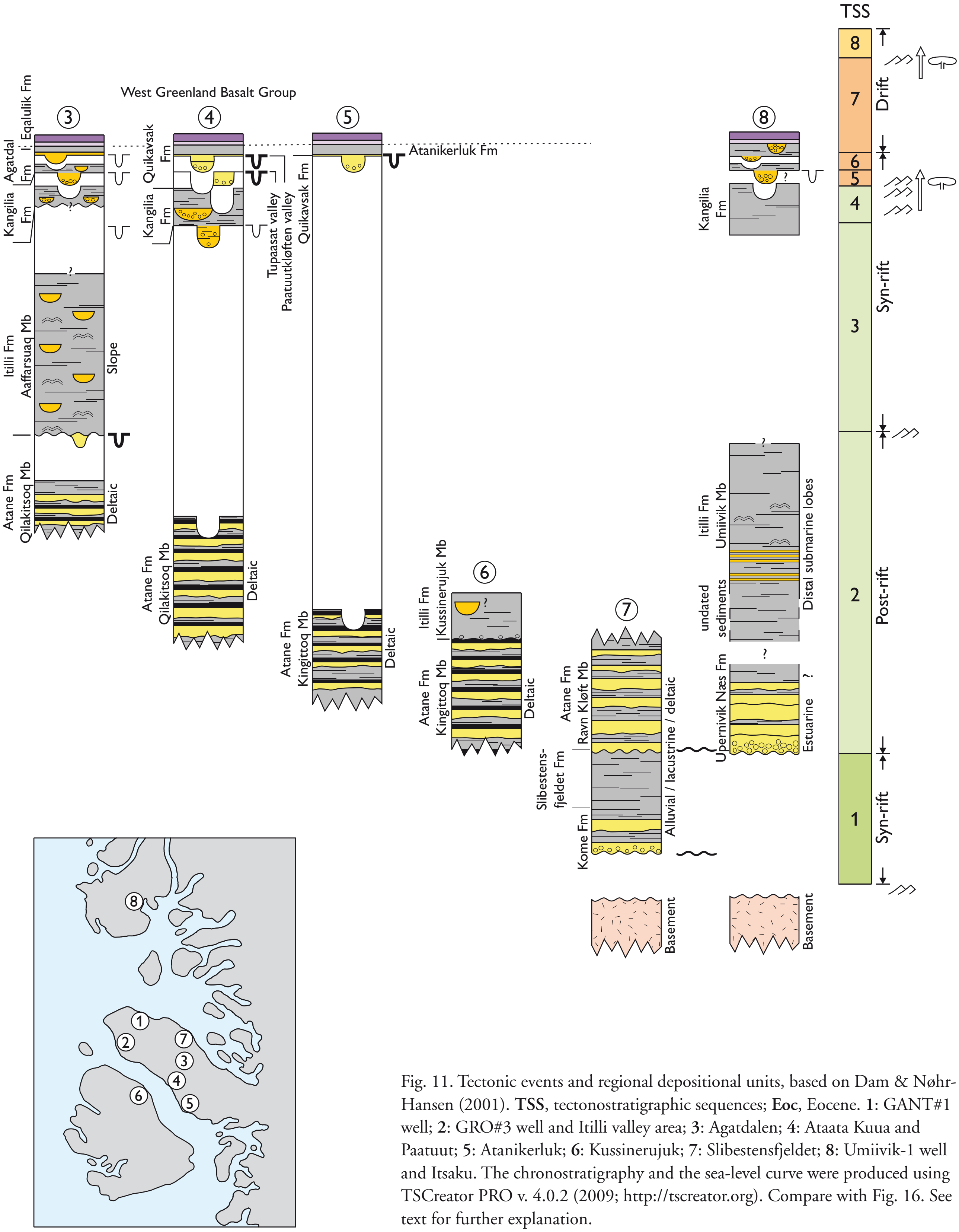


Fig. 11. Tectonic events and regional depositional units, based on Dam & Nøhr-Hansen (2001). **TSS**, tectonostratigraphic sequences; **Eoc**, Eocene. **1**: GANT#1 well; **2**: GRO#3 well and Itilli valley area; **3**: Agatdalen; **4**: Ataata Kuua and Paatuut; **5**: Atanikerluk; **6**: Kussinerujuk; 7: Slibestensfjeldet; **8**: Umiivik-1 well and Itsaku. The chronostratigraphy and the sea-level curve were produced using TSCreator PRO v. 4.0.2 (2009; http://tscreator.org). Compare with Fig. 16. See text for further explanation.

The Cretaceous–Paleocene sedimentary succession of the Nuussuaq Basin onshore West Greenland is best known from eastern Disko and Nuussuaq, with minor, and less well-known, outcrops in the northern part of the region on Upernivik Ø, Qeqertarsuaq and Svartenhuk Halvø (Fig. 10). Seismic and other geophysical data indicate that the Mesozoic succession is at least 6 km and possibly up to 10 km thick in the western part of the basin (Christiansen *et al.* 1995; Chalmers *et al.* 1999; Marcussen *et al.* 2002). The eastern part appears to have much shallower depths to basement (Chalmers *et al.* 1999), and this part of the basin could represent thermal subsidence following the initial rifting episode (Chalmers *et al.* 1999).

The outcrops record a complex history of rifting, subsidence and uplift commencing with an earliest Cretaceous (or earlier) rift episode followed by a phase of thermal subsidence during the Cenomanian – Early Campanian (Fig. 11). Rifting resumed in the Early Campanian and increased in the Maastrichtian – Early Paleocene (Dam & Sønderholm 1998; Dam *et al.* 2000; Dam 2002), culminating during the Early Paleocene. The first phase of these later rift episodes was characterised by large-scale normal faulting, whereas the later episodes were associated with continued extension and regional uplift (Dam & Sønderholm 1998; Dam *et al.* 1998a, 2000; Chalmers *et al.* 1999). The late phases were accompanied by widespread igneous activity and extrusion of a thick succession of flood basalts (Fig. 12; A.K. Pedersen *et al.* 2006a, and references therein).

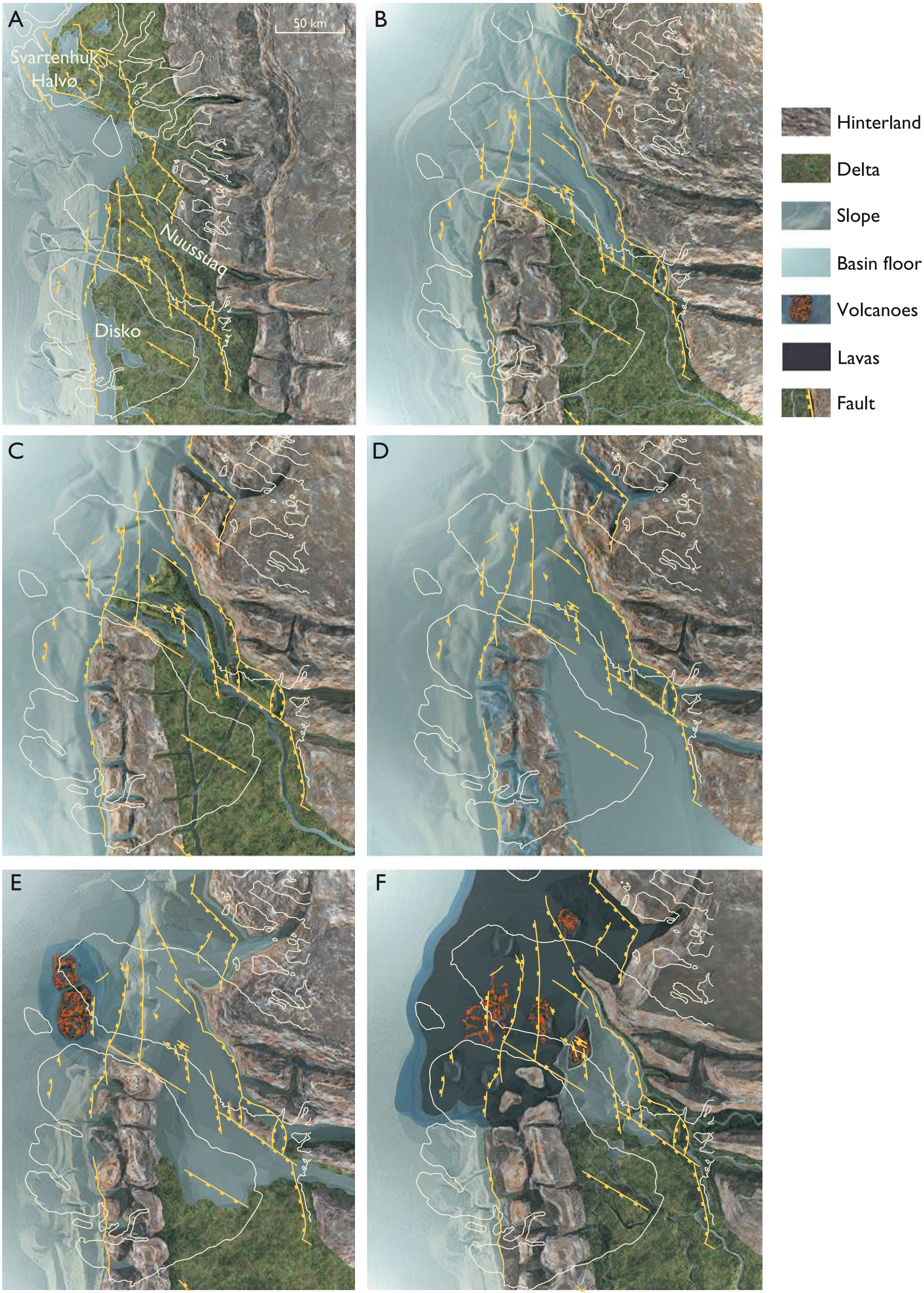
The exposed part of the succession in the Nuussuaq Basin can be divided into eight tectonostratigraphic sequences (TSS; Fig. 11); the early rift episode includes two sequences and the late episode six sequences. These sequences are mainly related to tectonic events marking discrete basin-fill phases (Dam & Nøhr-Hansen 2001).

TSS 1. The oldest sediments exposed in the Disko–Nuussuaq Basin represent a syn-rift episode of ?Aptian–Albian age represented by the Kome and Slibestensfjeldet Formations (Fig. 11). This rift episode is dominated by N–S extensional faults which, however, were also reactivated during later stages (L.M. Larsen & Pedersen 1990; Chalmers *et al.* 1999). The N–S trend is expressed particularly by the Disko Gneiss Ridge and this trend can be followed on western Nuussuaq in the Kuugannguaq–Qunnilik Fault (Figs 10, 12). The eastern boundary fault system has an overall NNW–SSE trend but is segmented with individual segments trending N–S or NW–SE (Fig. 10; Rosenkrantz & Pulvertaft 1969; Chalmers *et al.* 1999). The Kome Formation reflects an environment dominated by fluvial plains and local fan deltas amid basement highs. The Kome Formation is overlain locally by lacustrine deposits of the Slibestensfjeldet Formation.

TSS 2. Following the early rifting episode there was a long period of thermal subsidence that spanned the late Albian/Cenomanian – Turonian – earliest Campanian. It was initiated by a major flooding surface represented by offshore and deep marine deposits of the Itilli Formation to the north and west and by fluvio-deltaic and shallow marine deposits of the Atane and Upernivik Næs Formations to the east and south. The delta fanned out to the west and north-west from a point east of Disko (Figs 11, 12A; G.K. Pedersen & Pulvertaft 1992). On Nuussuaq, the transition from shallow marine and fluvio-deltaic deposition in the eastern part of the basin into deep marine deposition farther west was controlled by the N–S-trending Kuugannguaq–Qunnilik Fault that crosses Disko and Nuussuaq (Figs 10, 11, 12A). On Svartenhuk Halvø contemporaneous deep-water deposition in a slope setting is recorded by a thick distal turbidite succession assigned to the Itilli Formation (Dam 1997). This unit includes marine anoxic shales of presumed Cenomanian–Turonian age, that are possibly the source for the marine Itilli oil type (Dam *et al.* 1998b; Bojesen-Koefoed *et al.* 1999).

TSS 3. In earliest Campanian time a new tectonic episode was initiated that lasted from the Early Campanian to the Paleocene (Dam *et al.* 2000). The early phase of this rifting episode (TSS 3) is represented by the Aaffarsuaq Member of the Itilli Formation and lasted into the Maastrichtian. This phase is characterised by normal faulting, subsidence and syn-rift sedimentation. It resulted in the development of an angular unconformity, and deltaic deposition gave way to catastrophic deposition in a footwall fan setting along N–S-trending normal faults. In the eastern part of the region, uplift resulted in significant erosion of previously deposited Atane Formation deposits, and it is therefore expected that turbidite sandstone bodies of regional extent are present in the deep-water facies in the offshore basins to the west.

Facing page:
Fig. 12. Palaeogeographic reconstructions of the Nuussuaq Basin during **A**: the Cenomanian/Turonian – earliest Campanian (TSS 2); **B**: the latest Maastrichtian (TSS 4); **C**: the Danian (TSS 5); **D**: the earliest Selandian; **E**: early Selandian volcanism, and **F**: early Selandian dammed lake phase. See text for further explanation.



A
B
C
D
E
F
50 km
Svartenhuk
Halvø
Nuussuaq
Disko
Hinterland
Delta
Slope
Basin floor
Volcanoes
Lavas
Fault

TSS 4–6. In late Maastrichtian – early Paleocene times, the stress system in the region changed and extension took place along NW–SE- and N–S-trending faults. These form the present eastern limit of the basin and displaced and rotated the major N–S-trending blocks in the basin (e.g. Chalmers *et al.* 1999). This trend is identical to several shear zones in the Precambrian basement east of Disko Bugt, suggesting that these shear zones exerted an influence on later faulting and the trend of a possible major transfer fault situated in the Vaigat area (Dam 2002, Wilson *et al.* 2006). Major faulting also occurred along the NW–SE-trending faults and the rift blocks show evidence of major erosion before being covered by upper Maastrichtian – lower Paleocene marine sediments and middle Paleocene volcanic rocks (e.g. Dam & Sønderholm 1998; Dam *et al.* 1998a). Birkelund (1965), Rosenkrantz & Pulvertaft (1969), J.M. Hansen (1980b) and Nøhr-Hansen (1996) noted that the Cretaceous faunas and floras in the Nuussuaq Basin are similar to those of the North American Interior Seaway while there is an overwhelming European affinity in the Danian, suggesting that an important change in palaeogeography and palaeoceanography took place during the latest Cretaceous and earliest Paleocene (Rosenkrantz & Pulvertaft 1969; J.M. Hansen 1980b; Nøhr-Hansen & Dam 1997).

Three major tectonic episodes have been recognised in the latest Maastrichtian – earliest Paleocene, each associated with incision of valley systems and development of submarine canyons. The first of these episodes *(TSS 4)* is of latest Maastrichtian age and is represented by the Kangilia Formation in which two major SE–NW-trending submarine canyons have been documented from outcrops (Figs 11, 12B). The second, earliest Paleocene episode *(TSS 5)* is represented by the Tupaasat and Nuuk Qiterleq Members of the Quikavsak Formation. It was associated with major uplift of the basin and fluvial valley incision into Early Paleocene fault scarps and was characterised by catastrophic deposition (Figs 11, 12C). The third episode *(TSS 6)* was associated with renewed uplift during the Early Paleocene, and valleys were incised into the old valley system (Paatuutkløften Member of the Quikavsak Formation). Crossing the Kuugannguaq–Qunnilik Fault, the incised fluvial valleys pass westwards into a major submarine canyon system. The sand-dominated fill of this canyon system is referred to the marine Agatdal Formation, named after equivalent valley-fill sediments in central Nuussuaq. This episode was followed by very rapid subsidence. The incised valleys were eventually filled with transgressive estuarine and shoreface deposits before they were blanketed by offshore tuffaceous mudstones referred to the Eqalulik Formation (Figs 11, 12D) immediately prior to extrusion of picritic hyaloclastite breccias of the Vaigat Formation (Figs 11, 12E). The recurrent episodes of uplift and incision of submarine canyons and valleys in Atane Formation deposits in the eastern outcrop area resulted in major redistribution of sandstones into the deep-water environments to the west, and major turbidite sandstone bodies are thus suspected to be regionally present.

TSS 7. Extrusion of the volcanic succession can be divided into two phases and is related to continental break-up in the Labrador Sea region (A.K. Pedersen *et al.* 2006a, and references therein). The first phase, of Selandian to Thanetian (late Paleocene) age, was dominated by extrusion of olivine-rich basalts and picrites (Figs 11, 12E) and later by more evolved, plagioclase-phyric basalts (Vaigat and Maligât Formations of the West Greenland Basalt Group). The first volcanism recorded in the Nuussuaq Basin took place in a marine environment and eruption centres were located in the westernmost part of the basin (Fig. 12E). Thick hyaloclastite fans of the Anaanaa and Naujánguit Members prograded towards the east (Figs 12F, 16). As the volcanic front moved eastwards, large lakes were formed between the volcanic front to the west and the cratonic crystalline basement to the east (Fig. 12F), giving rise to synvolcanic lacustrine deposits (Atanikerluk Formation).

TSS 8. During the Eocene, magmatic activity in the Nuussuaq Basin resumed with an episode of intrusion of dyke swarms and extrusion of basalts and sparse comendite tuffs of the Kanísut Member. The volcanic succession was dissected by N–S-trending faults and a new NE–SW fault trend (the Itilli fault zone; Figs 10, 11). The tectonic activity probably waned during Late Palaeogene time, and during the Neogene the area was lifted by 1–2 km to its present elevation (Chalmers 2000; Bonow *et al.* 2007, and references therein; Japsen *et al.* 2009).

Nuussuaq Group

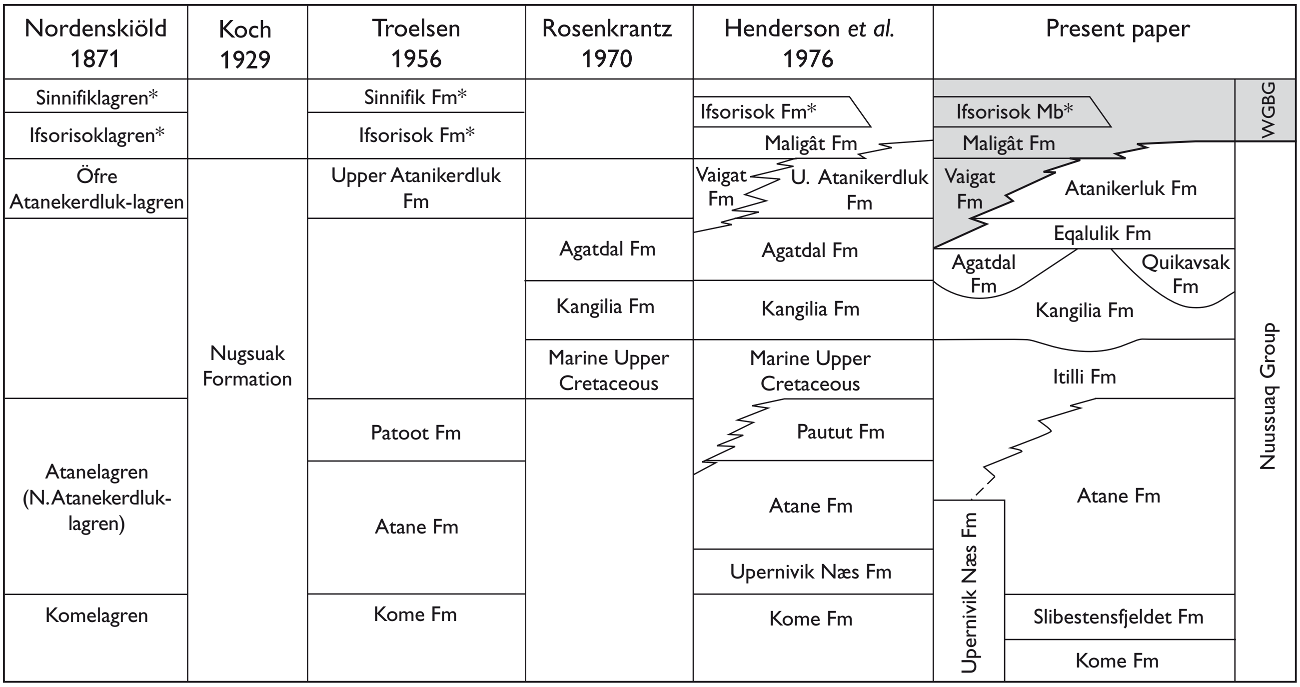
new group

History. The Nuussuaq Group comprises the pre- and synvolcanic Cretaceous–Paleocene sediments on a number of islands and peninsulas in West Greenland between 69° and 72°N (Fig. 10). Intrabasaltic sediments are not included in the Nuussuaq Group but in the overlying West Greenland Basalt Group, with the local exception of thin, intra-volcanic wedges of sediment that demonstrably interdigitate with prograding hyaloclastite breccias and lavas of the lowermost West Greenland Basalt Group. Initial investigations of the geology date back to K.L. Giesecke, who described the area in detail around 1810 (in: Steenstrup 1910), Rink (1853, 1857) and Nordenskiöld (1871); the latter erected three lithostratigraphic units for the pre-volcanic sediment, separate from the intra-basaltic Ifsorisok Beds (Fig. 13; see section on 'Previous work' above). However, these units were not recognised by L. Koch (1929) in his exhaustive account of the stratigraphy of Greenland. He referred all the sediments to one formation – the Nugsuak Formation – but also predicted that "future investigations will doubtlessly result in a division of the beds which I have included in one formation, into several formations" (L. Koch 1929 p. 258).

A more detailed lithostratigraphical scheme was developed as a result of the work during the Nûgssuaq Expeditions 1938–1968 (see section on 'Previous work' above; Rosenkrantz 1970). This was, however, rather incomplete and included units, especially at member level, that were not formally described (Fig. 13).

Name. After the Nuussuaq peninsula, where the most extensive outcrops occur (Fig. 10).

Type area. The south coast of Nuussuaq, where the most complete and best exposed sections of the Nuussuaq Group occur, e.g. at Atanikerluk, the coastal slopes at Paatuut, along the western slope of the Ataata Kuua river, and in river gorges in the southern part of the Itilli val-



* Intrabasaltic sediments

Fig. 13. Comparison of former lithostratigraphical subdivisions and the scheme used in this paper. All pre-volcanic and the earliest synvolcanic sedimentary rocks of the Nuussuaq Basin constitute the Nuussuaq Group (new), which comprises 10 formations (new or revised). **WGBG**, West Greenland Basalt Group.

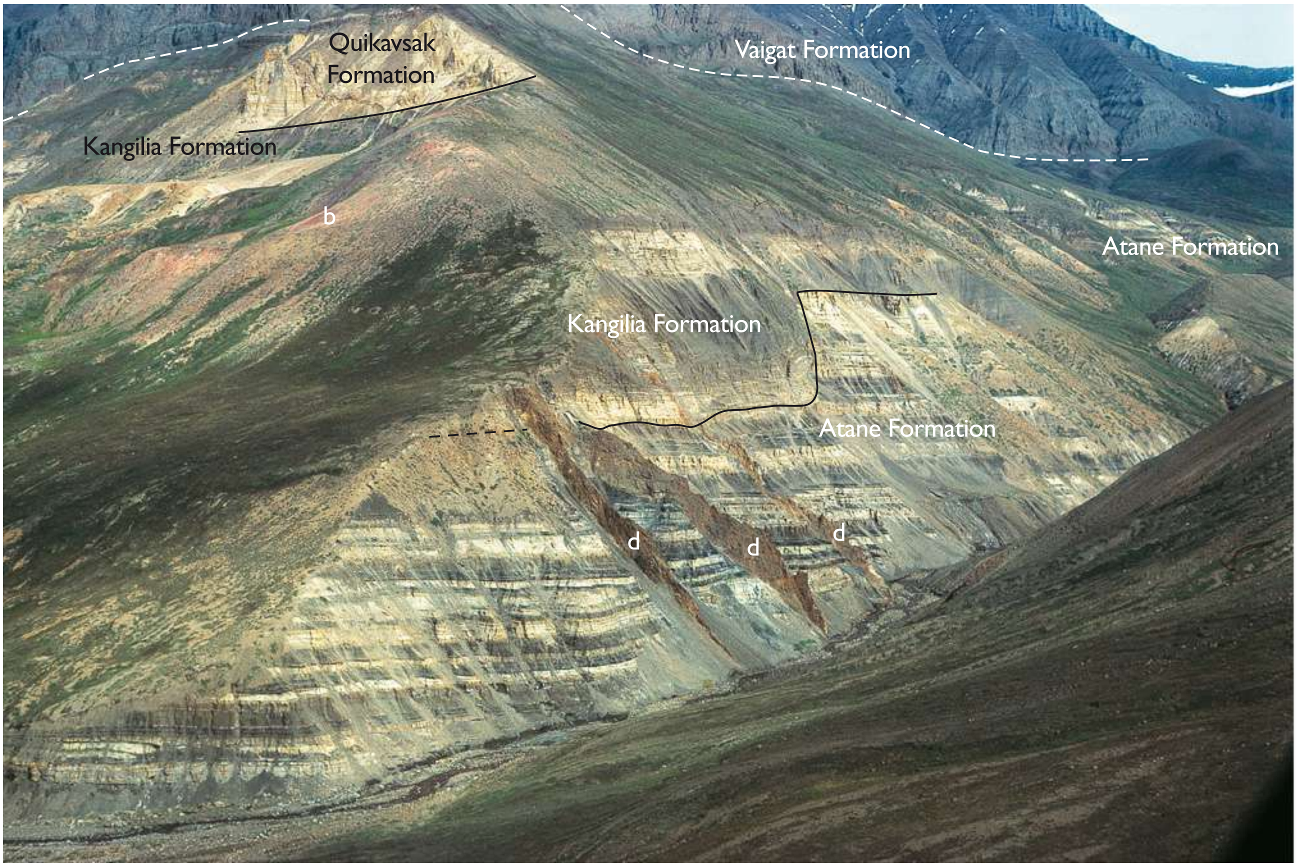


Fig. 14. The western side of the Ataata Kuua river gorge, in the type area of the Nuussuaq Group; **d**, dolerite dyke, **b**, burnt mudstones. For location, see Fig. 40; for scale, see Fig. 15.

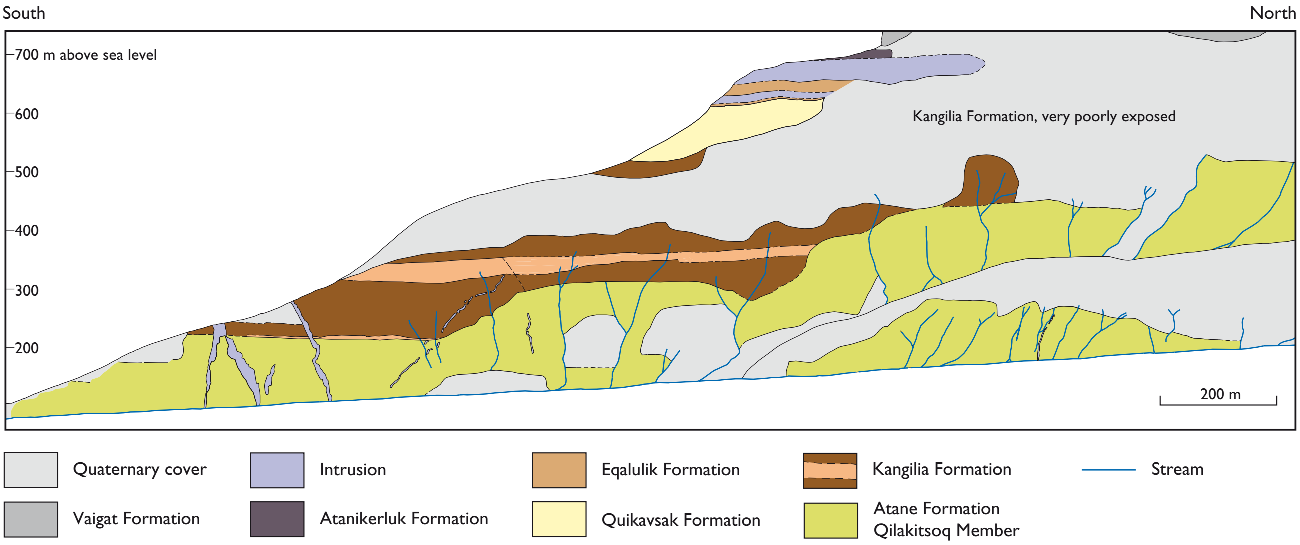


Fig. 15. The western side of Ataata Kuua, in the type area of the Nuussuaq Group, illustrates two phases of incision. The marine mudstone and turbidite sandstones of the Kangilia Formation represent a late Maastrichtian submarine canyon incised into the Santonian deltaic Atane Formation; mudstones of the Kangilia Formation are shown in brown, sandstones and conglomerates in beige. The Danian Quikavsak Formation represents a fluvial system incised into the Kangilia Formation. Photogrammetrically measured section, from A.K. Pedersen *et al.* (2007b). Borehole GGU 247801 is located *c.* 600 m north of the outcrop shown here (Figs 40, 43).

ley (Figs 2, 40, 65). The section along the west slope of Ataata Kuua has been measured photogrammetrically (Figs 14, 15; A.K. Pedersen *et al.* 2007b).

Distribution. The Nuussuaq Group outcrops in West Greenland between 69° and 72°N on Disko, Nuussuaq, Upernivik Ø, Qeqertarsuaq, Itsaku and Svartenhuk Halvø and has also been recorded in a number of shallow and deep wells in the region (Figs 2, 16, 17). Possible Palaeogene sediments have previously been reported on Angiissat, the south-easternmost island of a group of small islands in Disko Bugt named Grønne Ejland (Henderson *et al.* 1976 p. 345).

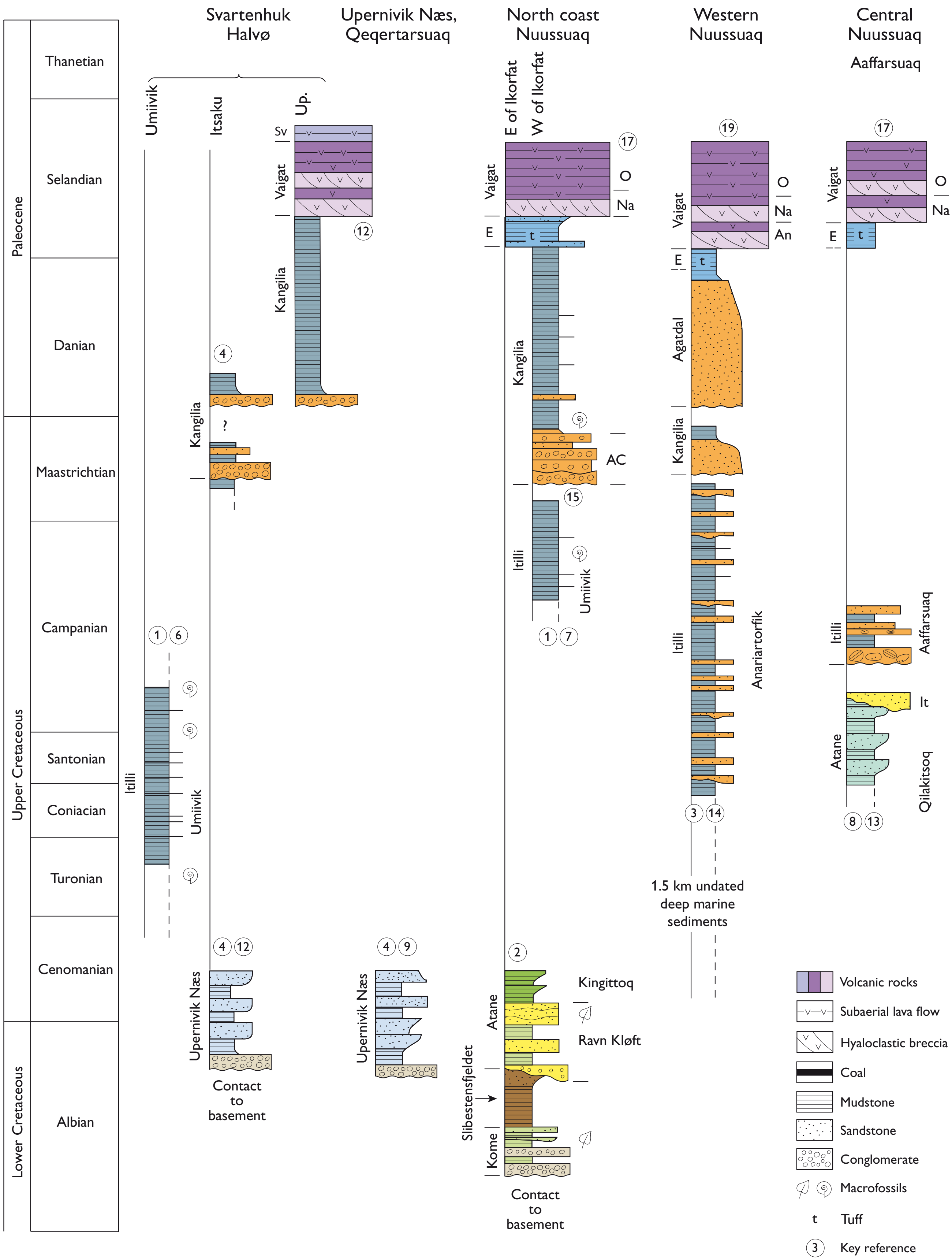
Differentiation of the Albian–Cenomanian Kome, Upernivik Næs and Atane Formations that form the lower part of the group can be difficult because these formations all include marginal marine deposits that are dominated by sandstones and have some sedimentary facies in common. For practical purposes, the Kome Formation is restricted to areas in northern Nuussuaq, east of Ikorfat, where alluvial sediments are in contact with basement. The Upernivik Næs Formation, which occurs north of Nuussuaq, comprises marginal marine sediments, while the fluviodeltaic Atane Formation is restricted to the Disko–Nuussuaq area.

Thickness. Composite sections of outcrops and wells show thicknesses of up to *c.* 3 km for the Nuussuaq Group (Fig. 17). In the western part of the area, seismic and magnetic data suggest that the Mesozoic sediments are at least 6 km and possibly as much as 10 km thick (Christiansen *et al.* 1995; Chalmers *et al.* 1999). A seismic section across the Vaigat indicates that the non-marine Cretaceous section is at least 2500–3000 m thick (Fig. 44; Marcussen *et al.* 2002).

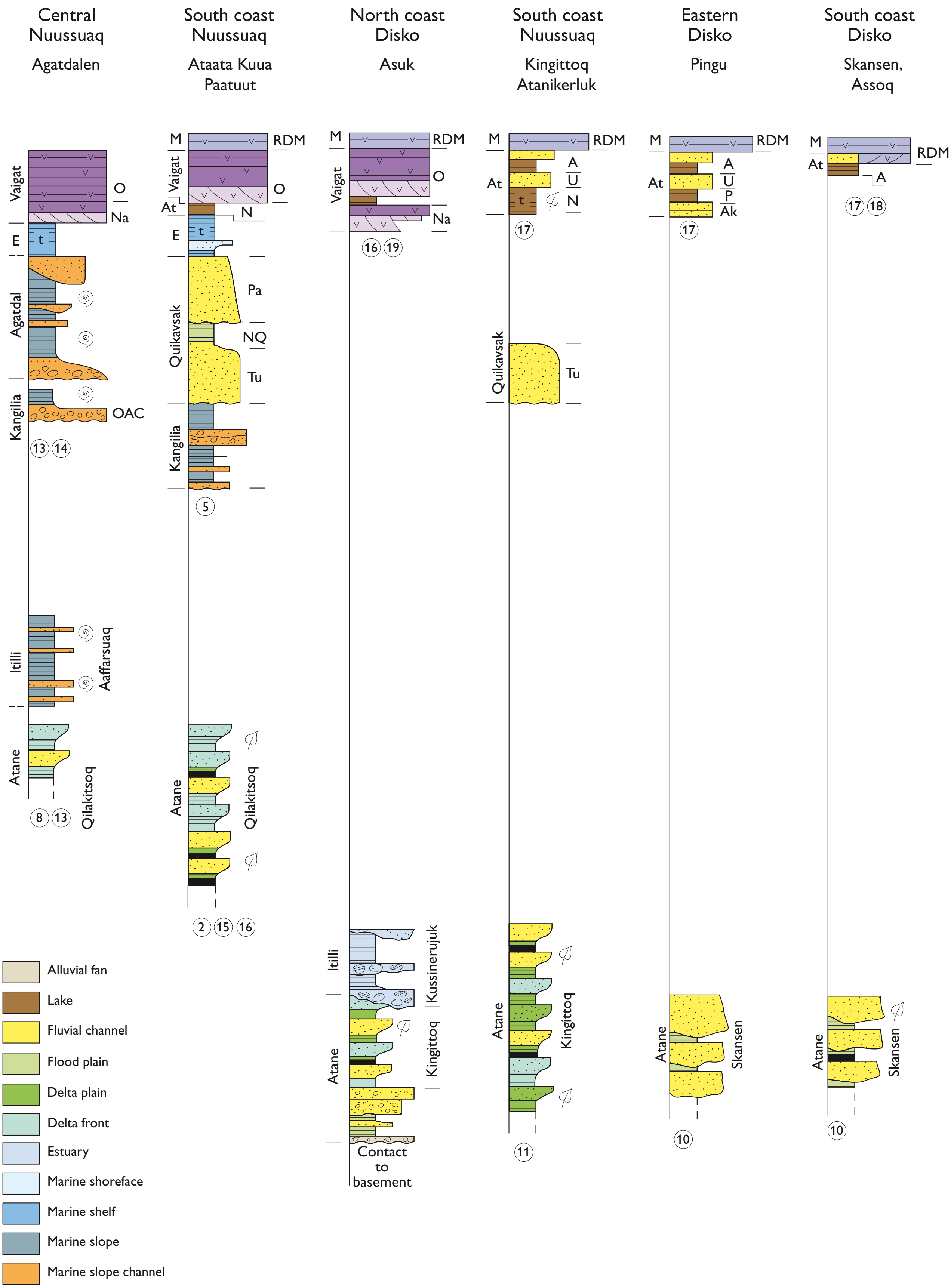
Lithology and depositional environment. The exposed part of the Nuussuaq Group consists entirely of siliciclastic sediments (Figs 16, 17). A reconnaissance study of the petrology of the Cretaceous and Paleocene sandstones revealed varying feldspar contents and three types of cement: carbonates, silica and Fe-hydroxides. Based on differences in texture, Schiener (1975) suggested two provenance areas: the Archaean crystalline basement rocks (angular feldspar grains) and older sedimentary rocks that have been recycled (well-rounded quartz grains). Detrital zircon dating of the sediments indicates that most of the Cretaceous sediments were transported from areas with Archaean basement, whereas the Late Cretaceous and Paleocene sediments at Itsaku on Svartenhuk Halvø contain Proterozoic zircons, probably derived from the Prøven Igneous Complex (Scherstén & Sønderholm 2007). The basal Lower Cretaceous part of the succession includes coarse-grained, syn-rift breccias and conglomerates that onlap basement highs and are overlain by sandstones, heteroliths and mudstones of non-marine, mostly alluvial origin (Fig. 16). Slightly younger braided river sandstones interbedded with sandstones, heteroliths and mudstones deposited in tidal estuarine and coastal plain environments crop out on Upernivik Ø and Qeqertarsuaq and are referred to the Upernivik Næs Formation.

On northern Nuussuaq, the Kome Formation is overlain by lacustrine mudstones and sandstones of the Slibestensfjeldet Formation. The Atane Formation unconformably overlies the Slibestensfjeldet Formation and possibly also the Kome Formation. The Atane Formation is dominated by coarsening-upward successions of mudstones and sandstones deposited in a deltaic and fluvial environment during the Albian to Santonian. Across the Kuugannguaq–Qunnilik Fault (Fig. 10), the deltaic sed-

Next pages 32-33:
Fig. 16. Stratigraphy and depositional settings of the formations and members of the Nuussuaq Group. The sections are located in Fig. 2 or in the detailed maps located in Fig. 2. **Up**., Uparuaqqusuitsut (Svartenhuk Halvø). Formations are shown on the left hand side of the logs and members on the right hand side. The vertical axis of the diagram indicates the approximate age of the lithostratigraphical units (data on ages are found in the selected numbered references below). Compare with Fig. 17.
Stratigraphic abbreviations: **A**, Assoq Member (Atanikerluk Formation); **Ak**, Akunneq Member (Atanikerluk Formation); **An**, Anaanaa Member (Vaigat Formation); **At**, Atanikerluk Formation; **AC**, Annertuneq Conglomerate Member (Kangilia Formation); **E**, Eqalulik Formation; **It**, Itivnera Bed (Atane Formation); **M**, Maligât Formation; **N**, Naujât Member (Atanikerluk Formation); **Na**, Naujánguit Member (Vaigat Formation); **NQ**, Nuuk Qiterleq Member (Quivaksak Formation); **O**, Ordlingassoq Member (Vaigat Formation); **OAC**, Oyster–Ammonite Conglomerate Bed (Kangilia Formation); **P**, Pingu Member (Atanikerluk Formation); **Pa**, Paatuutkløften Member (Quikavsak Formation); **RDM**, Rinks Dal Member (Maligât Formation); **Sv**, Svartenhuk Formation; **Tu**, Tupaasat Member (Quikavsak Formation); **U**, Umiussat Member (Atanikerluk Formation).
References: **1**, Birkelund (1965); **2**, Boyd (1998 a); **3**, Christiansen *et al.* (1999); 4, Christiansen *et al.* (2000); **5**, Dam & Nøhr-Hansen (2001); **6**, Dam *et al.* (1998b); 7, Dam *et al.* (1998c); 8, Dam *et al.* (2000); **9**, Koch (1964); **10**, Koppelhus & Pedersen (1993); **11**, Lanstorp (1999); **12**, J.G. Larsen & Pulvertaft (2000); **13**, Nøhr-Hansen (1996); **14**, Nøhr-Hansen *et al.* (2002); **15**, Olsen & Pedersen (1991); **16**, A.K. Pedersen (1985); **17**, A.K. Pedersen *et al.* (2006b); **18**, Piasecki *et al.* (1992); **19**, Storey *et al.* (1998).



Svartenhuk Halvø
Upernivik Næs, Qeqertarsuaq
North coast Nuussuaq
Western Nuussuaq
Central Nuussuaq
Aaffarsuaq
Paleocene
Upper Cretaceous
Lower Cretaceous
Thanetian
Selandian
Danian
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Umiivik
Itsaku
Up.
Sv
Vaigat
Kangilia
Itilli
Umiivik
Upernivik Næs
Contact to basement
E of Ikorfat
W of Ikorfat
E
O
Na
An
AC
Agatdal
Anariartorfik
1.5 km undated deep marine sediments
Kingittoq
Ravn Kløft
Atane
Slibestensfjeldet
Kome
It
Aaffarsuaq
Qilakitsoq
Volcanic rocks
Subaerial lava flow
Hyaloclastic breccia
Coal
Mudstone
Sandstone
Conglomerate
Macrofossils
t Tuff
3 Key reference


Central Nuussuaq
Agatdalen
South coast Nuussuaq
Ataata Kuua Paatuut
North coast Disko
Asuk
South coast Nuussuaq
Kingittoq Atanikerluk
Eastern Disko
Pingu
South coast Disko
Skansen, Assoq
M
RDM
O
Na
N
At
E
t
Pa
NQ
Tu
OAC
A
U
P
Ak
Vaigat
Agatdal
Kangilia
Quikavsak
Itilli
Aaffarsuaq
Atane
Qilakitsoq
Kussinerujuk
Kingittoq
Skansen
Contact to basement
Alluvial fan
Lake
Fluvial channel
Flood plain
Delta plain
Delta front
Estuary
Marine shoreface
Marine shelf
Marine slope
Marine slope channel

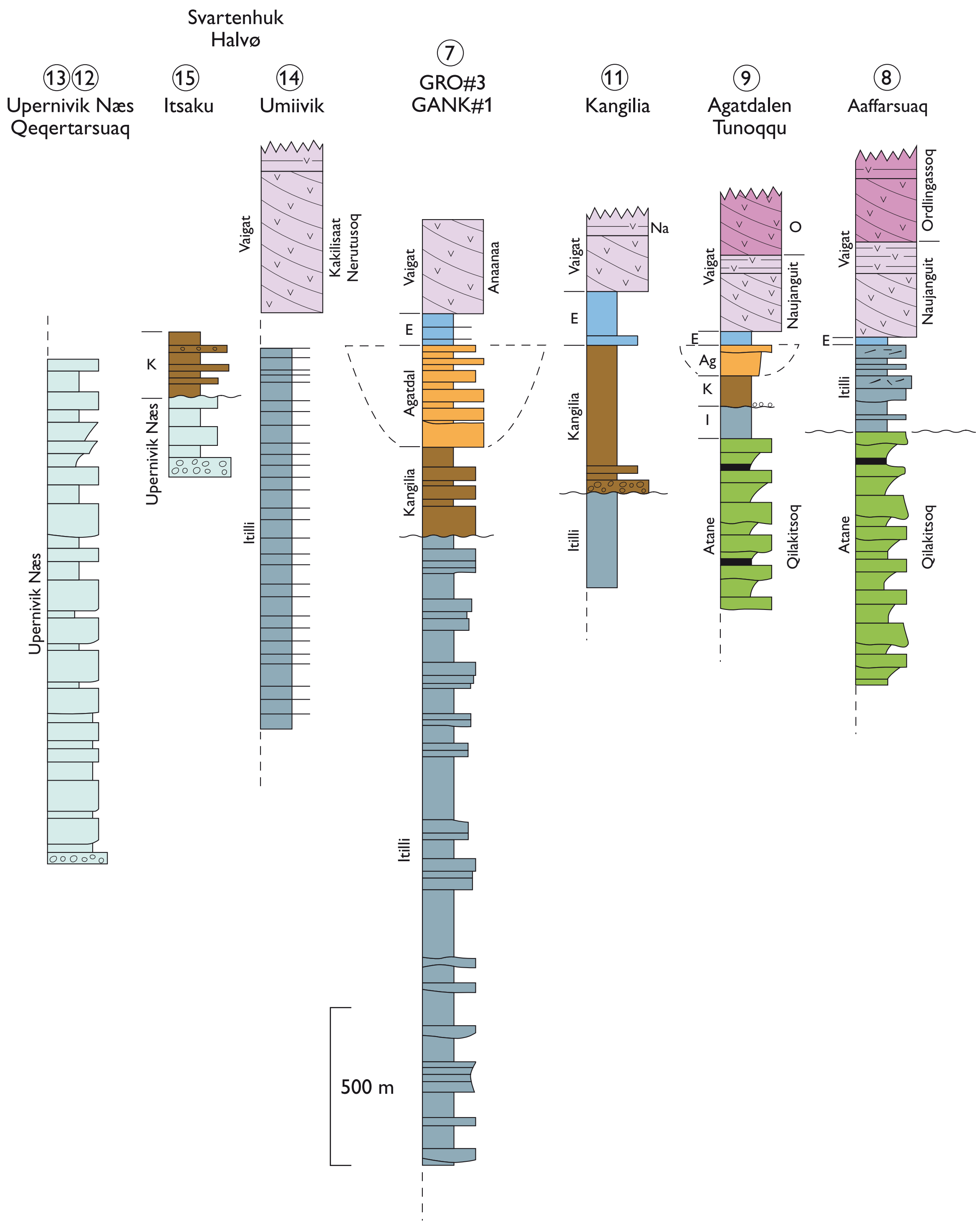
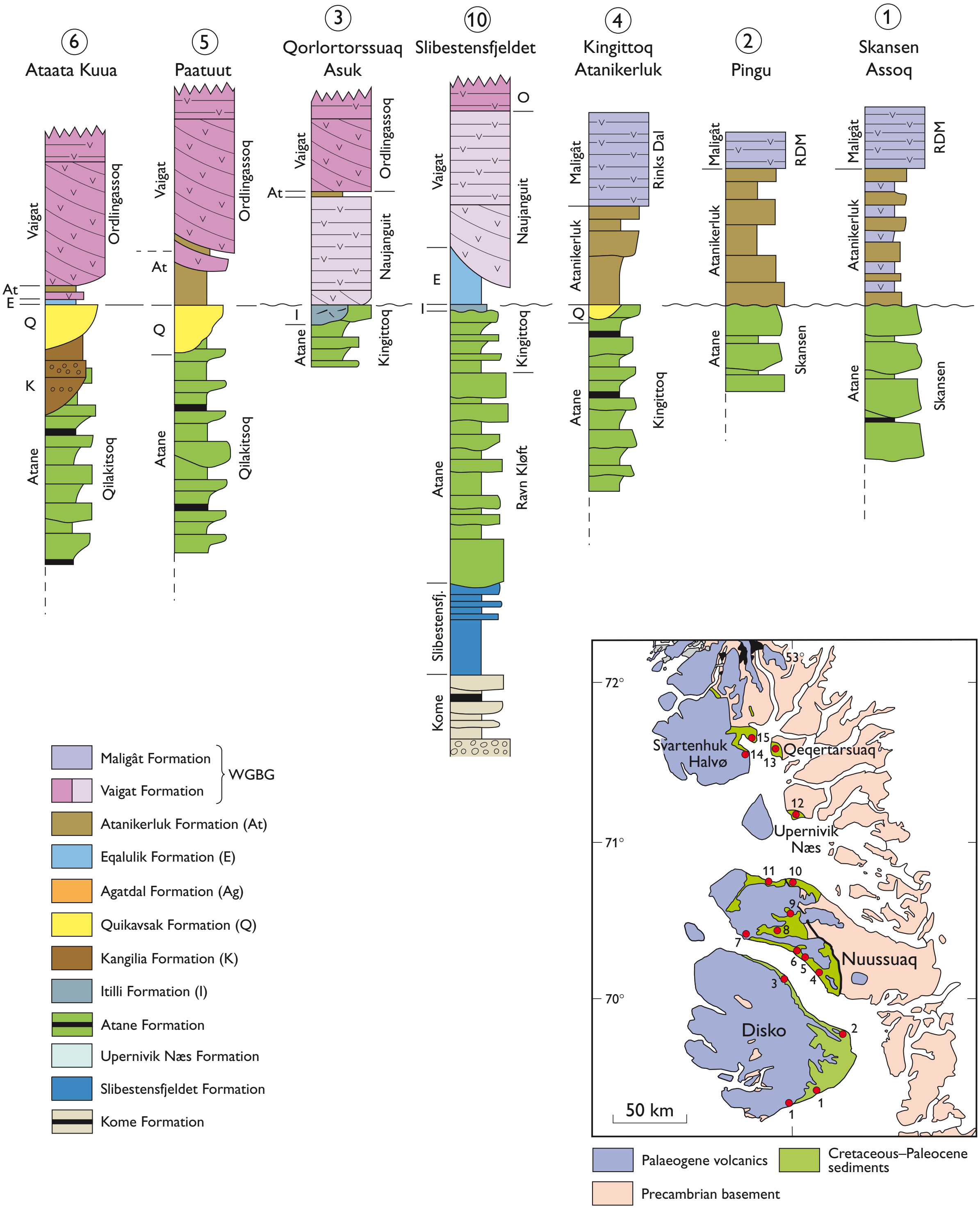


Fig. 17. Simplified logs showing the distribution and thickness of the formations of the Nuussuaq Group. Members are only indicated for the Atane Formation and for the volcanic formations. In most areas, the lower boundary of the Nuussuaq Group is not seen, and the thicknesses indicated for the formations are therefore minimum values. Note that the marginal marine deposits (Kome, Slibestensfjeldet, Upernivik Næs and Atane Formations) are thick on Disko, eastern Nuussuaq and northwards to Qeqertarsuaq. Deep marine deposits (Itilli, Kangilia and Agatdal Formations) are thickest on western and northern Nuussuaq and on Svartenhuk Halvø. At localities 1, 3, 5 and 6, the mudstones of the Atanikerluk Formation are interbedded with volcaniclastic breccias or subaqueous lava flows that have chemical compositions characteristic of the Vaigat and Maligât Formations. **Na**, Naujánguit Member; **O**, Ordlingassoq Member; **RDM**, Rinks Dal Member; **WGBG**, West Greenland Basalt Group. Compare with Fig. 16.


6
Ataata Kuua
5
Paatuut
3
Qorlortorssuaq
Asuk
10
Slibestensfjeldet
4
Kingittoq
Atanikerluk
2
Pingu
1
Skansen
Assoq
Vaigat
Ordlingassoq
At
E
Q
K
Atane
Qilakitsoq
I
Naujanguit
Kingittoq
O
Ravn Kløft
Slibestensfj.
Kome
Maligât
Rinks Dal
Atanikerluk
RDM
Skansen
Maligât Formation
Vaigat Formation
WGBG
Atanikerluk Formation (At)
Eqalulik Formation (E)
Agatdal Formation (Ag)
Quikavsak Formation (Q)
Kangilia Formation (K)
Itilli Formation (I)
Atane Formation
Upernivik Næs Formation
Slibestensfjeldet Formation
Kome Formation
72°
71°
70°
53°
Svartenhuk
Halvø
Qeqertarsuaq
Upernivik
Næs
Nuussuaq
Disko
50 km
Palaeogene volcanics
Cretaceous–Paleocene sediments
Precambrian basement

iments of the Atane Formation pass westwards into marine, fault-controlled slope deposits. These sediments are referred to the Itilli Formation, of Cenomanian to Maastrichtian age, and comprise mainly homogeneous mudstones, thinly interbedded mudstones and sandstones, and turbidite channel sandstones. In the Aaffarsuaq valley, an angular unconformity separates the deltaic Atane Formation from Campanian turbidite deposits of the Itilli Formation (Dam *et al.* 2000).

Major uplift during the Maastrichtian resulted in incision of underlying units; submarine canyon incision is seen at several localities on Nuussuaq, viz. at Ataata Kuua, at Kangilia, in Agatdalen and west of the Kuuganngguaq–Qunnilik Fault (Fig. 15, see Plate 3). At these localities, the valley and canyon fill consists of successions of homogeneous sandstones and conglomerates, in many instances resulting from catastrophic gravity flow deposition. Intercalated mudstones represent deposition from turbidity currents. These deposits are referred to the Kangilia Formation. Renewed uplift during the Danian generated new incision and fluvial to tidal valley deposits separated by lacustrine sediments filled the fluvial valleys. The lacustrine deposits comprise thin coarsening-upward successions composed of mudstones and sandstones with *in situ* and drifted tree trunks. These sediments are referred to the Quikavsak Formation (Dam 2002). The pre-volcanic phase culminated with major subsidence of the basin and deposition of sandstones from sediment gravity flows (the Agatdal Formation). During this period, the Disko area was characterised by sedimentary bypass.

The next phase of Nuussuaq Group sedimentation coincided with submarine volcanism west of Nuussuaq. The oldest rocks of the West Greenland Basalt Group are hyaloclastic breccias of the Vaigat Formation (Hald & Pedersen 1975; A.K. Pedersen 1985; A.K. Pedersen *et al.* 1993, 1996, 2002, 2006b; G.K. Pedersen *et al.* 1998). The contemporaneous siliciclastic marine sediments comprise mudstones, thinly interbedded sandstones and mudstones and chaotic beds. Volcaniclastic sandstones and conglomerates deposited from turbidity currents are common in this part of the succession. The marine syn-

Fig.18. The sediments onlapping and overlying the basement high at Ikorfat on the north coast of Nuussuaq (view towards the south) represent the base of the Nuussuaq Group. The basal sediments are represented by the Kome Formation overlain by the Slibestensfjeldet and Atane Formations. The highest peak is *c.* 2000 m a.s.l.; for location, see Fig. 22. **E**, Eqalulik Formation.

volcanic sediments are referred to the Eqalulik Formation from the latest Danian (Nøhr-Hansen *et al.* 2002). As the Early Paleocene volcanic breccias of the Vaigat Formation (West Greenland Basalt Group) prograded eastwards from sources west of the present coastline, the formerly marine basin was dammed and large lakes formed on eastern Nuussuaq and Disko. The lakes were filled from the west by hyaloclastite breccias while siliciclastic sedimentation continued from the south-east. These sediments are referred to the Atanikerluk Formation and consist of shales with thin tuff beds and fine-grained sandstones deposited in two coarsening-upward successions.

Fossils. A rich flora and fauna from the group has been described. The fauna numbers several hundred species including bivalves, gastropods, nautiloids, ammonites, belemnites, echinoderms, cirripeds, brachiopods, corals, decapod crustaceans, serpulids, fish, ostracods, foraminifera, bryozoans and insects. Fossil invertebrates are best known from the Itilli, Kangilia and Agatdal Formations. The rich flora comprises more than 600 species of plant leaves, wood, fruits, spores, pollen and dinoflagellate cysts (hereafter named dinocysts). Well-preserved plant fossils are mainly found in the Kome, Atane, Quikavsak, Agatdalen and Atanikerluk Formations (for summary of studies, see section on 'Previous work' above). Dinocysts form the basis of biostratigraphy and correlation in recent studies.

Boundaries. The lower boundary of the group is only exposed on the north coast of Nuussuaq at Kuuk, Vesterfjeld, Talerua and Ikorfat (Fig. 18), on the east coast of Itsaku and on Svartenhuk Halvø where the group overlies metamorphic basement that locally is strongly weathered. The boundary was also penetrated in the FP93-3-1 borehole on northern Disko where the Atane Formation overlies a basement high (Fig. 19).

The upper boundary with the West Greenland Basalt Group is diachronous (Hald & Pedersen 1975; A.K. Pedersen *et al.* 1993). During the Paleocene, volcanic breccias of the Vaigat Formation prograded eastwards from offshore sources and isolated the formerly marine basin in eastern Nuussuaq and Disko, eventually onlapping the Precambrian basement east of the Ikorfat fault zone (L.M. Larsen & Pedersen 1992; A.K. Pedersen *et al.* 1996, 2002; G.K. Pedersen *et al.* 1998).

Geological age. Dating of the exposed and drilled parts of the basin is mainly based on ammonites, corals, foraminifera, coccoliths, spores, pollen, dinocysts and macroflora fossils. The fossils indicate that outcrops of the Nuussuaq Group span the Albian to the Upper Danian – Selandian. Brackish-water dinocysts from sediments onlapping the basement indicate a pre-Late Albian age, and this is supported by the scarcity of angiosperms

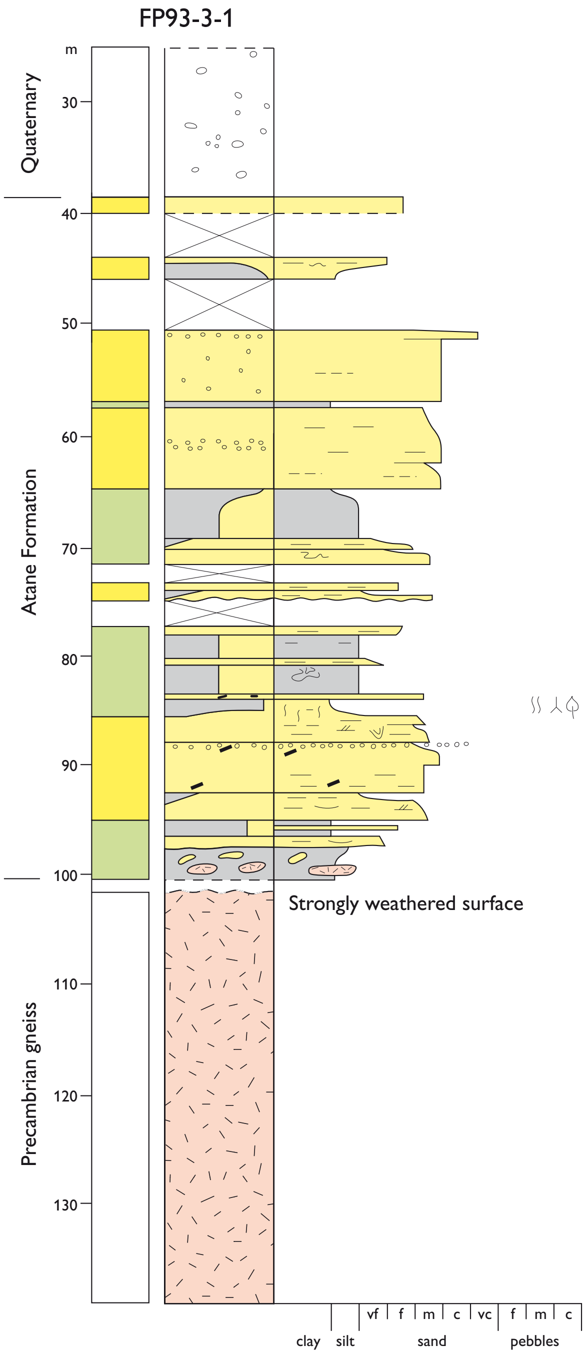


Fig. 19. Detailed sedimentological log of the Atane Formation overlying weathered gneiss basement in the the FP93-3-1 core in the Kuugannguaq valley on north-west Disko. The well dips 60° and driller's depths are shown. The stratigraphic thickness of the Atane Formation is *c.* 50 m; the sediments are not referred to a member. For location, see Fig. 2. Depositional environments are indicated by colours in the left column of the log (see Plate 1).

in the Ikorfat flora (Boyd 1998a, b, c, 2000). In the Umiivik-1 well, the oldest dateable marine dinocysts are of Turonian age; these were recorded 800 m above the base of the well (Dam *et al.* 1998b). In the GRO#3 well, the oldest dateable dinocysts are of Coniacian age and were recorded 1500 m above the base (Christiansen *et al.* 1999). Consequently, the deeper parts of these wells may have penetrated successions older than Albian.

Age-specific biomarker data from oil seeps at several outcrops of the Nuussuaq Group suggest that source rocks of Aptian–Albian and Cenomanian–Turonian age are present in the Nuussuaq Basin (Bojesen-Koefoed *et al.* 2004, 2007).

$^{40}Ar/^{39}Ar$ dating of the volcanic rocks coeval with the upper levels of the Nuussuaq Group (the Vaigat Formation and the Rinks Dal Member of the Maligât Formation) indicates an age of 60.4 ± 0.5 Ma for these rocks (Storey *et al.* 1998). This age has been recalculated to 60.8 ± 0.5 Ma based on recalibration of the Fish Canyon Tuff standard (Skaarup & Pulvertaft 2007).

Correlation. The Nuussuaq Group is coeval with the Cretaceous Hassel and Kanguk Formations and the uppermost Cretaceous–Oligocene Eureka Sound Group of the Canadian Arctic Islands (e.g. Miall *et al.* 1980; Miall 1986; Burden & Langille 1990; Harrison *et al.* 1999). It constitutes an onshore analogue to the Cretaceous–Paleocene basins offshore West Greenland (Rolle 1985; Chalmers & Pulvertaft 2001; Dalhoff *et al.* 2003; Sørensen 2006; Gregersen *et al.* 2007) and to the Cretaceous Bjarni, Markland and Cartwright Formations offshore eastern Canada in the Davis Strait and Labrador Sea (Balkwill *et al.* 1990; Government of Newfoundland and Labrador 2000; Sønderholm *et al.* 2003).

Subdivision. The Nuussuaq Group is subdivided into the Kome, Slibestensfjeldet, Upernivik Næs, Atane, Itilli, Kangilia, Quikavsak, Agatdal, Eqalulik and Atanikerluk Formations (Figs 13, 17).

Kome Formation

redefined formation

History. The geology of the Kuuk area was described by Giesecke in 1811 (diary entry for 18 June; in: Steenstrup 1910). He mentioned that the coal seams provided fuel for 'Kolonien Omenak', now the town of Uummannaq (Fig. 20). A 0.7–1.3 m thick coal seam was exposed and exploited until 1832 (Rink 1857). The Mineralogical Museum in Copenhagen received 21 samples of "shale with remains and imprints of different fossil plants, especially ferns" collected near Kome (Rink 1855 p. 214). Heer (1883b) described an Early Cretaceous fossil flora from the north coast of Nuussuaq that he termed the Kome flora. According to Nordenskiöld (1871), several of these fossils had been collected by Rink and were sent to Heer from the Mineralogical Museum in Copenhagen.

The Kome Formation was defined in the area between Kuuk and Ikorfat by Nordenskiöld (1871 p. 1040) and described as follows (translated by the authors): "The Komelagren [Kome Formation] constitutes the older part of the Cretaceous, according to Heer (1868). The name designates a sedimentary, coal-bearing formation exposed at various localities between Kuuk and Ikorfat along the coast of Nuussuaq, south-west of Uummannaq. The name originates from the outcrop which has the most important coal bed and where Giesecke and Rink most likely collected plant fossils. These beds [Komelagren, the Kome Formation] are not restricted to Kuuk, but are found, except where interrupted by gneiss highs, along the entire coastal section between Kuuk and Ikorfat" (Figs 2, 21, 22). Nordenskiöld (1871) proposed a stratigraphy with a geographically restricted Lower Cretaceous Kome Formation overlain by the Upper Cretaceous Atane Formation which also covered southern Nuussuaq and northern Disko. Gry (1940) interpreted the boundary between the Kome and the Atane Formations as an unconformity.

Koch (1964) described the Kome Formation as occurring almost continuously between Kuuk and Ikorfat, interrupted only between Angiarsuit and Ujarattoorsuaq where younger Upper Cretaceous deposits are downfaulted (Figs 21, 22). He suggested that the beds that unconformably overlie the Kome Formation on the north coast of Nuussuaq could be equivalent to the Atane Formation or, alternatively, to the Upernivik Næs Formation.

Schiener (1977) did not find convincing evidence for an unconformity within the section at Ikorfat and concluded that the majority of the sediments were deposited during the Early Cretaceous. He implied that the Atane Formation is absent on northern Nuussuaq east of the Ikorfat fault zone (Fig. 10).

In the Kuuk area, the Kome Formation was interpreted to comprise fluviodeltaic deposits (Pulvertaft 1979) that were suggested to form part of the Atane Formation by G.K. Pedersen & Pulvertaft (1992). In contrast, Midtgaard (1996b) distinguished five sedimentary units in the area between Ikorfat and Qaarsut and the lowest of these is here assigned to the Kome Formation.

Fig. 20. View from Uummannaq towards the coal-bearing deposits of the Kome Formation at Kuuk on the north coast of Nuussuaq. The coal was being mined as early as the 18th century for use in Uummannaq. View foreshortened due to the use of a telescopic lens. For location, see Figs 2, 21.

Name. In his descriptions of the coal seams on northern Nuussuaq that provided fuel for 'Kolonien Omenak' (the town of Uummannaq), Giesecke in 1811(in: Steenstrup 1910) spelled the name either 'Koome' or 'Kook'. Thalbitzer (1910) explained 'Koome' as *casus locativus* of 'Kook', e.g. 'in or at Kook'. The spelling 'Kome' was used by Rink (1857) and Heer (1882, 1883b). Rink (1853 p. 175) wrote: "The settlement of Kome lies at the mouth of the large valley Tuëparsoït [now Tuapassuit, Fig. 21]. Between this and Sarfarfik a broad open valley is found. This contains a small river (Kook) thus the name of the site, where it reaches the shore" (translation from Danish by the authors). The site is shown as Kook, Kûk or Kuuk on newer maps (Fig. 21).

Distribution. The Kome Formation is presently known from the coastal area on the north coast of Nuussuaq between Kuuk and Ikorfat (Figs 21, 22). Gry (1940, 1942) briefly described sediments onlapping the basement on Itsaku (Fig. 73) and referred these to the Kome Formation on the basis of plant fossils from the lower part of the sedimentary succession. These sediments were tentatively referred to the Atane Formation by Christiansen *et al.* (2000) and J.G. Larsen & Pulvertaft (2000) on the basis of sedimentological similarities. In the present paper they are referred to the Upernivik Næs Formation. East of Saqqaqdalen on southern Nuussuaq (Fig. 2), outcrops of fluvial pebbly sandstones overlying the basement are preserved in a small down-faulted area (Pulvertaft 1989a, b) and are tentatively assigned to the Kome Formation.

Type section. The type section is at Majorallattarfik, immediately west of the Kuuk delta (Figs 21, 23). The base of the type section is located at 70°38.60´N, 52°21.83´W.

Reference sections. Reference sections have been measured at Slibestensfjeldet and Ikorfat (Midtgaard 1996b) (Fig. 22). These sections illustrate the marked lateral and stratigraphic, lithological changes in the formation from stacked conglomerates to coarsening-upward, fine-grained sandstones and mudstones (Figs 24, 25).

Thickness. The thickness of the Kome Formation varies from *c*. 25 m at Vesterfjeld to more than 150 m between Talerua and Ikorfat, and 140 m at Majorallattarfik near Kuuk (Figs 21, 22).

Lithology. The basal part of the Kome Formation overlies and onlaps Precambrian basement at Kuuk, Talerua and Ikorfat. The basement rocks are in places weathered to a depth of 35 m (Heim 1910; Gry 1942; Pulvertaft 1979; Midtgaard 1996b). The uppermost part of the basement consists almost exclusively of quartz grains within a powdery matrix of kaolinite. The gneiss has a greenish colour probably due to alteration of biotite to chlorite (Heim 1910; Pulvertaft 1979). The basal sediments are typically one of three main facies: (1) poorly sorted sandstones, rich in kaolinite and devoid of sedimentary structures, (2) diamictites, with blocks of vein quartz in a sandy clay matrix, or (3) unsorted conglomerates with poorly rounded quartz boulders and slabs of silty mudstones (Fig. 26; Gry 1942; Schiener 1977; Pulvertaft 1979). At Talerua (between Vesterfjeld and

Ikorfat), the basal sediments are breccias with large clasts comprising both gneiss with weathered feldspars and carbonaceous mudstones (Fig. 25A). At Ikorfat, breccias with angular gneiss clasts are overlain by a conglomerate bed, a few metres thick, comprising subangular clasts of quartz and intensely kaolinised feldspars. The diamictites and poorly sorted conglomerates are not seen above the basement highs. The poorly sorted, coarse-grained deposits are overlain by thin conglomerates, cross-bedded, locally channellised, coarse-grained sandstones, mudstones and thin discontinuous coal beds (Fig. 25). Root horizons are frequent and the mudstones commonly contain abundant comminuted plant debris (Fig. 25; Schiener 1977; Pulvertaft 1979; Midtgaard 1996b). Fine-grained sandstones with wave-ripples forming coarsening-upward successions occur in the upper part of the formation and are common in the Ikorfat area. The topmost bed of the Kome Formation is a bleached, crumbly mudstone with abundant root-casts overlain by a coal bed (Fig. 25C; Midtgaard 1996b).

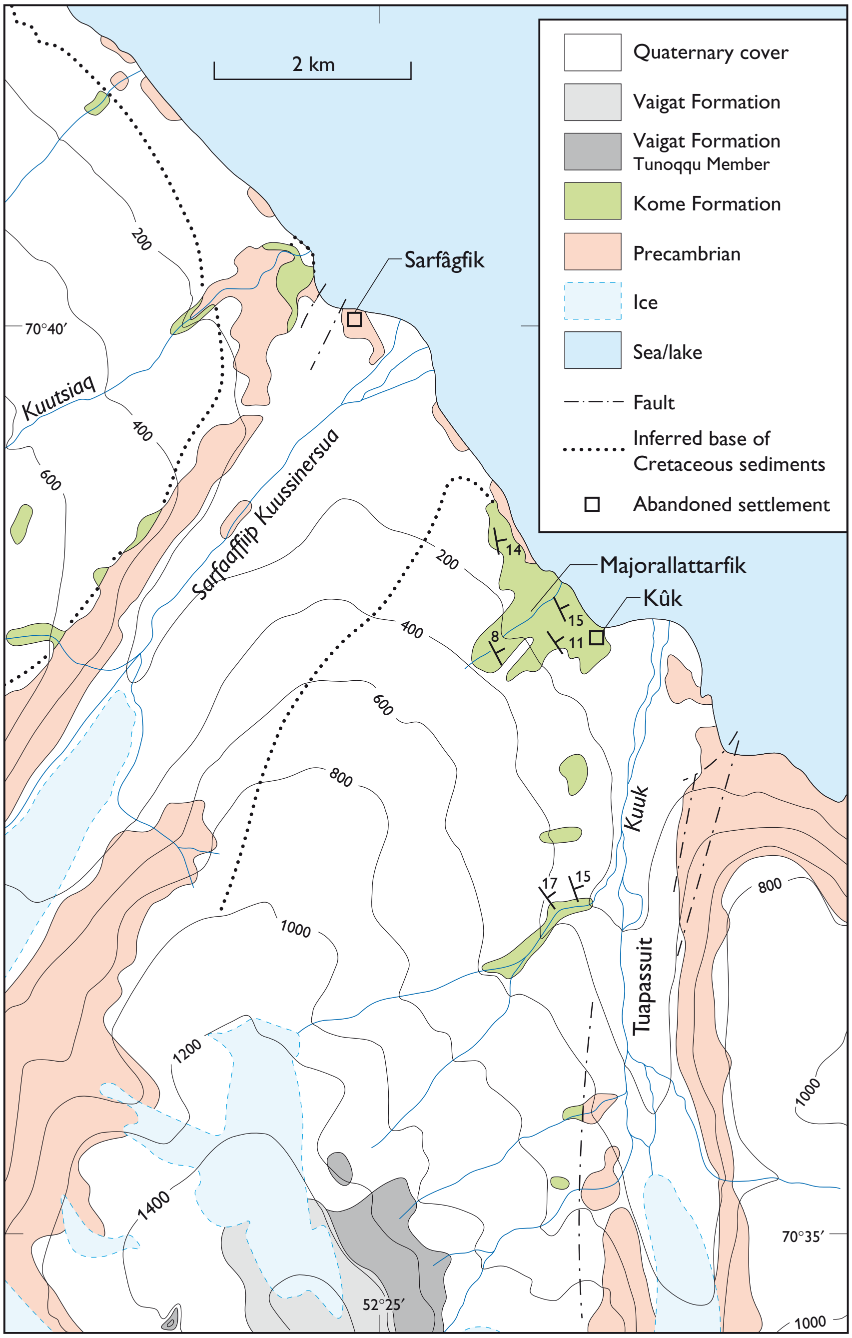


Fig. 21. Geological map of the area around Kuuk (from Pulvertaft 1979). Majorallattarfik is the type locality of the Kome Formation. The sediments overlie weathered basement and are well exposed. For location, see Fig. 2.

In the Kuuk area, the sediments overlying the coarse-grained, basal deposits consist of three facies associations: A, B and C (Figs 24, 27, 28). Association A is dominant and consists mainly of trough cross-bedded, erosionally based sandstones in shoe-string or irregular tabular bodies up to 5 m thick (Figs 24, 28). The sandstones are coarse-grained, often gravelly, with angular clasts, and is poorly sorted. It contains slightly to moderately kaolinised feldspars and kaolinite cement. Fragments of coalified wood and fine-grained plant debris are common. The orientation of shoe-string bodies and dip direction of foresets indicates transport from the south-east. The sandstones alternate with dark laminated silty mudstones containing much coalified plant debris, thin lenses of lustrous, coalified, woody tissue and thin coal seams (Fig. 24; Pulvertaft 1979). Association B consists of distinctive coarsening-upward successions of mudstones, cross-laminated siltstones, sandstones and locally thin layers of gravelly sandstones (Figs 24, 27). Association C is dominated by tabular cross-bedded, medium-grained, moderately well-sorted subarkosic sandstones with pebble lags of quartz or chert. Comminuted coalified plant debris and mica are common in the sandstones. Foresets dips are to the north-west. Cross-laminated, fine-grained

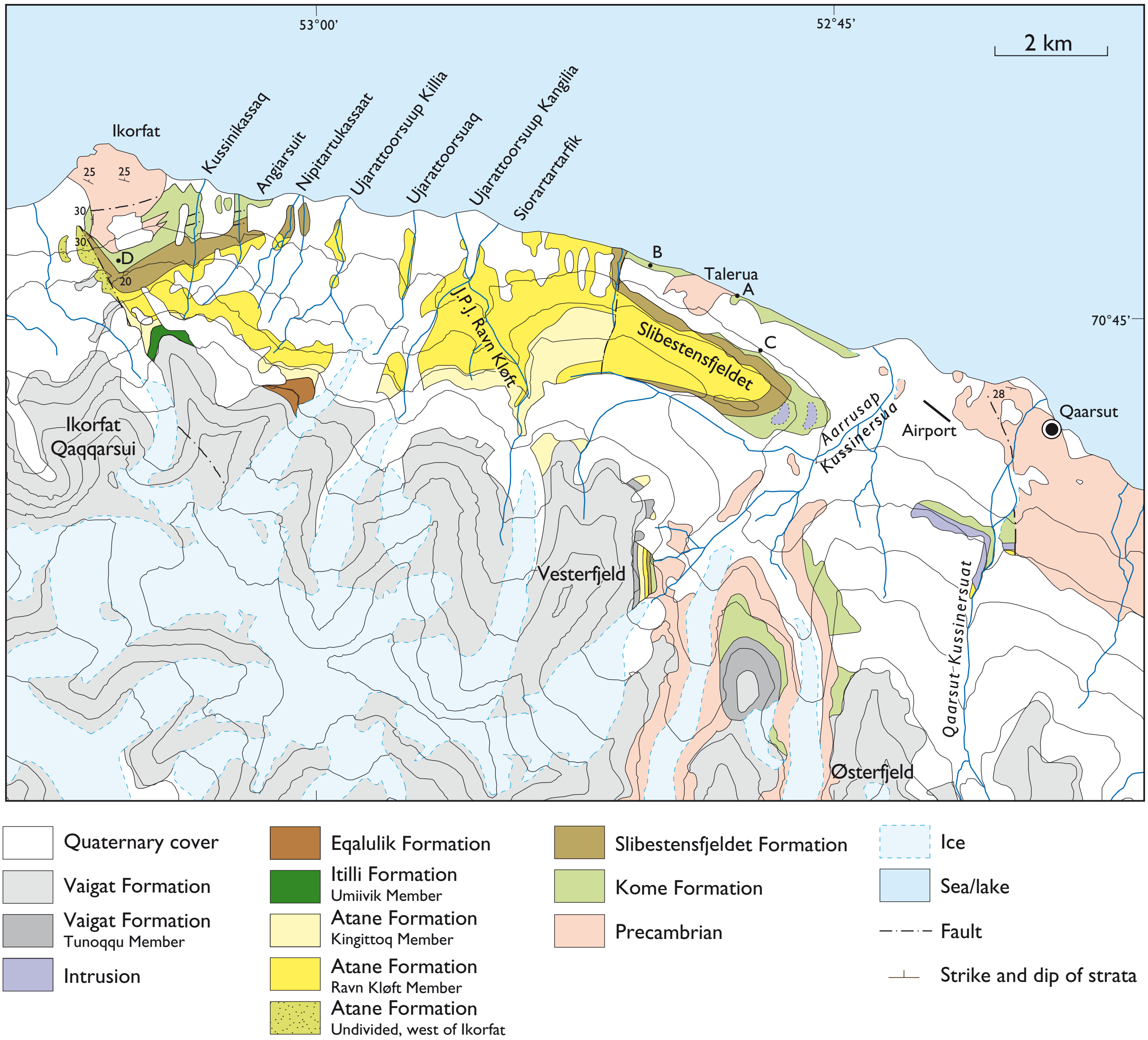


Fig. 22. Detailed geological map of the north coast of Nuussuaq, from Qaarsut to Ikorfat. The locations of the four sedimentological logs (**A–D**) in Fig. 25 are indicated. Contour interval 200 m. Modified from Rosenkrantz *et al.* (1974) and Midtgaard (1996b). For location, see Fig. 2.

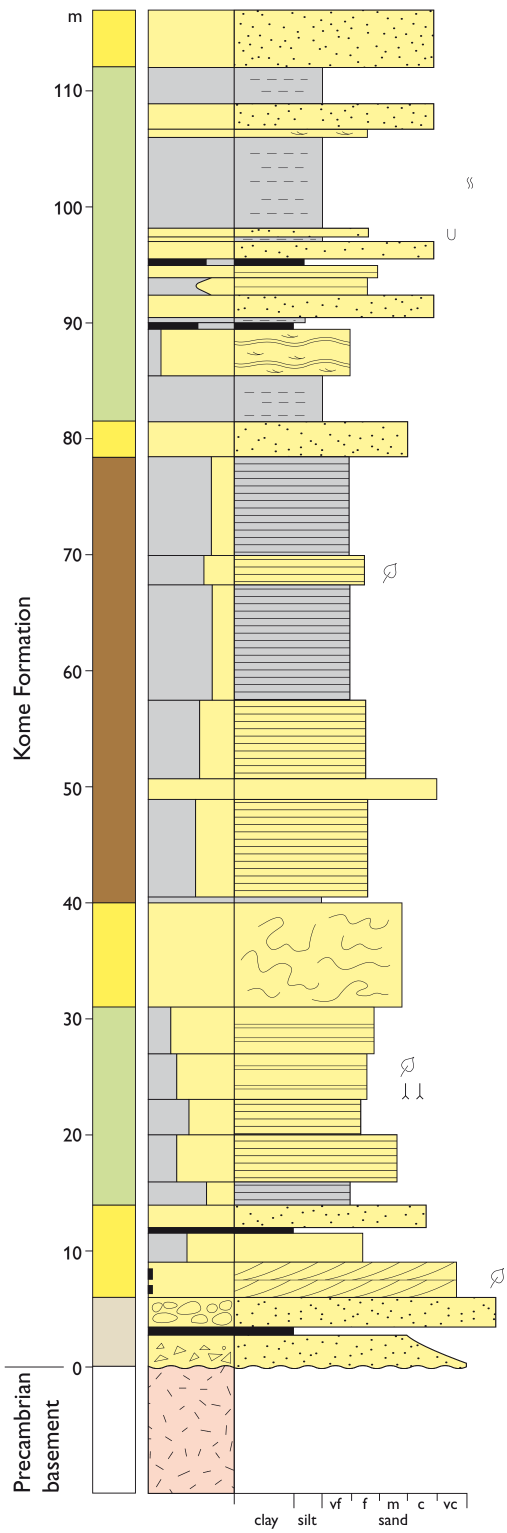


Fig. 23. Type section of the Kome Formation at Majorallattarfik, immediately west of Kuuk, redrawn from Croxton (1978a, b). The uppermost *c.* 20 m of the formation are poorly exposed and are not shown on the log. Note that the facies illustrated in detail in Fig. 24 recur here in a thicker succession. For location, see Fig. 21; for a possible correlation between Kuuk and Slibestensfjeldet, see Fig. 29; for legend, see Plate 1.

sandstones overlying the medium-grained sandstones form a minor part of the association. Wave-generated sedimentary structures or mud-draped foresets indicating tidal influence have not been seen (Pulvertaft 1979). Facies association C occurs at the top of the sections at Kuuk and Majorallattarfik (Fig. 28; T.C.R. Pulvertaft, personal communication 2008).

Fossils. The Kome Formation contains macrofossil plants referred to the Kome flora (Heer 1883a). The genera in the Kome flora were revised by K.R. Pedersen (1976). A separate Ikorfat flora has been distinguished by Boyd (1998a, b, c, 2000) in the Ikorfat area and is suggested to be slightly older than or contemporaneous with the Kome flora (Boyd 1998a, b, c, 2000).

Samples of mudstones collected by Croxton (1978a, b, section C20) at Majorallattarfik near the top of the section at Kuuk contain a poor assemblage of brackish-water dinocysts, spores and pollen. Few specimens of the dinocyst *Vesperopsis nebulosa* occur in the lower part, whereas few specimens of *Nyktericysta davisii* and *Pseudoceratium interiorense* occur in the upper part. The presence of the spore *Cicatricososporites auritus* may indicate a Middle to Late Albian age, whereas the absence of the pollen *Rugubivesiculites rugosus* indicates a pre-Late Albian age. The presence of *Nyktericysta davisii* may indicate a younger age, as at other localities this species first occurs in the overlying Ravn Kløft Member (Atane Formation).

Samples of mudstones collected by Midtgaard (1996b) from the upper part of the Kome Formation reference section at Slibestensfjeldet (Fig. 25C) also contain *Vesperopsis nebulosa* and common *Pseudoceratium interiorense* and, in common with the Kuuk section, the pollen *Rugubivesiculites rugosus* is absent.

Assemblages dominated by *Pseudoceratium interiorense* are known from the Slibestensfjeldet Formation, whereas assemblages dominated by *Nyktericysta davisii* first occur in the Ravn Kløft Member of the Atane Formation between Vesterfjeld and Ikorfat (Fig. 29). Croxton (1978a, b) noted the absence of angiosperm pollen and the presence of spores such as *Cicatricosisporites, Gleicheniidites, Pilosisporites* and *Vitreisporites*, indicating an early to mid-Cretaceous age.

Depositional environment. The diamictites and poorly sorted conglomerates in close association with the basement highs are interpreted as mass-flow deposits (Figs 25, 29); talus cones and alluvial fans filled the topographic lows on the basement surface with immature sediments (Midtgaard 1996b). The lack of mass-flow deposits above the basement highs suggests that the ini-

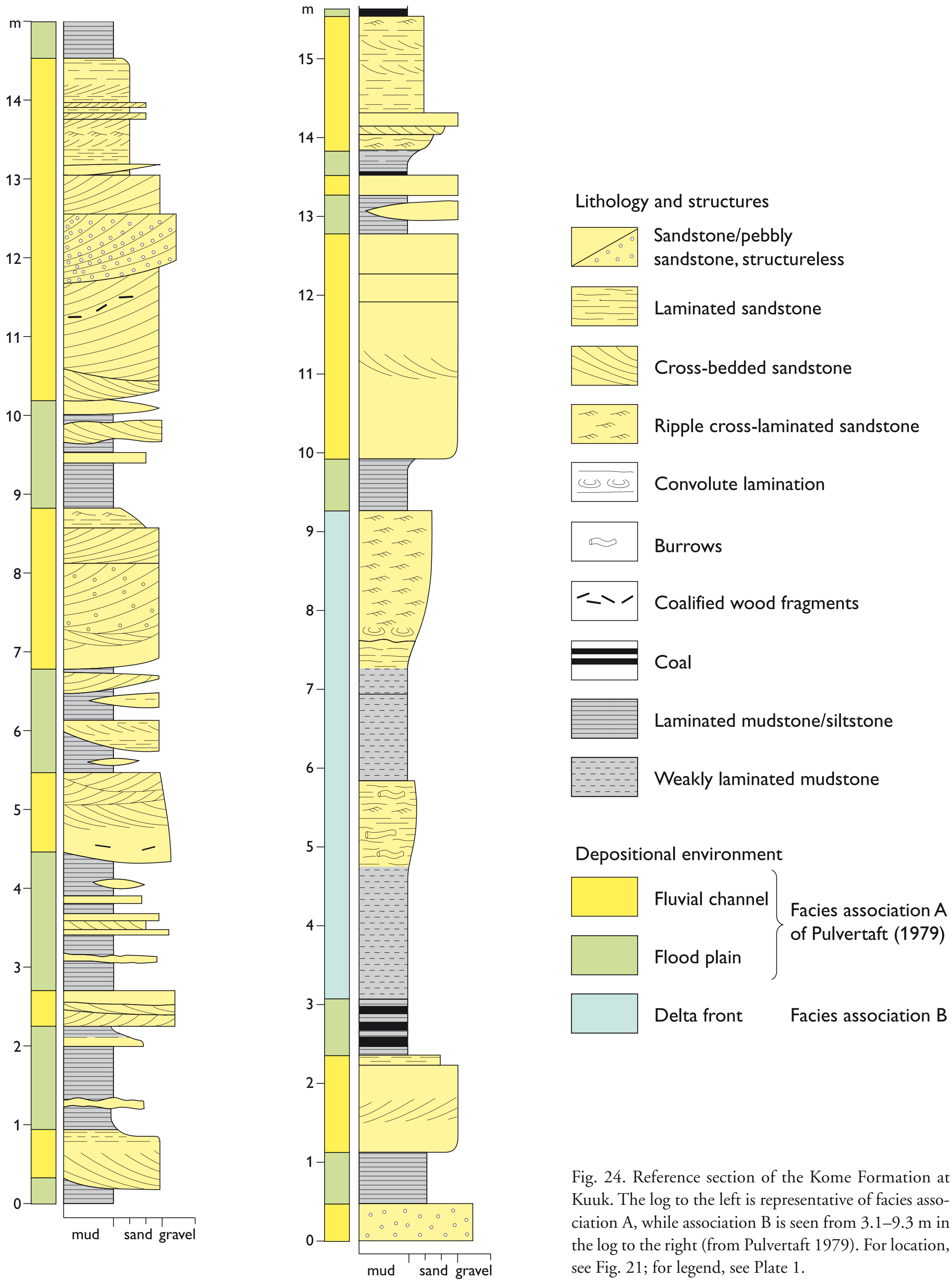


Fig. 24. Reference section of the Kome Formation at Kuuk. The log to the left is representative of facies association A, while association B is seen from 3.1–9.3 m in the log to the right (from Pulvertaft 1979). For location, see Fig. 21; for legend, see Plate 1.

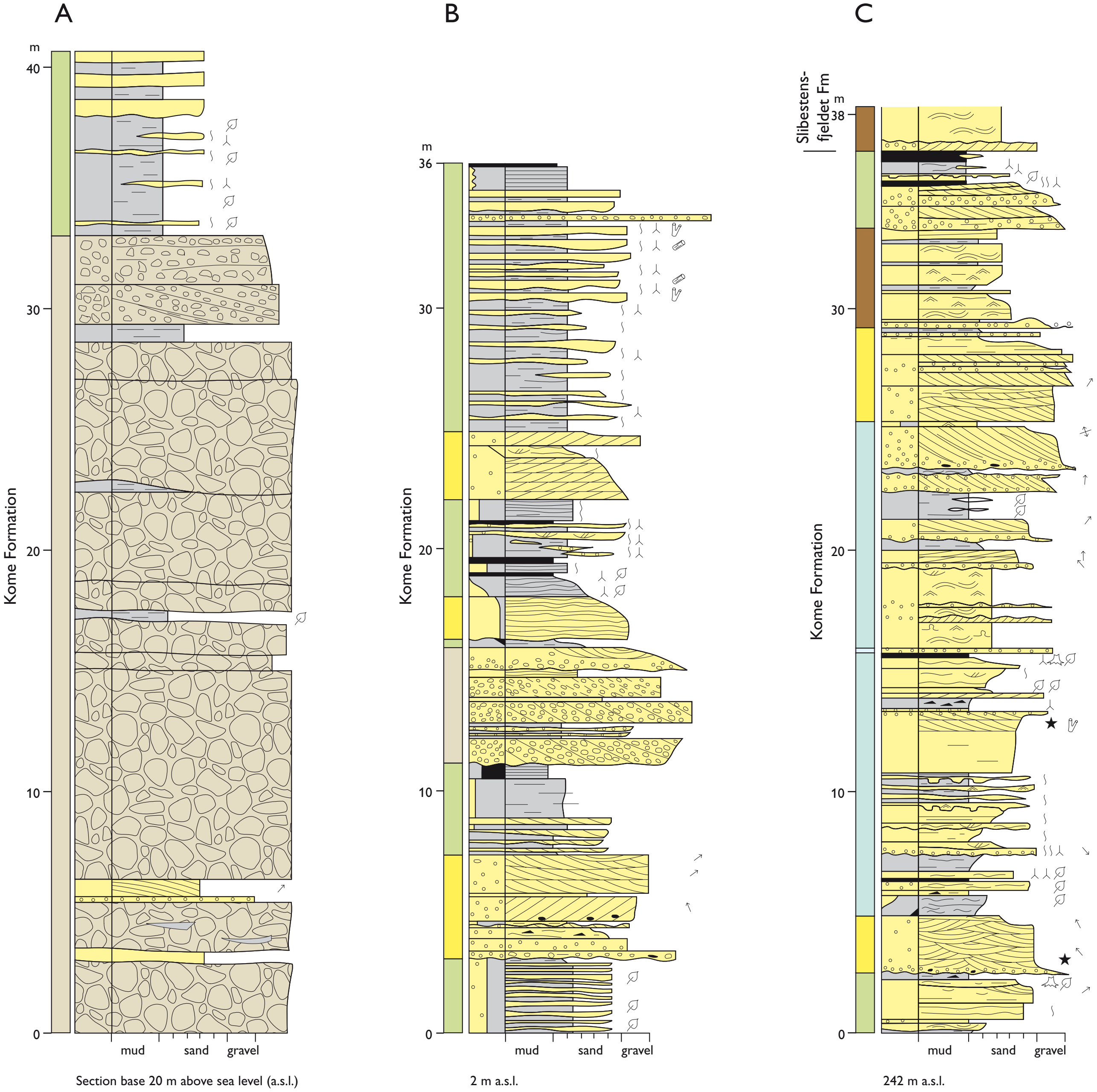
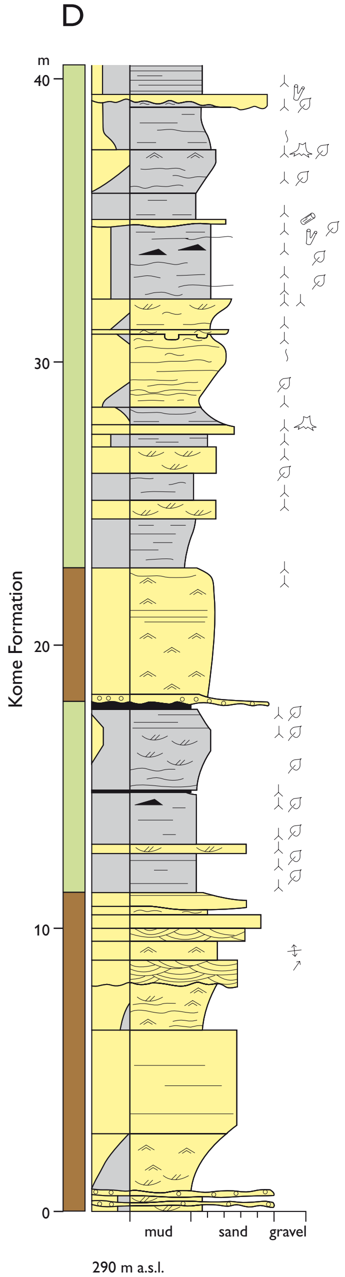


Fig.25. Reference sections of the Kome Formations illustrating abrupt facies change and numerous horizons with rootlets. **A** and **B** are from the lower part of the formation and **C** and **D** are from the uppermost part of the formation. Sections **C** and **D** also show the overall decrease in grain-size towards the west. The boundary between the Kome Formation and the overlying Slibestensfjeldet Formation is shown in section **C**. From Midtgaard (1996b). For legend, see Plate 1; for location, see Fig. 22.



tial relief was levelled out as sediments accumulated and buried the highs. The alluvial fans were succeeded by fan deltas representing both subaerial and subaqueous deposition; the latter increases towards Ikorfat (Fig. 25D). The sparse dinocyst assemblage indicates that the water was intermittently brackish.

The coarse sandstones of facies association A at Kuuk are interpreted as fluvial deposits. Their low textural and mineralogical maturity together with palaeocurrent indicators point to derivation directly from a weathered basement to the south-east, without reworking *en route*, and to rapid sedimentation. The dark mudstones are interpreted as overbank deposits of a floodplain environment or deposition in shallow lakes. The mudstones of facies association B are interpreted as having been deposited from suspension in bodies of standing water, presumably interdistributary bays or lakes (Fig. 23, 24). Sedimentary structures in the sandstones of facies association C suggest deposition from a sandy braided river flowing from the south, and the higher textural and mineralogical maturity of the sandstones indicates more protracted fluvial transport (Pulvertaft 1979). The palaeosol that caps the Kome Formation represents a widespread regressive event (Figs 25C, 30; Midtgaard 1996b).

Boundaries. The Kome Formation overlies an undulating Precambrian gneiss topography, filling valleys or depressions (Henderson *et al.* 1976; Schiener 1977; Pulvertaft 1979; Midtgaard 1996b). The lower boundary of the formation is exposed at Kuuk, Ikorfat and Talerua (Figs 2, 21, 22). In the coastal cliffs of northern Nuussuaq, the relief on the gneiss surface can be seen to exceed 225 m (Fig. 22). At Vesterfjeld, the basement is weathered to a depth of 30 m with a gradual downward transition into unaltered gneiss. In western Disko (Stordal), the Precambrian basement is exposed, locally with a 5–10 m thick weathered cap (A.K. Pedersen & Ulff-Møller 1980). In other exposures, the gneiss is relatively unweathered (Schiener 1977; Midtgaard 1996b). The lower boundary of the Kome Formation thus displays a variety of basement–sediment transitions.

The upper boundary of the Kome Formation is a sharp lithological boundary that varies very little laterally (Figs 25C, 30). It is placed on top of a palaeosol horizon and was interpreted as a sequence boundary by Midtgaard (1996b). Previous workers, e.g. Nordenskiöld (1871), Gry (1942) and Midtgaard (1996b), have considered the Kome Formation to be overlain by the Atane Formation on Nuussuaq. We propose that the new Slibestensfjeldet Formation separates the Kome and Atane

Fig. 26. Contact between Precambrian basement and the Kome Formation at Talerua. The sediments onlap the relief on the basement surface. The height of the coastal cliff is *c.* 30 m. For location, see Fig. 22.

Formations in the area between Ikorfat and Slibestensfjeldet.

Geological age. Various fossils contribute to the determination of the geological age of the Kome Formation. Plant macroflora suggests a Barremian to Aptian age (Heer 1882; K.R. Pedersen 1968). The Ikorfat flora suggests an Early to Middle Albian age (Boyd 1998a, b, c, 2000). Based on spores and pollen as well as scarce dinocysts, Ehman *et al.* (1976) suggested a Late Albian to Early Cenomanian age, whereas Croxton (1978a, b) interpreted the sediments to be older than Middle Albian. In this study, the spores, pollen and brackish-water dinocysts are considered suggestive of a pre-Late Albian age. Consequently, the Kome Formation is suggested to be of albian age.

Correlation. It has previously been stated by Troelsen (1956) and Rosenkrantz (1970) that the sediments exposed on the north coast of Nuussuaq, east of the Ikorfat fault zone, are older than the fluviodeltaic Cretaceous sediments known from the rest of the Nuus-

Fig. 27. The type locality of the Kome Formation at Majorallattarfik showing outcrop of facies association B (see text for explanation). Person for scale (circled) is standing on delta front deposits (see also Fig. 24, right-hand column). For location, see Fig. 21. Photo: T.C.R. Pulvertaft.

Fig. 28. Reference locality of the Kome Formation at Kuuk showing outcrop of facies associations **A** and **C** (see text for explanation, see also Fig. 29). For location, see Fig. 21. Photo: T.C.R. Pulvertaft.

suaq Basin. However, Lanstorp (1999) suggested a Middle to Late Albian age for the Atane Formation at Tartunaq (south-east Nuussuaq), thereby shortening (or removing) the time gap between the Kome and Atane Formations. Nevertheless, the Kome Formation is retained as a discrete lithostratigraphic unit characterised by the onlap relationship to the basement, the coarse-grained conglomeratic character and the significant lateral facies changes (Fig. 25). These features indicate a depositional environment that was markedly different from that which produced the cyclic, aggradational Atane Formation.

In the Kuuk area, the mudstones of association B and the sandstones of association C (Pulvertaft 1979), referred here to the Kome Formation, may correlate laterally with the Slibestensfjeldet and Atane Formations, respectively, farther to the north-west (Fig. 29). Thus, the mudstones of association B (Fig. 24) and the mudstone-dominated unit of the type section (40–80 m in Fig. 23) are thought to represent proximal correlatives of the Slibestensfjeldet Formation. The sandstones of association C display an erosional base and occur towards the top of the exposed sections (Fig. 29). This unit contains chert pebbles, a characteristic feature of the Atane Formation and particularly the fluvial sandstones of the Ravn Kløft Member of the Atane Formation (see below). It is tentatively suggested, therefore, that the erosional base of the sandstones in facies association C may correlate with the erosional boundary between the Slibestensfjeldet and Atane Formations, i.e. that the uppermost Kome Formation in the Kuuk area correlates with the lowermost Atane Formation to the north-west (Fig. 29).

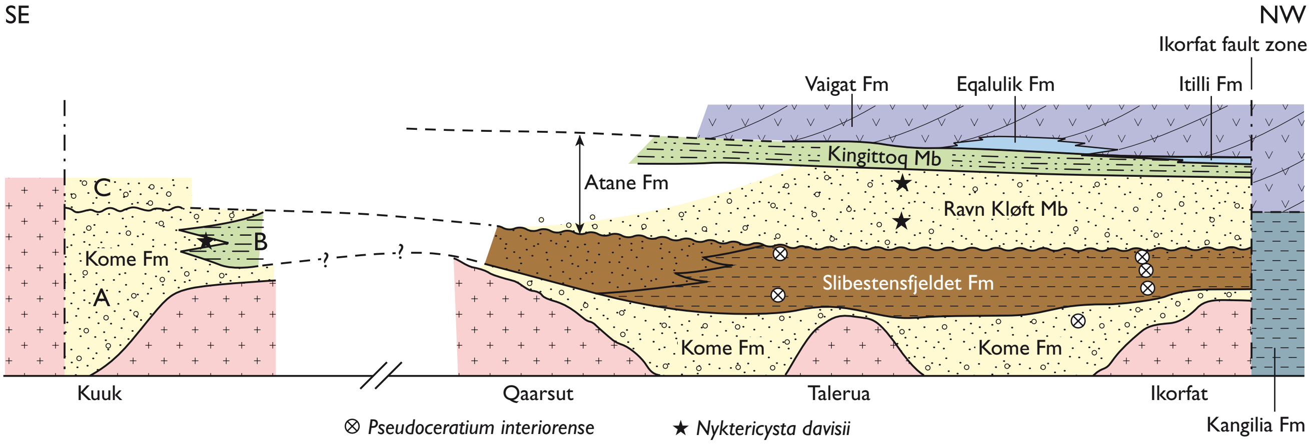


Fig. 29. Schematic profile (scale arbitrary) along the north coast of Nuussuaq between Kuuk and Ikorfat showing correlation of the lithostratigraphic units. The sediment outcrops are bounded to the east by the basin boundary fault and to the west by the Ikorfat fault zone. The occurrence of two species of dinoflagellate cysts is shown. These species are known from other localities in the Nuussuaq Basin. For location of outcrops, see Figs 21, 22; **A**, **B**, **C**, facies associations discussed in the text. Pale red indicates Precambrian basement.

Slibestensfjeldet Formation

new formation

History. The Slibestensfjeldet Formation has previously been described as Unit 2, an informal lithological unit in the Slibestensfjeldet–Ikorfat area (Midtgaard 1996b).

Name. After the prominent mountain of Slibestensfjeldet on the north coast of Nuussuaq (Fig. 22).

Distribution. The Slibestensfjeldet Formation is known only from the north coast of Nuussuaq between Vesterfjeld and Ikorfat (Fig. 22; Midtgaard 1996b). The formation is not known to be preserved north of Nuussuaq, but it is expected to continue southwards, for some distance, in the subsurface. The extent of the formation west of the Ikorfat fault is not known.

Type section. The type section is at Kussinikassaq where the formation is thickest (Figs 22, 30), immediately east of the basement high at Ikorfat beginning at an altitude of *c*. 60 m a.s.l. The base of the type section is located at 70°46.20′N, 53°03.37′W.

Reference sections. Reference sections are found at Vesterfjeld, *c*. 860 m a.s.l., and in two gullies on Slibestensfjeldet *c*. 1 km east of Talerua, beginning at an altitude of *c*. 320 m a.s.l. (Fig. 30).

Thickness. The Slibestensfjeldet Formation increases in thickness from 90 m at Vesterfjeld to *c*. 200 m at Kussinikassaq (Figs 22, 30).

Lithology. A considerable lateral change in lithology characterises the Slibestensfjeldet Formation from Vesterfjeld to Ikorfat, a distance of approximately 10 km (Fig. 30; Midtgaard 1996b). At the type section, the formation is dominated by mudstones, interbedded with 0.2–2 m thick sandstone beds, which are structureless, parallel laminated, cross-laminated or hummocky cross-stratified (Figs 30, 31, 32). The mudstones contain *c*. 5% carbon, almost entirely of organic origin, traces of pyrite are restricted to a thin coal bed, and the calculated carbon/sulphur (C/S) ratios are *c*. 100. The sandstone interbeds in the *c*. 200 m thick mudstone unit become increasingly common upwards. At the top of this coarsening-upward succession is a medium-grained sandstone unit 5 m thick, showing steeply dipping foresets; this facies is restricted to the areas west of the Talerua fault. In the east, the formation is dominated by sandstones interbedded with thin mudstones and conglomerate beds. Laminated black mudstones with sand streaks are abruptly overlain by very fine- to fine-grained, well-sorted sandstones dominated by horizontal lamination and hummocky cross-stratification, whereas low-angle cross-bedding and wave ripple cross-lamination are subordinate (Midtgaard 1996a). The sandstones are often slightly bioturbated. Thin conglomerate beds composed of well-rounded clasts and showing erosional bases and wave-rippled tops, recur throughout the formation (Midtgaard 1996a).

Fossils. The mudstones contain an assemblage of brackish-water dinocysts dominated by *Pseudoceratium interiorense* whereas the pollen *Rugubivesiculites rugosus* is absent (Figs 29, 30). Plant macrofossils from the lowermost part of the formation are referred to the Ikorfat flora, which has been assigned to the Early–Middle Albian (Boyd 1998a, b, c, 2000).

Depositional environment. The widely distributed and thick coal bed at the base of the Slibestensfjeldet Formation indicates accumulation of peat under a slowly rising ground-water table. The overlying fine-grained, wave-rippled sandstones are interpreted as lake shoreline deposits and indicate an increasing rate of water level rise, which continued to the deposition of mudstones at depths below wave-base. In the mudstones, the C/S ratios of *c*. 100 and the stratigraphical position between the fluvial Kome and the fluvial Ravn Kløft Member indicate that the Slibestensfjeldet Formation was deposited in a large and deep lake. The overall, coarsening-upward, vertical facies succession is interpreted to record the infill of the lake and progradation of the shoreline. The presence of dinocysts, which are interpreted as brackish-water forms, suggests that the lake was connected to a coastal lagoon. The lake increased in depth from east to west, and wave-influenced, relatively shallow-water facies are only known from Vesterfjeld and Slibestensfjeldet. The conglomerate beds represent transgressive lags created by wave erosion and winnowing. The nearshore sandstones accu- mulated in large complex bedforms overprinted by wave-ripples (Midtgaard 1996a). The upper part of the Slibestensfjeldet Formation locally developed as a

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Fig. 30. Type section of the Slibestensfjeldet Formation at Kussinikassaq; reference sections of the formation at Vesterfjeld and Slibestensfjeldet. Note the marked increase in thickness towards the west (Kussinikassaq). All logs are from the north coast of Nuussuaq (Fig. 22). For legend, see Plate 1; **GD**, Gilbert Delta; **Ps**, palaeosol.

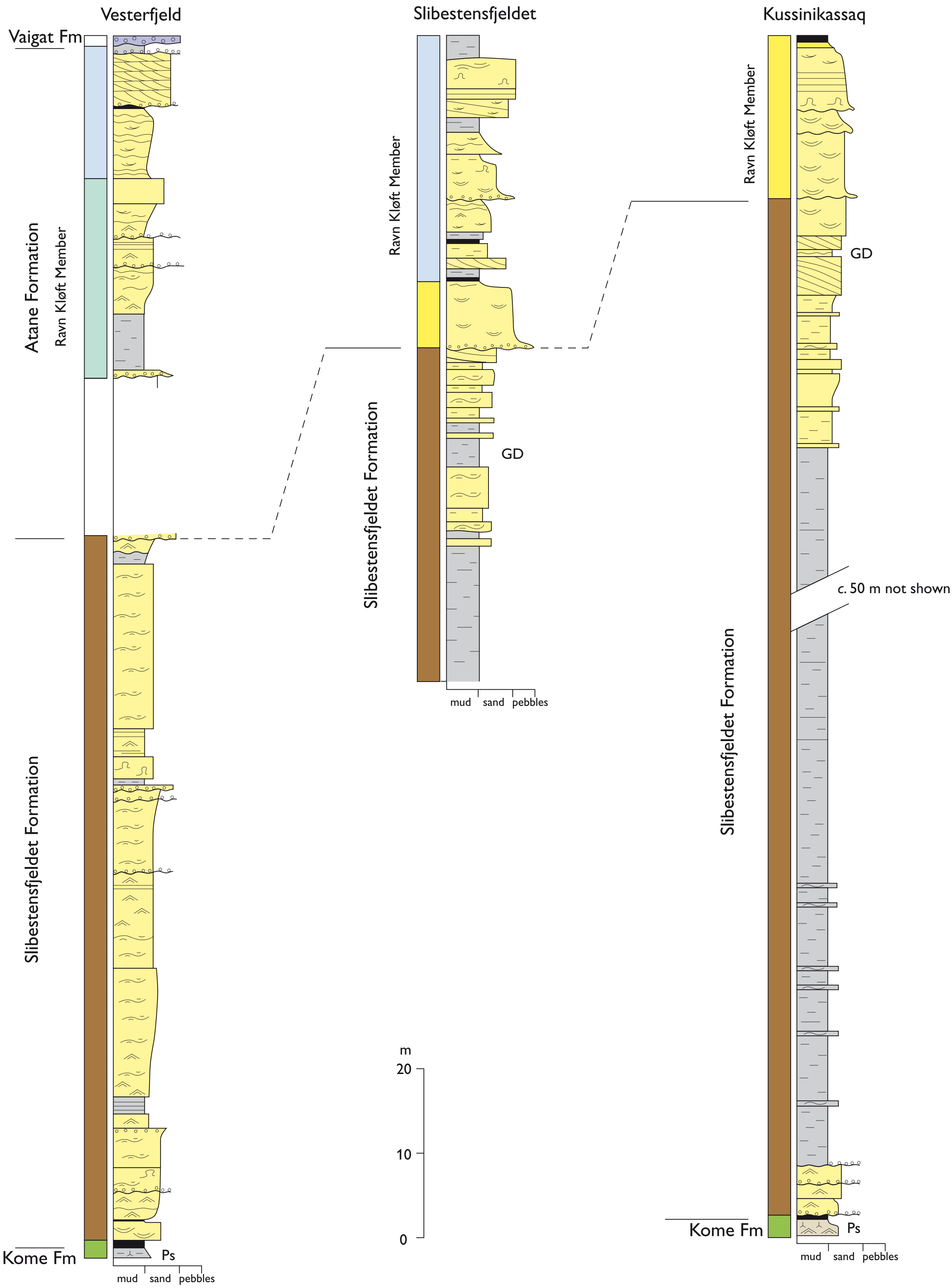
Vesterfjeld
Slibestensfjeldet
Kussinikassaq
Vaigat Fm
Atane Formation
Ravn Kløft Member
Slibestensfjeldet Formation
Kome Fm
Ps
mud
sand
pebbles
GD
c. 50 m not shown
m
20
10
0

Fig. 31. Mudstones with thin sandstone beds in the lower part of the Slibestensfjeldet Formation at Kussinikassaq, near Ikorfat. For location, see Fig. 22.

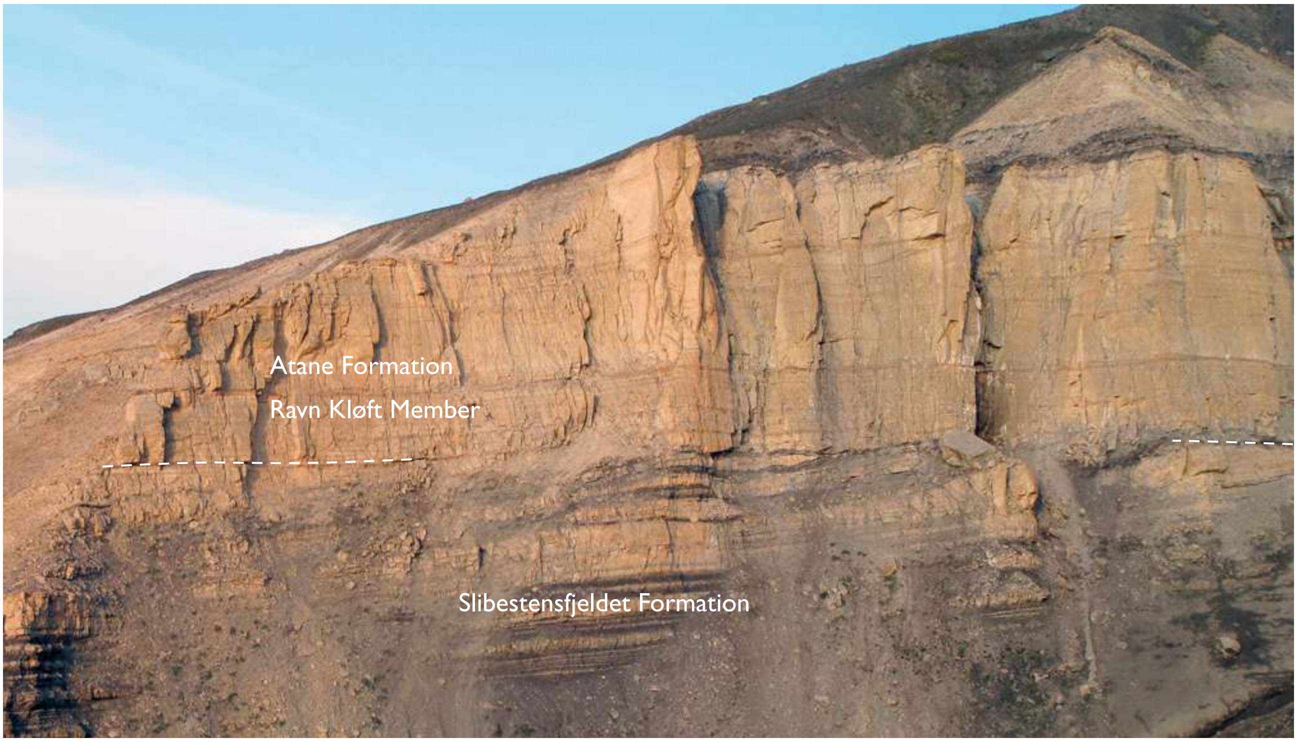

Fig. 32. The upper part of the Slibestensfjeldet Formation in its type locality at Kussinikassaq, where heterolithic sandstone bodies with wave-generated sedimentary structures (see also Midtgaard 1996 a, b) are overlain by lower shoreface sandstones (see Fig. 30) and locally by Gilbert delta foreset beds. The Slibestensfjeldet Formation is erosionally overlain (dashed line) by the fluvial Ravn Kløft Member of the Atane Formation. The height of the section is *c.* 100 m. For location, see Fig. 22.

Gilbert delta in the Ikorfat area (Figs 30, 32; Midtgaard 1996b). The extent of the lake or lagoon west of Ikorfat is not known. It may be speculated that subsidence along the Ikorfat Fault affected the development of the lake.

Boundaries. The lower boundary of the Slibestensfjeldet Formation is sharp and varies very little laterally; it is placed at the base of a 20–110 cm thick, continuous coal bed that overlies a palaeosol (Fig. 30).

The upper boundary of the Slibestensfjeldet Formation with the Atane Formation is defined by an abrupt contact between shoreface sandstones or Gilbert delta sandstones and coarse-grained, pebbly fluvial sandstones of the Ravn Kløft Member (Figs 30, 32). The boundary has been interpreted either as a minor angular unconformity (Gry 1940; Koch 1964) or as the conformable, yet erosional base of a channel (Ehman *et al.* 1976; Schiener 1977; Croxton 1978a, b; Midtgaard 1996b). Midtgaard (1996b) interpreted the boundary as a sequence boundary.

Geological age. Based on plant macrofossils referred to the Ikorfat flora, the Slibestensfjeldet Formation has been assigned an Early to Middle Albian age (Boyd 1998a). The dinocysts suggest a Late Albian age (Ehman *et al.* 1976; Croxton 1978a, b) or more likely a pre-Late Albian age (this study).

Correlation. The Slibestensfjeldet Formation in the Slibestensfjeldet outcrops may correlate with coarsening-upward successions in the Kome Formation at Kuuk (Fig. 29). Outcrops connecting these two areas are, however, not present.

Upernivik Næs Formation

revised formation

History. The sedimentary outcrops at Upernivik Næs were described by Steenstrup (1883b) who noted that the coal-bearing sediments have a thickness of at least 860 m. The lithology was not considered different from the coal-bearing successions known from Nuussuaq and Disko. The macrofossil plants collected at Upernivik Næs by Steenstrup were referred to the Atane flora by Heer (1883b). In contrast, Seward (1926) compared them to the Kome flora. Koch (1964) considered the fossil flora from Upernivik Ø as difficult to interpret due to similarities to both the Kome and the Atane floras and suggested that the Upernivik Ø flora could occupy an intermediate position. Troelsen (1956) did not recognise the Upernivik Næs Formation, which was later described by Koch (1964).

Name. The formation is named after Upernivik Næs on the south-western corner of the island of Upernivik Ø (Figs 2, 33).

Distribution. The formation is known from Upernivik Ø. The marginal marine sediments on the island of Qeqertarsuaq and on Itsaku are here referred to the Upernivik Næs Formation (Figs 2, 73; Ødum & Koch 1955, Christiansen *et al.* 2000; J.G. Larsen & Pulvertaft 2000).

Type section. The type section is located on the south-western corner of Upernivik Ø, along a large stream that flows out on the south coast of the island *c.* 2.5 km east of Upernivik Næs (Figs 33–35). The base of the type section is located at 71°09.88´N, 52°54.52´W.

Reference section. A reference section is exposed in a coastal cliff on western Qeqertarsuaq (Figs 2, 36, 73).

Thickness. The formation is *c.* 1600 m thick at Upernivik Næs, where the strata generally dip *c.* 15° towards the north-east (Henderson & Pulvertaft 1987). Croxton (1978b) measured a 1310 m long section (termed the C9 section) along the southern coast of Upernivik Næs; this section coincides with the type section in its upper part. In the type section, the formation is exposed up to *c.* 500 m a.s.l. (Fig. 33).

Lithology. The section at Upernivik Næs is dominated by sandstones; mudstones constitute only a minor part (Figs 34, 35). On Qeqertarsuaq, sandstone-dominated successions are locally overlain by clast-supported conglomerates, in which the clasts are dominantly from the metamorphic rocks of the widely exposed Karrat Group (Fig. 37; Henderson & Pulvertaft 1987). The formation has been studied at a reconnaissance level by Midtgaard (1996b), who divided the sediments of the formation into four facies associations.

Facies association A. Coarse-grained, poorly sorted sandstones constitute up to 34 m thick composite depositional units (Fig. 38). Some of these are distinctly fining upwards. Basal channel lags contain pebbles of crystalline rocks and locally also mudstone clasts, logs and carbonaceous debris. The sandstones are cross-bedded with most palaeocurrent directions towards the western quadrant. Soft-sediment deformation structures are common.

Facies association B. Well-sorted, fine- to medium-grained sandstones with abundant mudstone clasts characterise the association. Siltstone and mudstone beds and laminae form an important component and in places are heterolithic and ripple-cross laminated. The sandstones are dominated by planar or trough cross-bedding that indicates palaeocurrents to the north. Some sandstones have mud-draped foresets and show bundled lamination (Fig. 39). The mud-dominated heteroliths and mudstones contain much comminuted plant debris; bioturbation varies from moderate to intense (Fig. 39).

Facies association C. Sandstones interbedded with mudstones constitute 3–8 m thick successions. The sandstones range from very fine- to very coarse-grained, the beds are erosionally based and pinch out laterally. They are cross-laminated, cross-bedded or locally horizontally stratified. The tops of the sandstone beds are moderately bioturbated. The mudstones are black, fissile and sand-streaked, and sometimes contain abundant plant debris and vitrinite lenses. Sandstone dykes are common, and gentle folding indicates that they were intruded before or during compaction.

Facies association D. Coarsening-upward successions comprising black fissile mudstones, mudstones with sandstone lenses, mud-draped ripple cross-laminated, fine-grained sandstones, and trough cross-bedded sandstones with comminuted plant debris (Midtgaard 1996b). These deposits constitute only a minor part of the section shown in Fig. 34.

Fossils. The Upernivik Næs Formation contains angiosperm plants referred to the Upernivik Næs flora (or Upernivik flora), which is interpreted as intermediate in age between the Kome flora and the Atane flora (Koch 1964; Boyd 1998a). Macrofossil plants from Qeqertarsuaq correspond to species known from outcrops at Upernivik Næs and Atanikerluk (Ødum & Koch 1955). Few palynomorphs have been recorded from Croxton's (1978b) C9 section through coastal exposures and the type section at Upernivik Næs. The presence of a few specimens of the pollen *Rugubivesiculites rugosus* throughout the section indicate a Middle Albian to Turonian age, and the co-occurrence with a few specimens of the dinocysts *Nyktericysta davisii* and *Quantouendinium dictyophorum* in the lower part of the section suggests correlation to the lower part of the Atane Formation (?Ravn Kløft Member). A large specimen of the dinocyst *Nyktericysta davisii* has been recorded from the middle part of the C9 section. Similar forms are common in sediments on Qeqertarsuaq (Christiansen *et al.* 2000) and from a single fully marine sample from the Atane Formation at Ikorfat dated as Early Turonian. The sediments in facies

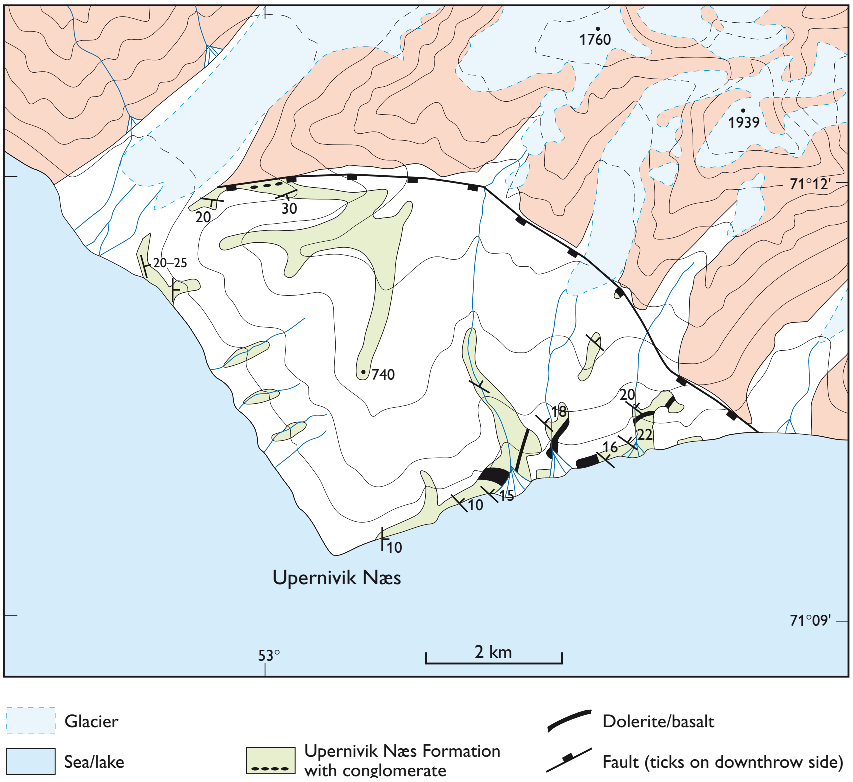

Fig. 33. Geological map of Upernivik Næs on the south-western tip of Upernivik Ø. The type section of the Upernivik Næs Formation is located in the ravine 2.5 km east of Upernivik Næs. Slightly modified from Henderson & Pulvertaft (1987). For location, see Fig. 2. The contour interval is 200 m.

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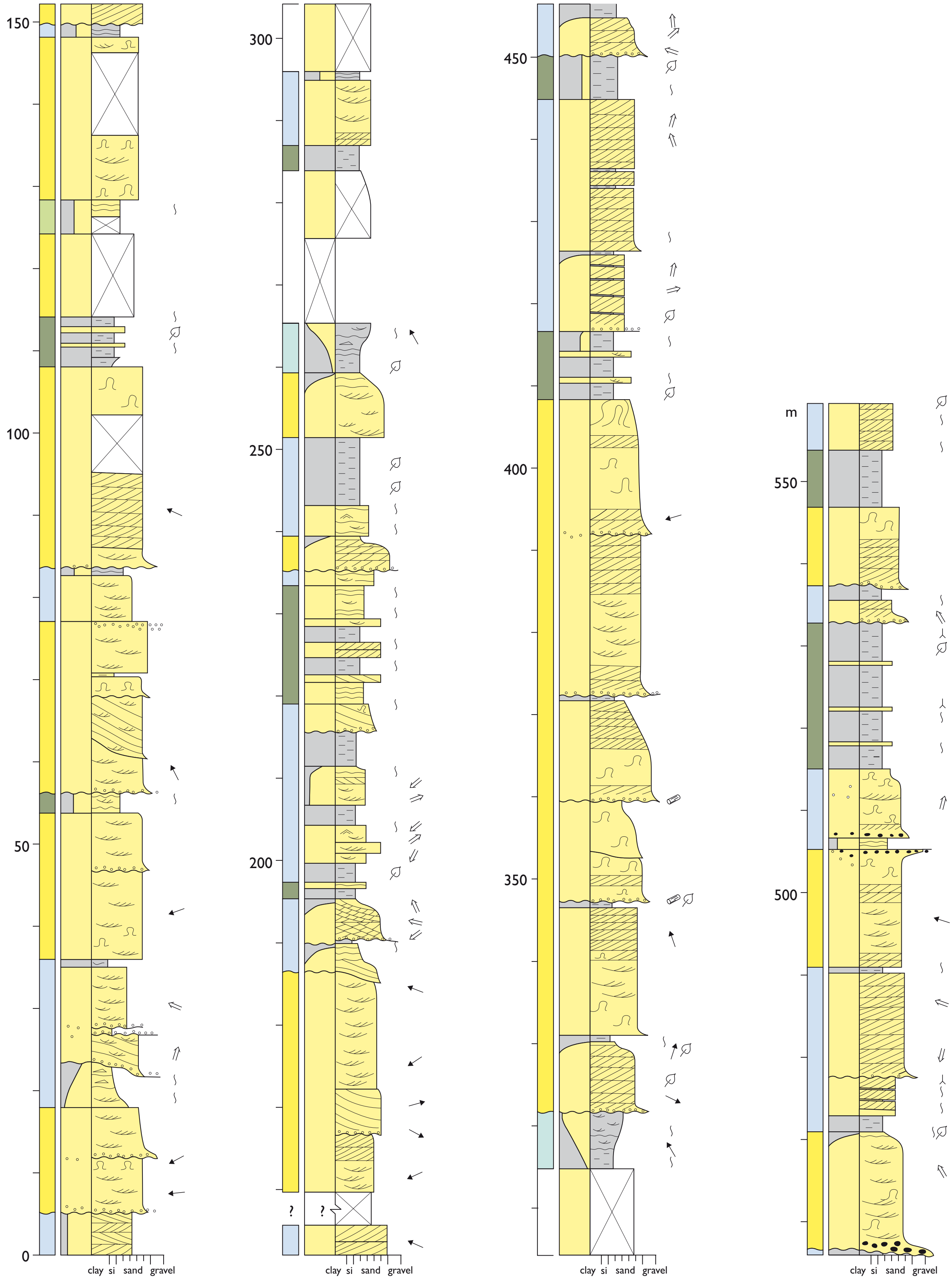
Fig. 34. Type section of the Upernivik Næs Formation; from Midtgaard (1996b). Notice the presence of tidal deposits. For legend, see Plate 1; for location, see Fig. 33.


150
100
50
0
clay si sand gravel
300
250
200
?
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clay si sand gravel
450
400
350
clay si sand gravel
m
550
500
clay si sand gravel

Fig. 35. Type locality of the Upernivik Næs Formation. The central peak is *c.* 1700 m high. For location, see Fig. 33.

association B contain trace fossils such as *Skolithos, Arenicolites, Conichnus, Planolites, Rhizocorallium* and *Pelecypodichnus* (Midtgaard 1996b).

Depositional environment. The sandstones of facies association A are interpreted to have been deposited in braided fluvial channels. The scarcity of interbedded floodplain or levee facies suggests that the channels were migrating laterally. The abundant soft-sediment deformation structures suggest synsedimentary tectonic activity.

The heterolithic, burrowed sandstones (facies association B) are interpreted to have been deposited in an estuarine environment – in tidal channels, tidal point bars, tidal deltas, tidal flats, bay mudstones, and on the shoreface as transgressive lags. The palaeocurrents are interpreted to reflect longshore tidal transport.

The interbedded sandstones and mudstones (facies association C) are thought to represent a coastal plain environment and include lagoonal, mudflat and marsh deposits, crevasse splay deposits and deposits in small channels. The scarcity of rootlets and the presence of trace fossils suggest brackish-water conditions. Intrusion of the sandstone dykes may have been triggered by earthquakes.

The coarsening-upward successions (facies association D) are interpreted as deltaic deposits. The lack of wave-generated sedimentary structures in facies association D in the Upernivik Ø section indicates deposition in a low-energy environment, probably an interdistributary bay or the inner part of an estuary, i.e. a bayhead delta (Midtgaard 1996b). Higher-energy facies on Qeqertarsuaq and Itsaku suggest the influence of waves and storms on the delta deposits (J.G. Larsen & Pulvertaft 2000).

Boundaries. The lower boundary of the Upernivik Næs Formation is not exposed in the type section nor in the reference section. Conglomerates with large clasts of both weathered and fresh basement rocks have been reported close to the boundary fault at Upernivik Næs (Fig. 33), from a small outcrop on the north-western part of Upernivik Ø (Henderson & Pulvertaft 1987 fig. 46), from Qeqertarsuaq and from Itsaku (Rosenkrantz &

Fig. 36. Outcrop of the Upernivik Næs Formation on Qeqertarsuaq; for location, see Fig. 73. Reddish-brown intrusions cross-cut (right) and cap the sediments.

Pulvertaft 1969). The boundary between the Kome and the Upernivik Næs Formations is at present not known.

The upper boundary of the formation is an erosional contact with the Kangilia Formation on Itsaku and with Quaternary deposits on Upernivik Næs and Qeqertarsuaq.

Geological age. The Upernivik Næs flora contains angiosperm plants, which suggests a greater similarity to the Atane flora than to the Kome flora (Koch 1964). Koch recommended, however, that until the Cretaceous floras are thoroughly revised, the Upernivik Næs flora should

Fig. 37. Clast-supported conglomerate of the Upernivik Næs Formation on Qeqertarsuaq. Hammer for scale; for location, see Fig. 73.

Fig. 38. Channellised sandstones of the Upernivik Næs Formation in the lower part of the type section. Thickness of sandstone unit is approximately 10 m. For location, see Fig. 33.

be eliminated from the discussion of the age of the Kome and Atane Formations and treated as an independent problem (Koch 1964 p. 540).

Rosenkrantz (1970) suggested that the Upernivik Næs flora is of Albian–Turonian age. Boyd (1998a) suggested that the Upernivik Næs flora is contemporaneous with his Ravn Kløft flora which he referred to the Middle–Late Albian and earliest Cenomanian. The poor palynological assemblage indicates a Late Albian to Early Turonian age (Croxton 1978a, b; this study).

Fig. 39. Detail of tidally influenced deposits of the Upernivik Næs Formation in the lower part of the type section. Person for scale; for location, see Fig. 33.

Correlation. The Upernivik Næs flora was suggested to be coeval with the Ravn Kløft flora by Boyd (1998a). This suggests a correlation between the Upernivik Næs Formation and the Ravn Kløft Member of the Atane Formation (Figs 13, 16).

Atane Formation

redefined formation

History. Nordenskiöld (1871) erected the Atane Formation (Atanelagren), naming it after the now-abandoned settlement of Atane (now Ataa, Figs 3, 40). He described the unit to be more shaly than both the underlying Kome Formation and the overlying Upper Atanikerdluk Formation, and interpreted the Atane Formation as freshwater deposits. He referred the formation to the Upper Cretaceous, following Heer (1868), with a distribution on southern Nuussuaq (between Atanikerluk and Ataa), northern Disko (at Qullissat) and at Kuuk on northern Nuussuaq (at altitudes above 250–300 m). Outcrops with coal seams were visited by Steenstrup (1874), who noted the occurrence of marine invertebrates in mudstones between the coal seams at Paatuut and Nuuk Qiterleq.

The Atane Formation normally appears as a striped white, grey and black sandy and shaly unit rich in coalified plant fossils (Fig. 41) that formed the basis of the classic studies by Heer (1868, 1870, 1874a, b, 1880, 1883a, b). However, self-combustion of the mudstones has locally produced brick-red, hard and fissile burnt slabs (Fig. 42) in which fossils are excellently preserved as impressions. Burnt mudstones are fairly common in the Paatuut (formerly spelled Patoot, Pâtût or Pautût) and Kingittoq areas, and they were included in the regional collection that Steenstrup sent to O. Heer (Steenstrup 1883a, b). Based on their colour, Heer treated the samples of burnt mudstones from Paatuut as lithostratigraphically different from those containing the Atane flora. Thereby a Patoot Formation (i.e. the sediments comprising the Patoot flora) was introduced and subsequently treated as a formal unit (Troelsen 1956). Steenstrup (1883c) objected to Heer's interpretation of a stratigraphic boundary between the unburnt and the burnt mudstones from Paatuut since he had observed that the burnt mudstones are laterally equivalent to the normal, unburnt sediments.

Steenstrup (1883a) suggested that all the Cretaceous sediments from Svartenhuk Halvø to Disko should be enclosed in one lithostratigraphic unit. He envisaged the depositional environment of the horizontally bedded mudstones and sandstones as shallow marine on account of his collections of invertebrates (bivalves and echinoids), although the well-preserved plant remains indicated deposition close to vegetated areas (Steenstrup 1883a p. 48).

The Early Cretaceous to Miocene age proposed by Heer for the coal-bearing deposits in West Greenland was discussed by A. Heim and J.P.J. Ravn, who both suggested that Heer's interpretation spans too long a period. Instead they interpreted all the sediments as Upper Cretaceous to Eocene (Heim 1910), more specifically the Kome flora as Albian, the Atane flora as Cenomanian, the Patoot flora as Senonian and the Atanikerdluk flora as Eocene (Ravn 1918 p. 320). Ravn (1918) envisaged the plant bearing sediments as having been deposited in a fresh- to brackish-water environment, in which the rate of deposition equalled the rate of subsidence. The inoceramids provided evidence of marine conditions and Ravn therefore concluded that at times subsidence exceeded deposition and marine environments were established. Furthermore, he observed no changes in the style of sedimentation during the Cretaceous and inferred that deposition had occurred continuously, presumably within a restricted period and consequently at relatively high rates of sediment accumulation.

Troelsen (1956) maintained the distinction between the Kome, Atane and Patoot Formations, quoting descriptions by Nordenskiöld (1871) and Heer (1883b). These authors suggested that the Kome and Atane Formations are separated by a slight angular unconformity (Troelsen 1956).

Koch (1964) regarded the Pautût Formation (*sensu* Heer 1883b) as an artificial unit. Henderson *et al.* (1976 fig. 303) quoted the lithostratigraphy of Troelsen (1956), but stressed that the Kome, Atane and Pautût formations lacked formal stratigraphic definition and referred all the fluvial and deltaic Cretaceous sediments on Disko and southern to central Nuussuaq to the Atane Formation. Ehman *et al.* (1976) used the term Atane Formation informally for the Cretaceous non-marine deposits and found that the sediments range in age from Albian through Santonian.

G.K. Pedersen & Pulvertaft (1992) referred all non-marine Cretaceous sediments on Disko and Nuussuaq to the Atane Formation. They claimed (p. 263) that the term Atane Formation "had outlived the other formation names that have been used in the past for the different isolated outcrops of Cretaceous non-marine strata in West Greenland". Based on the data available at that time, G.K. Pedersen & Pulvertaft (1992 p. 263) interpreted these strata as "belonging to the same deposi-

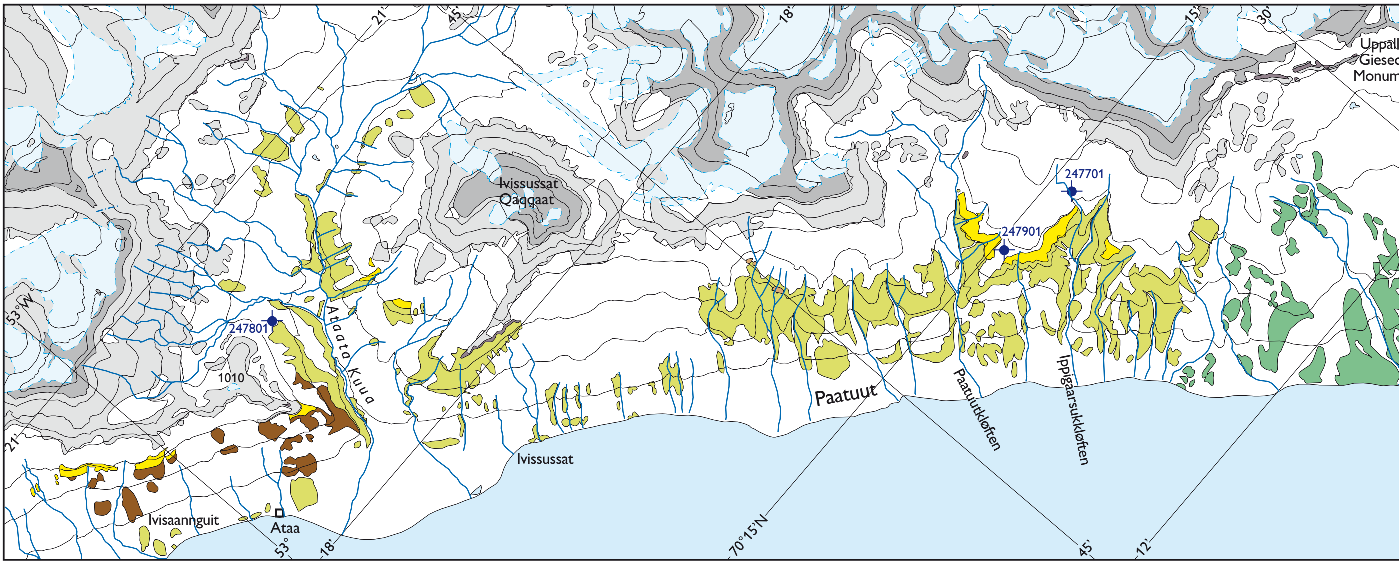
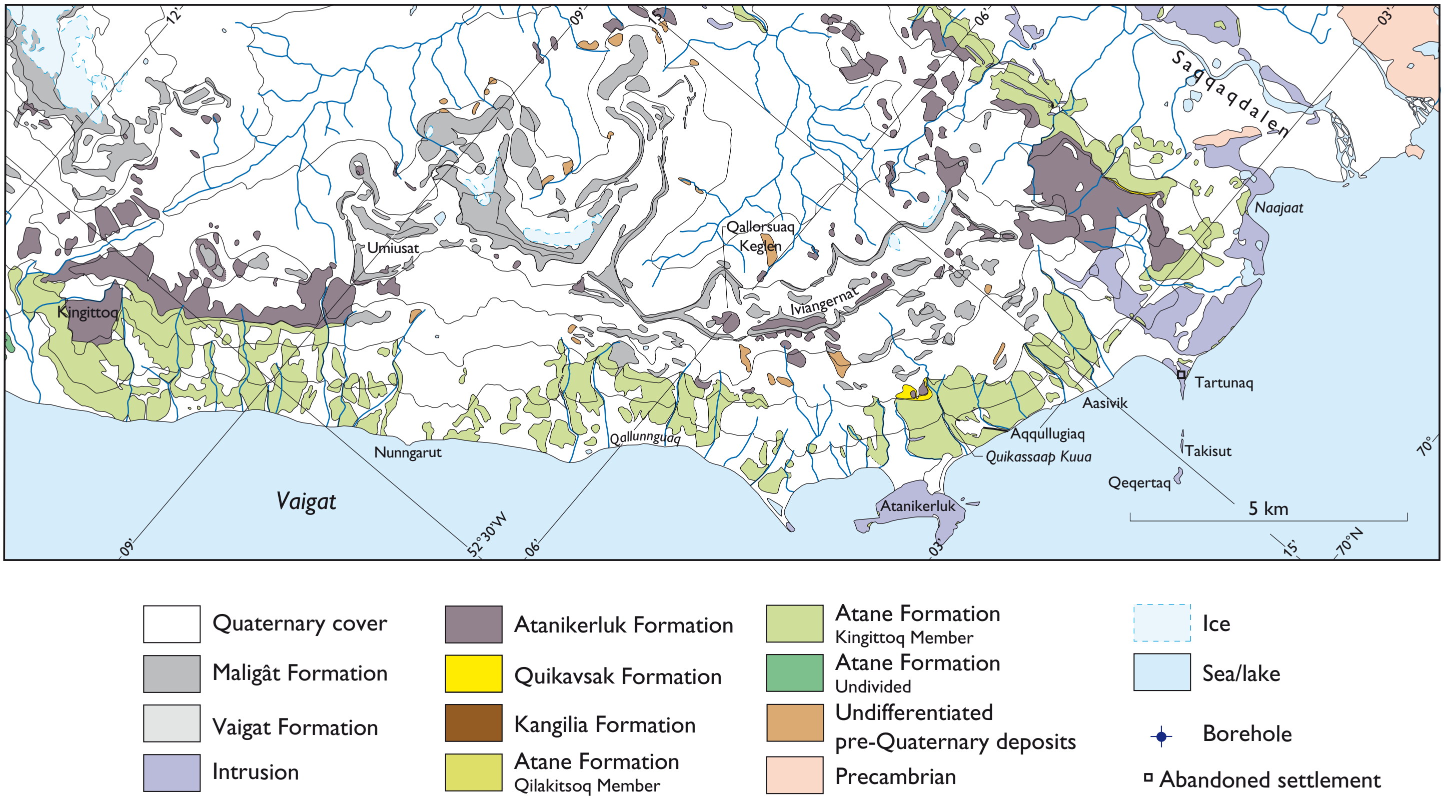


Fig. 40. Geological map of the south coast of Nuussuaq from Saqqaqdalen to Ivisaannguit, simplified from A.K. Pedersen *et al.* (2007b). The type localities of the Atane, Quikavsak and Atanikerluk Formations are all found within this area. The wells GGU 247701, GGU 247801 and GGU 247901 indicated on the map were drilled to obtain technical information on the coal-bearing strata of the Atane Formation. Contour interval is 200 m; for location, see Fig. 2.

Fig. 41. Typical outcrop of the Atane Formation at Paatuut on southern Nuussuaq. Note the prominent cyclic alternation of lithologies. For location, see Fig. 40. **Q**, Quikavsak Formation; compare with Fig. 14.



tional system and the same age interval, so that no more than one formation name seems at present to be required for the entire non-marine Cretaceous of the area". Later, from sedimentological studies, Midtgaard (1996b) argued for the continued distinction between the Atane, Kome and Upernivik Næs Formations, as well as for the new Slibestensfjeldet Formation. Boyd (1993) considered, mostly on floral evidence, that the sediments at Paatuut should not be included in the Atane Formation. He therefore retained the Pautût flora and the Pautût Formation (Boyd 1993 p. 253). There are, however, no lithological or sedimentological arguments for retaining the Pautût Formation of Troelsen (1956) or Boyd (1993), and we therefore recommend that it be abandoned and included in the Atane Formation.

Name. From a former settlement Ataa (old spellings Atane, Atâ) on the south coast of Nuussuaq immediately west of Ataata Kuua (Figs 2, 3, 40; Nordenskiöld 1871 plate XXI). Today only ruins of a few turf houses are seen at Ataa.

Distribution. The Atane Formation is restricted to Disko and Nuussuaq. It comprises the lowermost exposed deposits on eastern Disko and southern and central Nuussuaq. Marginally marine successions of Albian–Cenomanian age in the northern parts of the Nuussuaq Basin are referred to the Upernivik Næs Formation.

Exposures of the Atane Formation are found east of the Disko Gneiss Ridge and east of the Kuugannguaq–Qunnilik Fault (Fig. 10; Chalmers *et al.* 1999). On northern Nuussuaq, the Atane Formation is present east of the Ikorfat fault zone where it overlies the Slibestensfjeldet Formation (Fig. 22; Midtgaard 1996b).

The distribution of the Atane Formation west of the outcrop area is little known. There are, however, no sedimentological data from the Atane Formation to indicate that the Disko Gneiss Ridge formed a morphological element during deposition of the formation. Finds of sandstone xenoliths with chert pebbles in lava flows on western Disko have been suggested to be derived from the Atane Formation (Chalmers *et al.* 1999). The xenoliths could, however, also have been derived from the Itilli Formation, which occurs on western Nuussuaq.

Type section. The type section of the formation is the cored well GGU 247801 (70°19.87′N, 52°55.18′W) in the gorge of the Ataata Kuua river (Figs 14, 40) where these sediments were first described by Nordenskiöld (1871). The next geologist on the site was K.J.V. Steenstrup. He noted in 1872 that the description given by Nordenskiöld did not match the outcrop and that the

Fig. 42. Well-exposed outcrop at Paatuut showing the self-combusted burnt shales (red) that grade into the typical black-and-white unburnt sediments of the Atane Formation (Qilakitsoq Member). Height of section is approximately 50 m. For location, see Fig. 40.

geographical position was inaccurate (Steenstrup 1874). He suggested that Nordenskiöld had measured the type section of the Atane Formation south-east of the Ataa river, at "the northern end of the Patoot gorges" (Steenstrup 1883b p. 64). Later Rosenkrantz (1970 p. 422) stated that: "... the type locality Atâ, 14 km south-east of the old village Atâ on the south coast of Nûgssuaq, is rather close to Pautût..", but in Henderson *et al.* (1976) the type locality of the Atane Formation was again given at Atâ (Ataata Kuua). The exposures along the western and eastern slopes of the Ataata Kuua gorge constitute a long, well-exposed section through the Atane Formation, and this has been measured photogrammetrically (Fig. 15; A.K. Pedersen *et al.* 2007b). The sedimentological log representing the type section (Fig. 43) was measured in the continuously cored borehole GGU 247801, which reached a depth of 566 m below terrain (76 m below sea level).

Reference sections. Skansen, J.P.J. Ravn Kløft, Kingittoq and Qilakitsoq provide well-exposed reference sections for the Atane Formation (Figs 48, 51, 53, 60). The two continuously cored boreholes GGU 247701 and GGU 247901, both from the Paatuut area, are reference boreholes for the Atane Formation. They comprise strata from the Qilakitsoq Member and have been described in detail by Ambirk (2000).

Thickness. The Atane Formation occurs in a number of fault blocks (J.M. Hansen 1980b; Chalmers *et al.* 1999; Marcussen *et al.* 2001, 2002). The faults are, however, rarely exposed and although they have been recognised on seismic profiles acquired in Vaigat and Uummannaq Fjord (Marcussen *et al.* 2002), it has not been possible to determine their throw. Furthermore the lower boundary of the formation is very rarely exposed. Therefore the thickness of the Atane Formation can only be given as an estimate.

The thickest exposed sections occur at Ivissussat on the south coast of Nuussuaq (700 m) and at Qilakitsoq on central Nuussuaq (800 m). Seismic data from the south coast of Nuussuaq show an unconformity at a depth of 1.5–2 km that has been suggested to represent the base of the Atane Formation (Christiansen *et al.* 1995; Chalmers *et al.* 1999). A seismic line across Vaigat indicates a minimum thickness of 3000 m for the Atane Formation (Fig. 44; Marcussen *et al.* 2001, 2002).

Lithology. The Atane Formation comprises mudstones, heteroliths, sandstones and coal beds; the relative proportion of the lithologies varies regionally. The formation is characterised by aggradation of 10–40 m thick depositional cycles, which often coarsen upwards (Fig. 45).

The sandstones are typically fine- to medium-grained, well sorted or heterolithic, with various types of cross-

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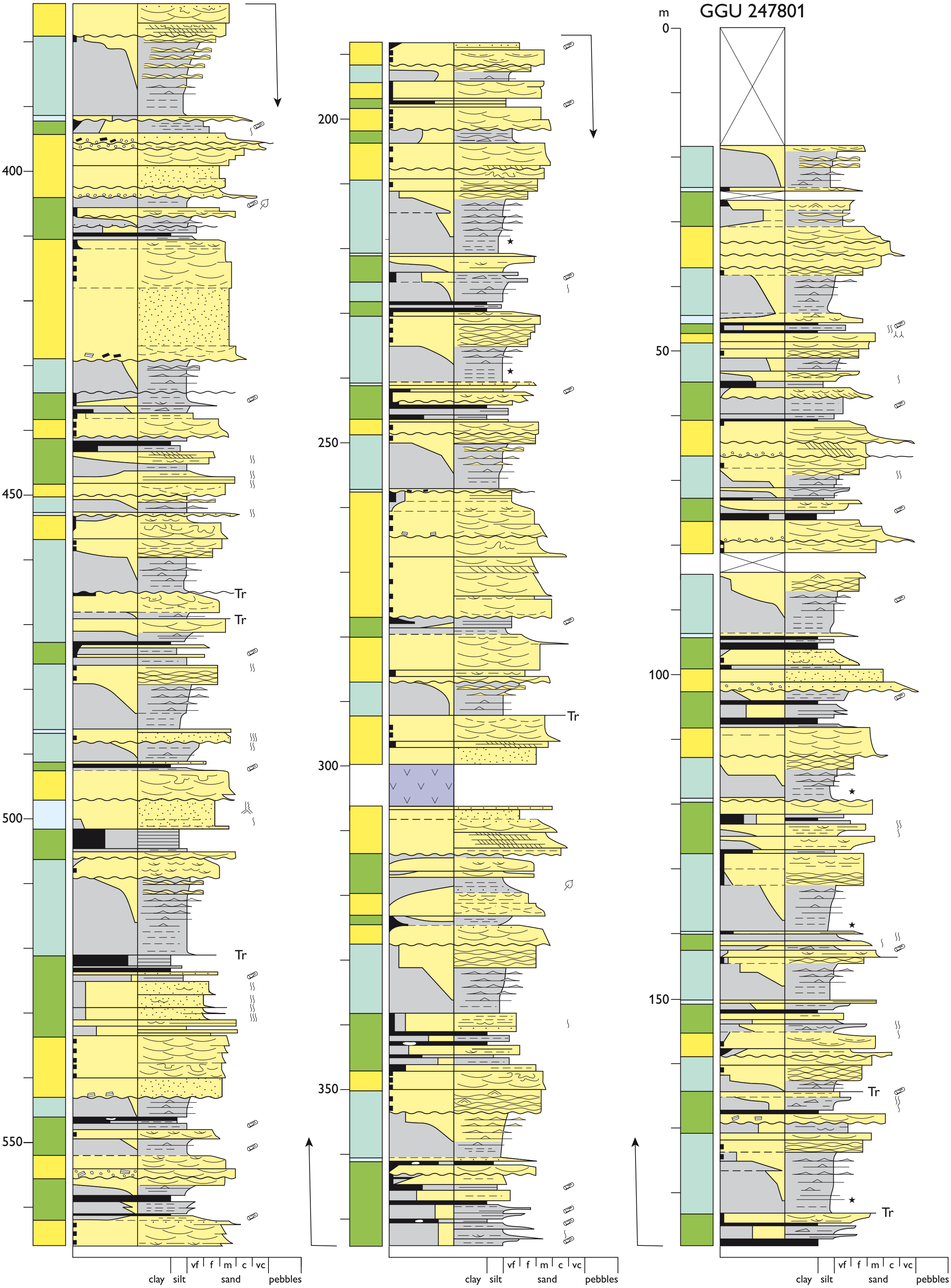
Fig. 43. Type section of the Atane Formation (and reference section for the Qilakitsoq Member) from Ataata Kuua, borehole GGU 247801. This core documents the stratigraphic interval known from the well-exposed section in the Ataata Kuua river gorge and extends this section down to 76 m below sea level. **Tr**, transgressive sandstones. For legend see Plate 1; for location, see Fig. 40.



GGU 247801
m
0
50
100
150
200
250
300
350
400
450
500
550
Tr
clay
silt
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f
m
c
vc
sand
pebbles

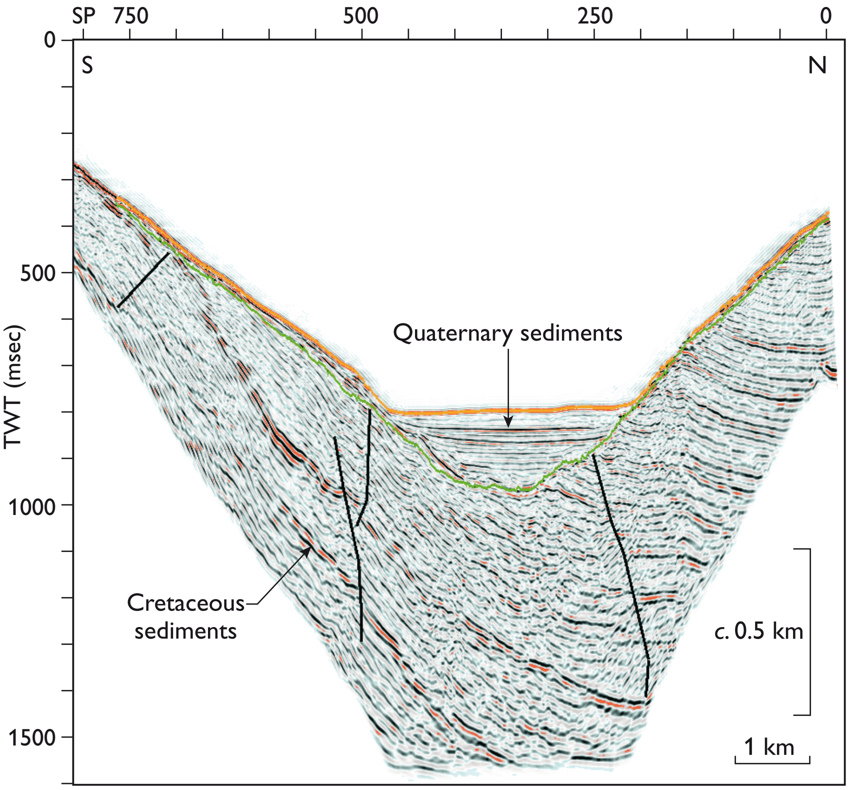


Fig. 44. Seismic section across the Vaigat (for location, see Fig. 2; sea level is at TWT=0). The submarine section continues into exposures of the formation up to 200–400 m a.s.l. on both sides of Vaigat indicating a minimum thickness of the Atane Formation of 3000 m (from Marcussen *et al.* 2002). **SP**, seismic shot points.

bedding, numerous soft-sediment deformation structures and local bioturbation. The sandstones consist of quartz, variably kaolinised feldspars, fragments of older quartz-rich sedimentary rocks, and small amounts of mica and other detrital minerals together with comminuted plant debris. Trace fossils are locally abundant. The sandstones are cemented by carbonate or clay minerals but are generally friable. Pervasive cementation is only patchily developed. The sandstones have sheet or ribbon geometries.

The mudstones are weakly laminated, typically silty, with kaolinite as the dominant clay mineral accompanied by a little mica. The mudstones fall into two groups: (1) mudstones ranging from silt-streaked mudstone to

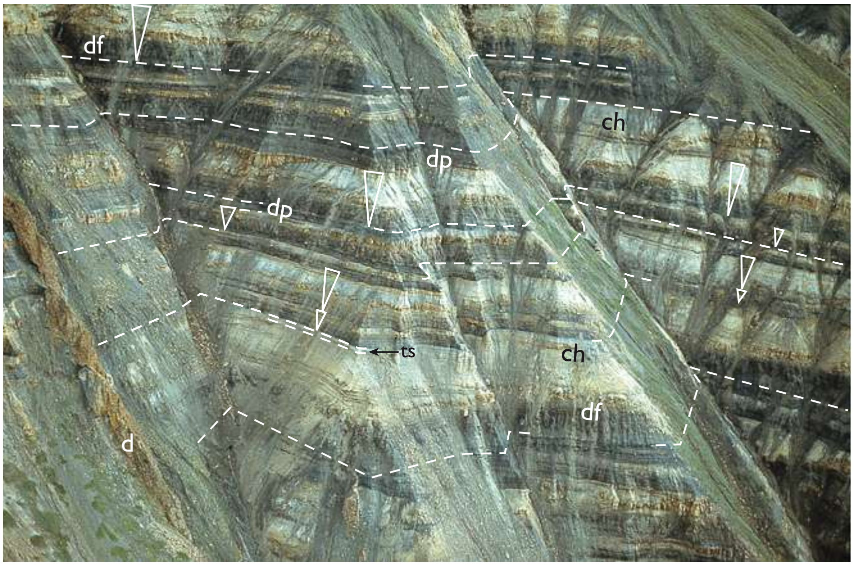


Fig. 45. Outcrop of the Atane Formation in the Paatuut area showing the four depositional environments characterising the Atane Formation: delta front (**df**), delta plain (**dp**), fluvial or distributary channel (**ch**) and transgressive shoreface deposits (**ts**). The delta front deposits form coarsening-upward units, indicated by triangular symbols. The dashed lines trace the bases of delta front mudstones. The sedimentary succession is cut by a dyke (**d**). The thickness of the section is *c.* 120 m; for location, see Fig. 40.

wave-rippled sand streaked mudstone to heterolithic sandstone, and (2) mudstones with plant debris, ranging from carbonaceous mudstone to clayey coal.

The coal beds are interbedded with carbonaceous mudstones, sand-streaked mudstones and heterolithic cross-laminated sandstones with local root horizons. The coal beds are typically less than 0.8 m thick. In several horizons, coal balls are observed, and silicified wood fragments are common. The coals belong to the 'banded coal' type dominated by the lithotypes vitrain and clarain. Macerals of the vitrinite group are often well preserved owing to the prevailing low rank of the coal. Detailed study of the organic particles and their geochemistry permit a distinction between fresh- and brackish-water environments of coal deposition (Shekhar *et al.* 1982; Bojesen-Koefoed *et al.* 2001; G.K. Pedersen *et al.* 2006).

The Atane Formation is characterised by depositional cycles that are typically 10–40 m thick (Figs 41, 46). The simplest cycles are seen on eastern Disko where they consist of 10–30 m thick sandstone sheets separated by *c.* 5 m thick units of mudstone and coal beds. On southern and central Nuussuaq, the cycles range in thickness from 5–15 m up to 40 m. They include coarsening-upward units beginning with mudstones at the base passing up into heterolithic mudstones, then heterolithic sandstones with hummocky cross-stratification and ripple cross-lamination and finally into cross-bedded sandstones, often with coal debris. The typical coarsening-upward cycle is capped by carbonaceous mudstones with thin sandstone or coal beds (Pedersen & Pulvertaft 1992 fig. 5). Bioturbated sandstones form part of many cycles. In the Paatuut area, 32 such cycles have been identified (Olsen 1991; Dueholm & Olsen 1993).

Fossils. The fossils of the Atane Formation comprise macroflora, spores and pollen, dinocysts, and invertebrate fossils (Heer 1868, 1870, 1874a, b, 1880, 1883a, b; Ravn 1918; Koch 1964; Birkelund 1965; Ehman *et al.* 1976; Croxton 1978a, b; Boyd 1990, 1992, 1993, 1994, 1998a, b; Olsen & Pedersen 1991; Koppelhus & Pedersen 1993; McIntyre 1994a, b, c; Nøhr-Hansen 1996; Lanstorp 1999; Dam *et al.* 2000).

Macrofossil plants from the Atane Formation are referred to three floras. The Ravn Kløft flora is characterised by angiosperms and conifers, and has few species in common with the Atane flora (Boyd 1998a, b). The Atane flora is a mixture of older Cretaceous species together with well-differentiated angiosperm species representative of many families (Koch 1964; K.R. Pedersen 1976). The Paatuut flora is dominated by conifer and angiosperm leaf species, and has many species in common with the Atane flora as well as numerous endemic species (Koch 1964; Boyd 1992, 1993, 1994).

Spores and pollen occur in most mudstone samples from the Atane Formation, although often the preservation is poor or the number of identifiable specimens is low. Regional studies of the spore and pollen assemblages have been carried out by Ehman *et al.* (1976) and Croxton (1976, 1978a, b). The latter distinguished two stratigraphically important assemblages, the first without angiospermous (tricolpate) grains (supposed to be Cenomanian or older), the second with angiospermous grains but lacking both *Aquilapollenites* and complex triporate grains. The second assemblage was proposed to be older than Late Campanian (Croxton 1978a p. 76). A large number of samples from the Cretaceous were examined on a reconnaissance basis by McIntyre (1994a, b, c, personal communication 1997) whereas Koppelhus & Pedersen (1993) and Lanstorp (1999) studied fewer sections in greater detail.

Marine dinocysts were described from central Nuussuaq (Ilugissoq, Qilakitsoq, Tunoqqu, southern part of Agatdalen) and from southern Nuussuaq (Paatuut, Ataata Kuua, Nuuk Qiterleq and Nuuk Killeq) by Nøhr-Hansen (1996), Croxton (1978a, b), McIntyre (1994a, b, c, personal communication 1997) and Dam *et al.* (2000). Brackish-water dinocysts of Late Albian to Cenomanian age have been described from northern Nuussuaq (Figs 29, 30; Nøhr-Hansen in Sønderholm *et al.* (2003), Asuk and in the F93-3-1 core from Kuugannguaq, northern Disko.

A sparse fauna of marine invertebrates (echinoids and bivalves) is known from southern and central Nuussuaq including *Sphenoceramus patootensis, Sphenoceramus pinniformis*, and *Oxytoma tenuicostata* (Ravn 1918; Olsen & Pedersen 1991). Ammonites from a single horizon at Alianaatsunnguaq were referred to the *Scaphites ventricosus – Inoceramus involutus* Zone by Birkelund (1965); the Atane Formation in Agatdalen has yielded *Baculites codyensis* (Reeside) and radially ribbed inoceramids of the *steenstrupi* species-group, an assemblage referred to the *Clioscaphites montanensis* Zone (Birkelund 1965; Dam *et al.* 2000). Ammonites from the Atane Formation occur as redeposited fossils in the Itilli Formation on central Nuussuaq (Dam *et al.* 2000). *Clioscaphites saxitonianus septentrionalis* (Birkelund) has been described from Ilugissoq, and at Tunoqqo *Clioscaphites* sp. aff. *saxitonianus* (McLearn) occurs together with a single *Scaphites* cf. *Svartenhukensis* (Birkelund 1965; Dam *et al.* 2000).

Although Koch (1964) suggested that the marine fossils are restricted to a few horizons, Olsen & Pedersen (1991) reported that the marine fossils recur through

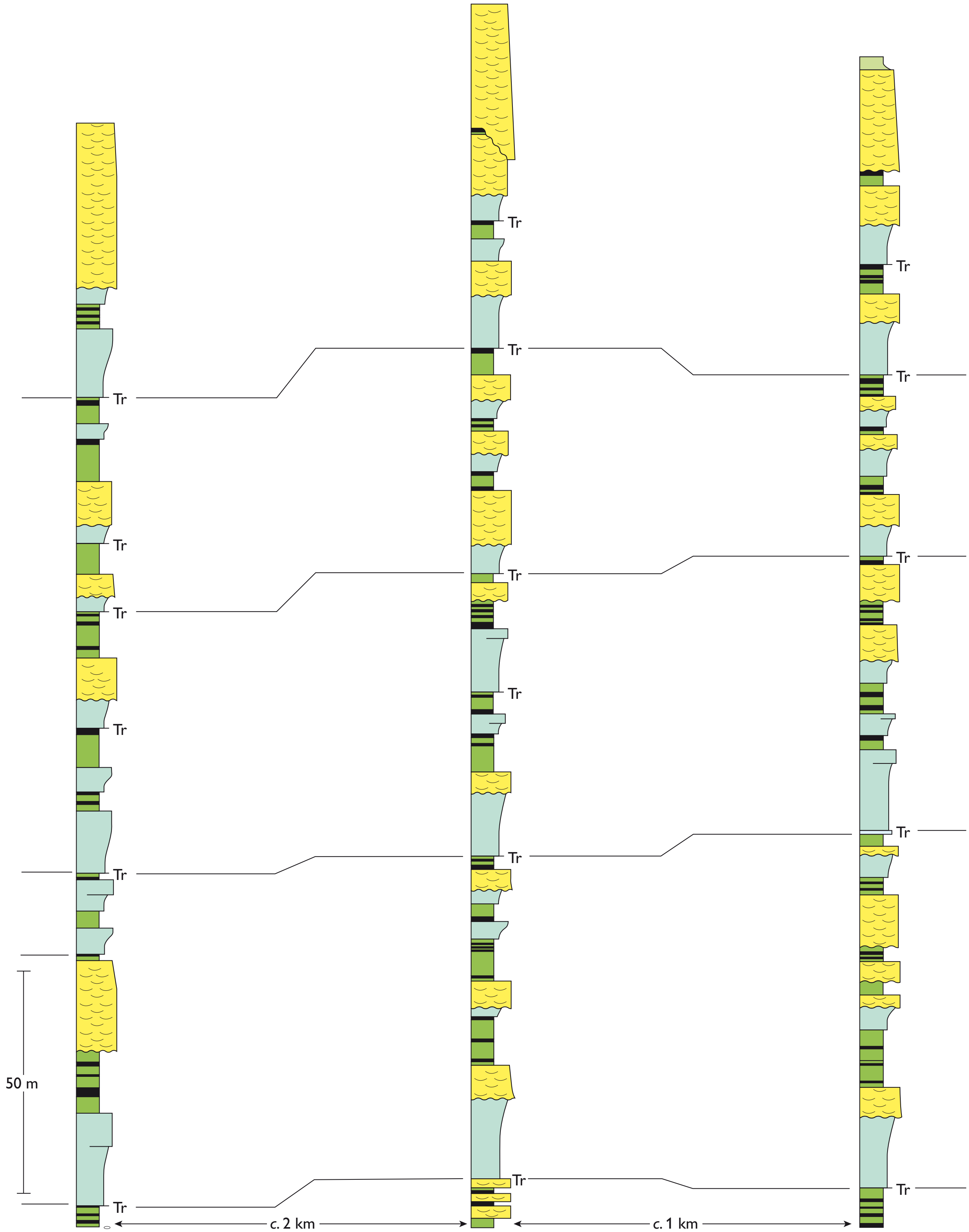


Fig. 46. Simplified sedimentological logs from the Ivissussat–Paatuut area; colours depict depositional environments, see Plate 1. The logs document the cyclic depositional pattern and local variations in thickness and lateral changes of facies. Individual phases of delta progradation may be correlated over short distances between neighbouring sections. The resulting high-resolution lithostratigraphy has only local significance. For legend, see Plate 1; **Tr**, Transgressive sand. For location, see Fig. 40.

the formation in the marine mudstones at the base of the delta front cycles. Boyd (1993) also reported marine invertebrates from several stratigraphic horizons.

Trace fossils are locally abundant and include *Dactyoloidites ottoi, Ophiomorpha nodosa, O. irregulaire, Taenidium serpentinum, Planolites* isp., *Teichichnus* isp., *Thalassinoides* isp., *Diplocraterion* isp., *Skolithos* isp. (Fürsich & Bromley 1985; G.K. Pedersen & Rasmussen 1989; Bojesen-Koefoed *et al.* 2001; G.K. Pedersen & Bromley 2006, Bromley & G.K. Pedersen 2008).

Depositional environment. The Atane Formation is interpreted as having been deposited in a major delta system, and four depositional environments are distinguished: the prograding marine delta front, fluvial or distributary channels of the delta plain, lakes and swamps of the delta plain, and the marine shoreface.

The coarsening-upward successions of mudstones, heteroliths and fine-grained sandstones are interpreted as delta front deposits. In some successions, they include interdistributary bay deposits (J.M.Hansen 1976; Midtgaard & Olsen, 1989; Midtgaard 1991; Olsen 1991; Olsen & Pedersen 1991; G.K. Pedersen & Pulvertaft 1992; Dueholm & Olsen 1993, Nielsen 2003) (Figs 45, 46). They are interpreted to have resulted from progradation of shelf deltas *sensu* Elliott (1989). Olsen (1993) described channel mouth complexes from the uppermost part of many delta front cycles at Paatuut.

The fluvial sandstone sheets on eastern Disko are interpreted as sandy braided river deposits (Johannessen & Nielsen 1982; Koppelhus & Pedersen 1993; Bruun 2006). These may constitute the multi-storey fill of fluvial valleys on south-east Nuussuaq (Jensen 2000; Jensen & Pedersen in press). Fluvial sandstones with ribbon geometry are interpreted as slightly sinuous distributary channel deposits (Olsen 1991, 1993). The carbonaceous mudstones, sandstones and coal seams are interpreted as freshwater lake or swamp deposits on the delta plain (Midtgaard 1991; Olsen & Pedersen 1991; G.K. Pedersen & Pulvertaft 1992; Koppelhus & Pedersen 1993; Nielsen 2003; Møller 2006; G.K. Pedersen *et al.* 2006). This facies association is interpreted as representing the vertical aggradation of a subaerial to shallow limnic, upper and lower delta plain. The thin beds of sand with marine trace fossils are interpreted as transgressive sand sheets, the erosional base of which constitutes a ravinement surface (Midtgaard 1991; Olsen & Pedersen 1991; G.K. Pedersen & Rasmussen 1989).

Olsen (1991) and Dueholm & Olsen (1993) documented 32 cycles of delta progradation in the Paatuut area and comparable numbers of delta cycles are known from the Qilakitsoq area. J.M. Hansen (1976) observed that the deltaic cycles in a vertical section at any locality show a remarkable similarity, indicating an aggradational stacking pattern. Correlation of individual deltaic cycles is only possible between closely spaced outcrops (Fig. 46), but lateral changes in depositional environment within the Atane Formation may be demonstrated on a larger scale (Fig. 16).

Boundaries. On Disko, the Atane Formation overlies a basement high in the FP-93-3-1 well (Fig. 19). On Nuussuaq, the base of the Atane Formation is exposed along the north coast where the formation erosively overlies the Slibestensfjeldet Formation between Ikorfat and Vesterfjeld (Figs 30, 32). The boundary has been interpreted either as a minor angular unconformity (Gry 1940; Koch 1964) or as a conformable, erosional base of a channel (Ehman *et al.* 1976; Schiener 1977; Croxton 1978a, b; Midtgaard 1996b). Midtgaard (1996b) interpreted the unconformity as a sequence boundary (Fig. 32).

The upper boundary of the Atane Formation is a marked erosional unconformity (see Fig. 16). On eastern Disko and Nuussuaq, it is overlain by fluvial and lacustrine Paleocene deposits of the Atanikerluk Formation. On northern Disko, the Atane Formation is erosively truncated by the Itilli Formation at Kussinerujuk and Asuk and by the volcanic Vaigat Formation at Naajannguit (Hald & Pedersen 1975; A.K. Pedersen 1985). Along the south coast of Nuussuaq, the Atane Formation is unconformably overlain by the marine Kangilia Formation (Dam *et al.* 2000), by incised valley fills of the Quikavsak Formation (Dam *et al.* 1998a; Dam & Sønderholm 1998; Dam *et al.* 2000; Dam 2002), and by the Eqalulik Formation. In the Aaffarsuaq valley the Atane Formation is unconformably overlain by the Itilli Formation (Dam *et al.* 2000) with rare ammonites (Birkelund 1965). West of Ilugissoq (central Nuussuaq), the upper boundary of the Atane Formation is not exposed.

On northern Nuussuaq, the upper boundary of the formation can only be seen between Vesterfjeld and Ikorfat but is generally poorly exposed. Directly east of the Ikorfat fault zone, the Atane Formation is overlain by mudstones with Late Campanian to Maastrichtian ammonites (Birkelund 1965), referred to the Itilli Formation. Between Vesterfjeld and Ikorfat, the Atane Formation is overlain by the Eqalulik Formation or by volcanic rocks of the Vaigat Formation (Figs. 22, 29; A.K. Pedersen *et al.* 1996, 2006b).

Geological age. The scarcity of marine fossils combined with the long range of many terrestrial plants, spores and pollen makes it difficult to determine the age of the Atane Formation with precision; for this purpose not only the presence but also the abundance of palynomorphs is important. The age of the formation is bracketed by the palynomorphs or plant macrofossils in the underlying Kome and Slibestensfjeldet Formations and by dinocysts and ammonites in the overlying Itilli Formation on central and northern Nuussuaq (Fig. 16).

The oldest parts of the Atane Formation are Albian–Cenomanian and Early Turonian and occur on Disko, on southern Nuussuaq at Kingittoq and eastwards, and on northern Nuussuaq around J.P.J. Ravn Kløft (Croxton 1978a, b; Koppelhus & Pedersen 1993; McIntyre 1994a, b, c, personal communication 1997; Boyd 1998a, b; Lanstorp 1999; this study). Sediments of Albian–Cenomanian to Turonian age have been reported from Asuk, and at Kussinerujuk the Atane Formation is overlain by the Cenomanian Kussinerujuk Member of the Itilli Formation (McIntyre 1994a, b; Bojesen-Koefoed *et al.* 2007). The presence of Coniacian deposits is based on the occurrence of *Scaphites ventricosus* at Alianaatsunnguaq (Birkelund 1965). The youngest parts of the formation are of Late Santonian to earliest Campanian age and occur on southern and central Nuussuaq (Paatuut, Qilakitsoq, Agatdalen; Olsen & Pedersen 1991; Boyd 1992, 1993, 1994; Nøhr-Hansen 1996; D.J. McIntyre, personal communication 1997; Dam *et al.* 2000). These sediments are dated from ammonites (*Clioscaphites montanensis* Zone), dinocysts and macroplant fossils (Birkelund 1965; Boyd 1992, 1993, 1994; Nøhr-Hansen 1996; Dam *et al.* 2000). Coniacian to Early Santonian ammonites in the Itilli Formation on central Nuussuaq overlying the Atane Formation indicate that the latter is Santonian or older in this area (Birkelund 1965; Dam *et al.* 2000).

Correlation. The Atane Formation is in part coeval with the marginally marine Upernivik Næs Formation north of Nuussuaq, and with the lower part of the deep marine Itilli Formation on Nuussuaq (west of the Kuugannguaq–Qunnilik Fault) and on Svartenhuk Halvø (Figs 13, 16).

Subdivision. The Atane Formation is divided into four members: the Albian–Cenomanian Skansen Member and Ravn Kløft Member, the Albian to Lower Turonian Kingittoq Member, and the Upper Turonian to Santonian – lowermost Campanian Qilakitsoq Member, which includes the ?lower Campanian Itivnera Bed.

Skansen Member

new member

History. The Skansen Member includes the sediments referred to the Atane Formation on southern and eastern Disko. The coal beds at Skansen were visited by Giesecke in 1807 and 1811 (in: Steenstrup 1910). He described the alternation between sandstones and coal beds, and noted that spherical concretions (Kieskugeln) are frequent in the sandstones. The history of coal mining at Skansen was summarised by K.J.V. Steenstrup, who also measured a geological profile of the coastal cliff at Skansen (Steenstrup 1874 plate VIII).

Name. The name is taken from the former settlement Skansen (old spelling Skandsen) or Aamaruutissat, on the south coast of Disko (Fig. 124). The name 'Skansen' (meaning rampart or palisade) originates from a thick and very prominent sill of columnar jointed basalt, named Innaarsuit in Greenlandic.

Distribution. The Skansen Member crops out on southern and eastern Disko (Figs 124, 132; A.K. Pedersen *et al.* 2000, 2001, 2003). The sediments are exposed in stream sections along the coast and in the inland valleys such as Kvandalen and Laksedalen. The Skansen Member is not known from wells and its distribution outside the area of outcrop is unknown. The Cretaceous sediments recorded in seismic sections in Disko Bugt south and east of Disko (Chalmers *et al.* 1999) presumably in part belong to the Skansen Member.

Type section. The type section of the Skansen Member is on the south-facing slope behind the settlement of Skansen (Figs 47, 48, 124). The sedimentology and palynology of this section have been studied in some detail (Koppelhus & Pedersen 1993; Bruun 2006; Møller 2006a, b). The base of the type section is located at 69°26.40′N, 52°26.32′W.

Reference sections. Reference sections are found at Illunnguaq (Koppelhus & Pedersen 1993) and Pingu (Fig. 132).

Thickness. Only the upper 470 m of the Skansen Member are exposed. However, geophysical data indicate that sediments with a thickness of *c.* 2 km are present east of Disko (Chalmers *et al.* 1999), suggesting that the Skansen Member may reach a considerable thickness in the subsurface.

Fig. 47. Type locality of the Skansen Member of the Atane Formation at Skansen, southern Disko (for location, see Fig. 124). The Skansen Member is dominated by fluvial sandstones, interbedded with fine-grained floodplain deposits and thin coal seams. The peak is at 470 m a.s.l. and the sediments are cut by several dykes (**d**).

Lithology. The Skansen Member is dominated by white to yellow sandstones with sheet geometry, intercalated with coal seams, mudstones and heteroliths rich in plant debris arranged in a cyclic depositional pattern (Figs 47, 49). Sixteen cycles are recognised, typically 20–30 m thick (Bruun 2006). The sandstones consist of quartz, more or less kaolinised feldspars, fragments of older quartz-rich sedimentary rocks, and small amounts of mica and other detrital minerals together with comminuted plant debris. The sandstones are generally friable, since carbonate or clay mineral cement is only locally developed. The sandstones are medium- to coarse-grained, in places with pebbly channel lags of intraformational mudstones, coal clasts or pebbles of chert and Ordovician limestone (A.K. Pedersen & Peel 1985). They are dominantly cross bedded or structureless (Fig. 49), but commonly show soft-sediment deformation structures. Sandstone sheets with a width: thickness ratio in excess of 15 are characteristic. The interbedded fine-grained sediments are dark grey to black due to the ubiquitous presence of comminuted plant debris. Facies vary rapidly both vertically and laterally between heterolithic, cross laminated sand, mudstone with plant debris, massive brownish mudstone and coal beds, most of which are less than 1 m thick. Locally, root horizons or rare tree stumps are present. The coal beds are *c*. 0.5 m thick, and the coals are subbituminous, with up to 20% siliciclastic particles and very little pyrite. The coals are dominated by huminite which originates from wood and plant tissue rich in cellulose (Møller 2006a, b).

Fossils. Macroflora, spores and pollen are known from the Skansen Member (Heer 1883a, b; Seward 1926; Miner 1932a, b, 1935; Ehman *et al.* 1976; Croxton 1978a, b; Koppelhus & Pedersen 1993). The plant fossils from six localities (Innanguit, Killusat, Skansen, Pingu, Ujarasussuk, Illukunnguaq) were referred to the Atane flora by Heer (1883b p. 93). Assemblages of palynomorphs

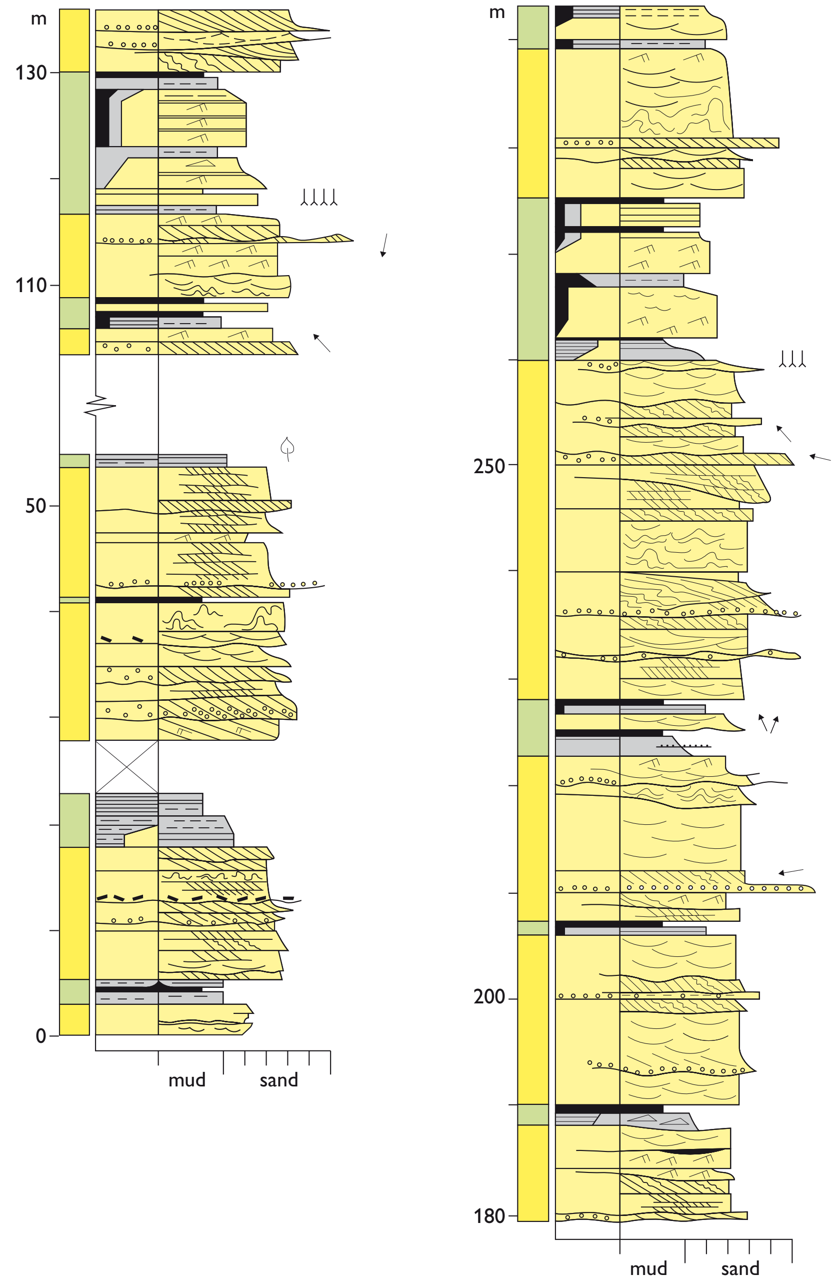


Fig. 48. Type section of the Skansen Member; note the dominance of fluvial channel deposits, (see also Figs 47 and 49). Base of section is at *c*. 120 m a.s.l. For legend, see Plate 1.

have been studied at reconnaissance level at Marraat (southern Disko) and Skansen (Ehman *et al.* 1976), at Kuuk Quamasoq and Pingu (Croxton 1978a, b; D.J. McIntyre, personal communication 2003) and in more detail at Skansen and Illunnguaq (Koppelhus & Pedersen 1993) (Fig. 124).

Depositional environment. The sandstone sheets in the Skansen Member are interpreted as sandy braided river deposits. The sediment transport directions on eastern Disko vary from north-north-west at Pingu to south-west at Gule Ryg and Skansen (G.K. Pedersen & Pulvertaft 1992 fig. 6), suggesting the presence of a huge alluvial cone with its apex east of Disko. Apparently, the Disko Gneiss Ridge did not affect the depositional pattern of the Skansen Member (Johannessen & Nielsen 1982; G.K. Pedersen & Jeppesen 1988; Koppelhus & Pedersen 1993; Bruun 2006).

The carbonaceous mudstones, sandstones and coal seams are interpreted as freshwater lake or swamp deposits representing the vertical aggradation of a subaerial to shallow, limnic floodplain to upper delta plain. The

Fig. 49. Cross-bedded medium- to coarse-grained fluvial sandstones of the Skansen Member at Skansen. Note the intraformational conglomerate (**C**) composed of mudstone and coal clasts (lower part of photo), and the thin interval of carbonaceous mudstone (floodplain deposits; **fp**) in the upper part.

spores and pollen represent vegetation dominated by conifers and ferns; there are no indications – neither palynological evidence nor the presence of pyrite – to suggest marine or brackish-water conditions (G.K. Pedersen & Pulvertaft 1992; Koppelhus & Pedersen 1993; Møller 2006).

Boundaries. The lower boundary of the Skansen Member is not exposed. The upper boundary is an erosional unconformity overlain by the Paleocene Atanikerluk Formation. At Pingu, the Skansen Member is overlain by fluvial sand of the Akunneq Member (Figs 16, 132), while it is overlain by lacustrine mudstones of the Assoq Member at Tuapaat on southern Disko. The presence of late Cenomanian or Turonian strata at the top of the Illunnguaq section was suggested by Koppelhus & Pedersen (1993), but was not confirmed by examination of additional samples. The upper boundary of the Skansen Member corresponds to the upper boundary of the Atane Formation in the area where the Skansen Member occurs.

Geological age. The Skansen Member is dated on the basis of spores and pollen. At its type locality, a mid-Cenomanian age seems most likely, with a maximum age range of Late Albian to Cenomanian for the palynomorph assemblages from this member (Croxton 1978a, b; Ehman *et al.* 1976; Koppelhus & Pedersen 1993).

Correlation. The fluvial Skansen Member is laterally equivalent to the deltaic Kingittoq Member on northern Disko (between Qullissat and Kussinerujuk), and on southern Nuussuaq (between Atanikerluk and Kingittoq) (Fig. 16). The Skansen Member also correlates with the fluviodeltaic Ravn Kløft Member on north-eastern Nuussuaq and in part at least with the Upernivik Næs Formation on Upernivik Ø. Palynomorphs are not preserved in the lower part of the Itilli Formation on Svartenhuk Halvø and on western Nuussuaq, which precludes firm correlation between the Skansen Member and the Itilli Formation (Figs 13, 16).

Ravn Kløft Member

new member

History. The Ravn Kløft Member is part of the Cretaceous succession overlying the Slibestensfjeldet Formation on north-eastern Nuussuaq. These sediments have previously been referred to the Atane Formation (Nordenskiöld 1871; Gry 1942; Midtgaard 1996b) or to the Upernivik Næs Formation (Rosenkrantz 1970; Henderson *et al.* 1976).

Name. The member is named after the gorge J.P.J. Ravn Kløft where it forms impressive outcrops (Fig. 50A, B). J.P.J. Ravn studied the geology of the Nuussuaq Basin in 1909, with focus on the marine invertebrates from the region (Ravn 1918).

Distribution. The Ravn Kløft Member is known from outcrops along the north coast of Nuussuaq between Ikorfat

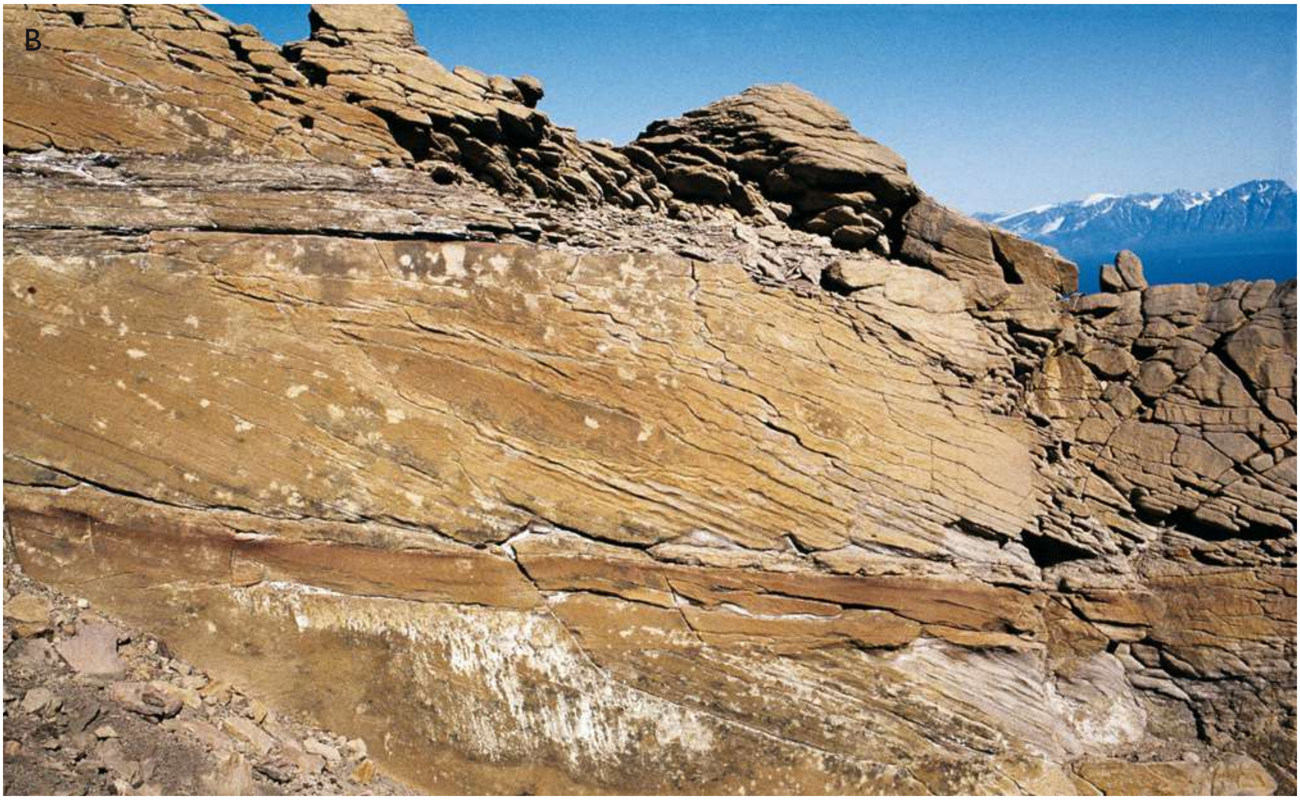


Fig. 50. **A**: Type locality of the Ravn Kløft Member on the west-facing slopes of the J.P.J. Ravn Kløft gorge on Slibestensfjeldet. Note the very thick fluvial sandstone bodies at the top of the Ravn Kløft Member that can be traced westwards to Ikorfat. The Ravn Kløft Member is overlain by the Kingittoq Member (Atane Formation). For location, see Fig. 22. **B**: Large-scale cross-bedding in sandstones of the thick, amalgamated fluvial channel deposits at the top of the Ravn Kløft Member at Ravn Kløft (*c*. 395 m in Fig. 51A). The height of the exposure is *c*. 3 m.

and Qaarsut (Fig. 22). Its wider distribution is not known due to lack of exposures.

Type section. The eastern slope of J.P.J. Ravn Kløft constitutes the type section (Figs 22, 51A). The base of the type section is located at 70°45.18′N, 52°55.08′W.

Reference sections. Reference sections are found in stream exposures just east of Ikorfat, at Slibestensfjeldet and at Vesterfjeld (Figs 22, 51B, 52).

Thickness. The thickness of the Ravn Kløft Member is about 450 m in the type section, thinning both towards the east and the west (Midtgaard 1996b). The basal pebbly sandstone varies in thickness from less than 2 m to a maximum of 56 m. The overlying deposits are *c*. 400 m thick in J.P.J. Ravn Kløft.

Lithology. A variety of lithologies and sedimentary facies are present in the Ravn Kløft Member. The member is tripartite, comprising a lower pebbly sandstone unit, a middle unit of mudstones, heteroliths and fine-grained sandstones with coarsening-upward or fining-upward depositional patterns, and an upper unit of thick-bedded medium- to coarse-grained sandstones interbedded with mudstones and heteroliths (Fig. 50B; Midtgaard 1996b). The lower unit (*c*. 35–62 m on Fig. 51A) includes a *c*. 3 m thick conglomeratic sandstone with rounded pebbles and large clasts of coaly mudstone, fossil wood and mudstone, interpreted as a channel lag. This is overlain by pebbly coarse-grained sandstones with large-scale cross-bedding, followed by coal-bearing mudstones with beds consisting of small *Scaidopityoides* leaves (Midtgaard 1996b). The cross-bedding indicates unidirectional northward sediment transport.

The middle unit (*c*. 62–340 m on Fig. 51A) comprises a variety of facies. Coarsening-upward successions comprise laminated mudstones, heterolithic sandstones and hummocky cross-stratified sandstones, which locally are capped by trough cross-bedded sandstones, mudstones with root horizons and thin coal beds. Wave-ripple crests are oriented ESE–WNW. Comminuted carbonaceous debris is abundant. Fining-upward successions comprise medium- to coarse-grained, well-sorted sandstones with cross-bedding, double mud-drapes, and abundant reactivation surfaces. They are overlain by heteroliths with current and wave ripple cross-lamination followed by black, laminated mudstones. Synaeresis cracks are common.

The upper unit (*c*. 340–400 m on Fig. 51A) of the Ravn Kløft Member consists of thick, erosively based bodies of greyish sandstone alternating with dark heterolithic mudstone. The sandstones are fine- to coarse-grained or conglomeratic, and dominantly cross-bedded. Foresets are often oversteepened and large-scale soft-sediment deformation structures are very common (Fig. 52). Composite sandstone bodies may be up to 60 m thick (Fig. 50), and may extend laterally for at least 8 km. The cross-bedding indicates sediment transport to the NE–N–NW. The sandstone bodies alternate with thinly interbedded rippled sandstones, laminated mudstones and heteroliths containing abundant rootlets and plant fossils, thin coal beds and palaeosols at certain levels.

Fossils. A brackish-water dinocyst assemblage dominated by *Nyktericysta davisii* has been identified in a number of the mudstone beds. The pollen *Rugubivesiculites rugosus* has its first stratigraphical occurrence within the member (Fig. 29).

Depositional environment. The lower unit of the Ravn Kløft Member is interpreted as a basal fluvial valley-fill conglomerate overlain by fluvial sandstones deposited by unidirectional northward-flowing currents. The middle units are interpreted as interbedded deltaic and tidal estuarine deposits, and wave-ripple crestlines suggest an ESE–WNW-oriented coastline. The overlying single to multi-storey sandstone bodies represent a variety of fluvial styles from slightly sinuous single channels to braided rivers with multiple channels and northward palaeocurrents. The presence of rootlets, vitrinite lenses and local coal beds in the floodplain sandstones and mudstones indicates the existence of a range of sub-environments from subaerial floodplain to shallow-water swamps or ponds adjacent to the fluvial channels. The fluvial sandstones show an increasing tendency up-section to amalgamate and form thick, multi-storey sandstone sheets (Midtgaard 1996b).

Boundaries. The lower boundary of the Ravn Kløft Member is the same as for the Atane Formation. The thickness variation of the lower fluvial sandstones of the Ravn Kløft Member suggests that the base had a relief of nearly 55 m on a regional scale (Midtgaard 1996b).

The upper boundary is placed at the top of a *c*. 60 m thick, amalgamated multi-storey fluvial sandstone sheet which is abruptly overlain by a succession of interbedded mudstones, heteroliths, sandstones and thin coal seams referred to the Kingittoq Member (Fig. 50).

Geological age. Based on the palynomorphs, the Ravn Kløft Member is assigned a Late Albian – Early Ceno-

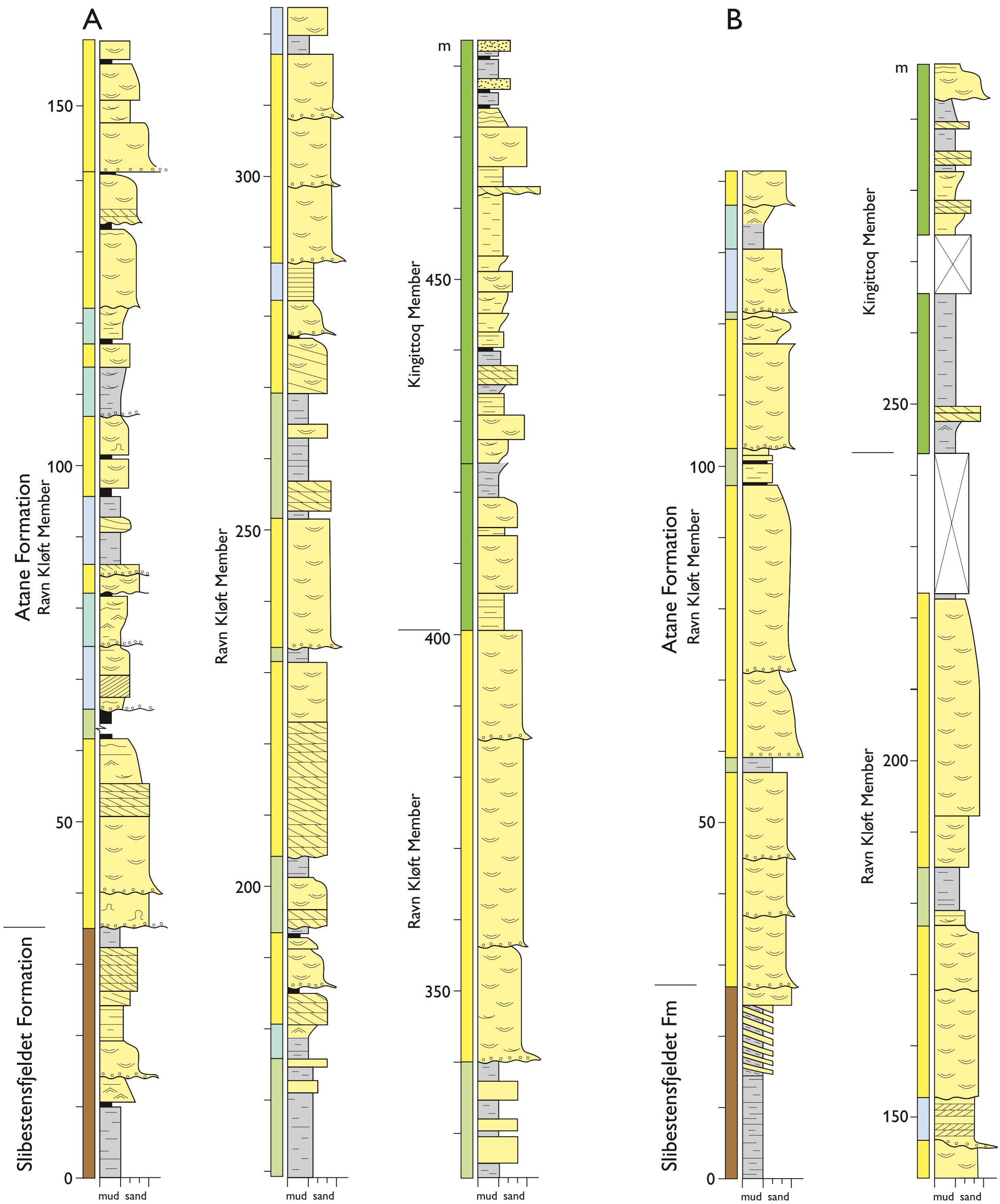


Fig. 51. **A**: Type section of the Ravn Kløft Member at J.P.J. Ravn Kløft. **B**: Reference section at Ikorfat. The thick sandstone beds at the top of the member are overlain by the Kingittoq Member. For legend, see Plate 1; for location, see Fig. 22.

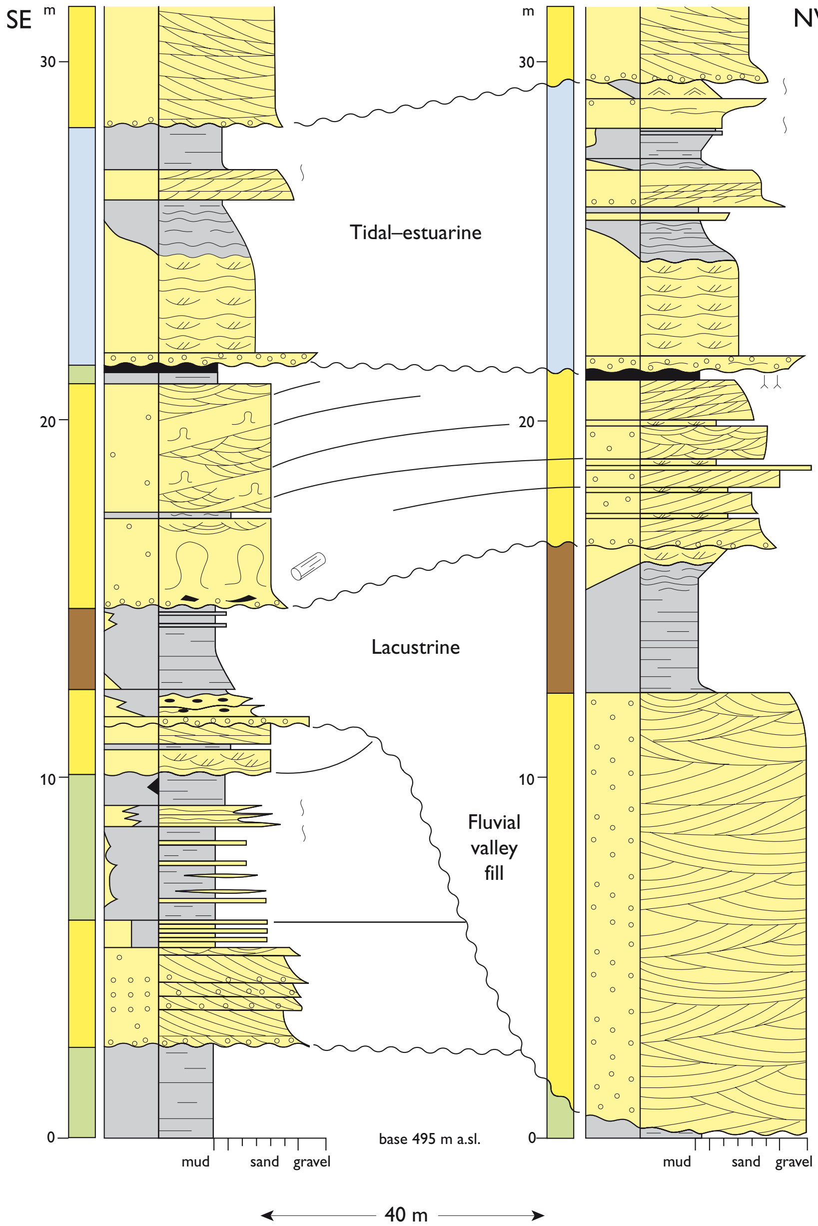


Fig. 52. Two closely spaced sections through the Ravn Kløft Member showing the rapid lateral facies changes especially of the fluvial channel deposits. The sections correspond approximately to the interval 255–285 m in Fig. 51A. For legend, see Plate 1; for location, see Fig. 22.

manian age (Ehman *et al*. 1976; Croxton 1978a, b; this study). A distinct macroflora (the Ravn Kløft flora) of Middle Albian to Early Cenomanian age was established by Boyd (1998a, b, c, 2000); this flora was broadly contemporaneous with the Upernivik Næs flora of Rosenkrantz (1970).

Correlation. The Ravn Kløft Member is laterally equivalent to the Skansen Member in southern and eastern Disko and the older parts of the Kingittoq Member on central and southern Nuussuaq and northern Disko. The Ravn Kløft Member is possibly coeval with the lower part of the Itilli Formation on western Nuussuaq and Svartenhuk Halvø and with parts of the Upernivik Næs Formation on Upernivik Ø (Fig. 16).

Kingittoq Member

new member

History. The Kingittoq Member includes the sediments referred to the Atane Formation on northern Disko, south-eastern Nuussuaq, as well as some of those on northern Nuussuaq.

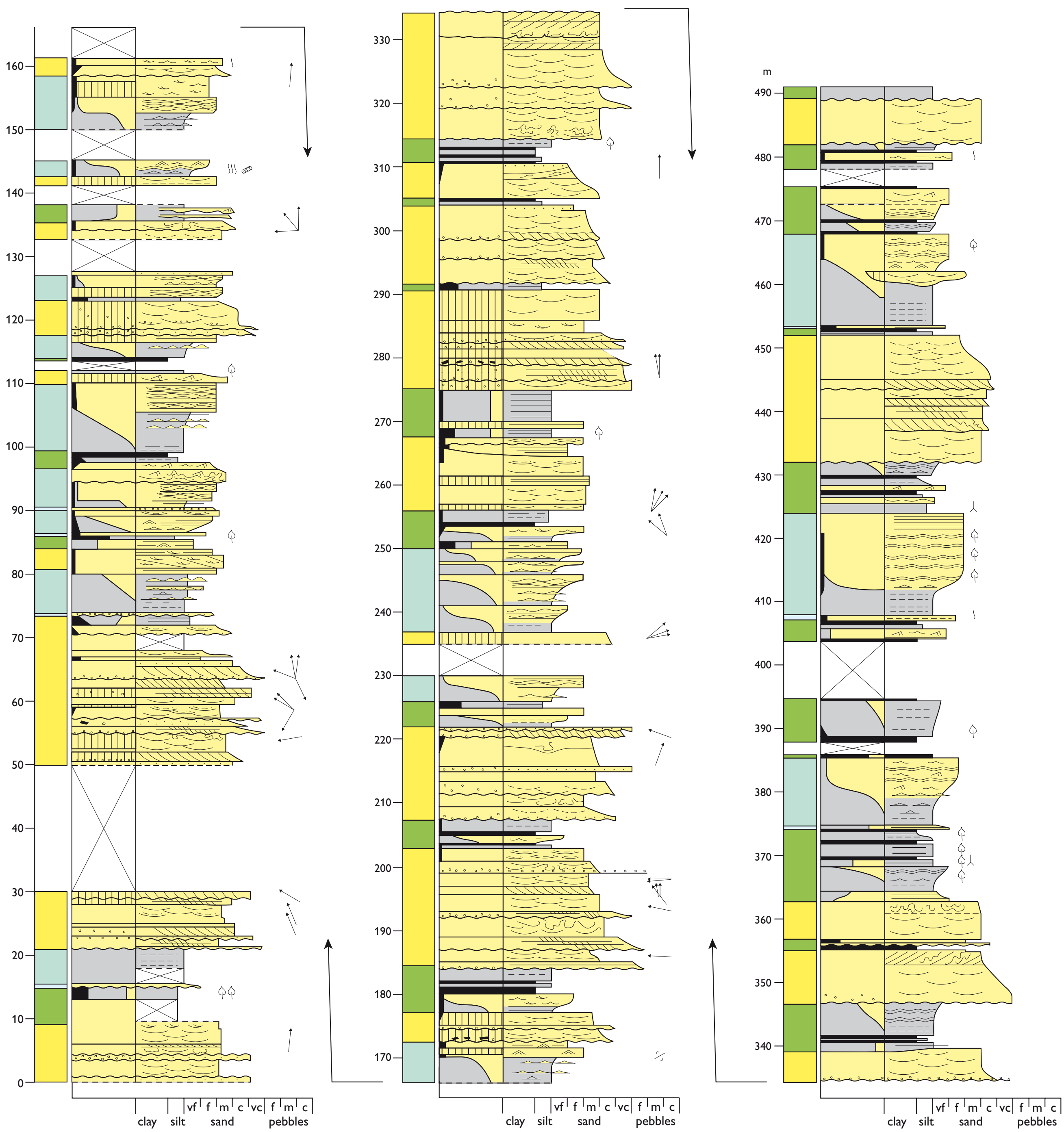


Fig. 53. Type section of the Kingittoq Member of the Atane Formation at Kingittoq, south coast of Nuussuaq (for location, see Fig. 40). Note the higher proportion of delta channel deposits compared to the Qilakitsoq Member (Fig. 60). Compare with Figs 54 and 55 to appreciate the facies variations within the member. Marine dinocysts are only found in a few of the delta front units. For legend, see Plate 1.

Name. The member is named from the coastal slopes at Kingittoq on the south coast of Nuussuaq, where it is well exposed (Fig. 40).

Distribution. The Kingittoq Member is known from outcrops on southern Nuussuaq from Saqqaqdalen to Kingittoq, on northern Disko from Qullissat to Kussinerujuk, and on northern Nuussuaq from Vesterfjeld to Ikorfat (Figs 2, 22, 40, 50A).

Type section. The type section of the Kingittoq Member is exposed in the slopes at Kingittoq on southern Nuussuaq (Figs 40, 53, 59). The base of the type section is located at 70°09.77′N, 52°31.38′W.

Reference sections. Reference sections are found in the upper reaches of J.P.J. Ravn Kløft and at Asuk (Figs 54, 55).

Thickness. The thickness of the Kingittoq Member is not known, but it probably exceeds 1 km. In the area of the type section, more than 600 m are exposed (A.K. Pedersen *et al.* 2007a), *c.* 450 m are exposed at Kuussinerujuk and up to 150 m are exposed above the Ravn Kløft Member on northern Nuussuaq.

Lithology. On southern Nuussuaq, the Kingittoq Member is characterised by 10–25 m thick depositional cycles, which comprise coarsening-upward successions of mudstones, heteroliths and well-sorted sandstones (Figs 53–58). Complex sandstone sheets, up to 40 m thick, are often overlain by carbonaceous heterolithic mudstones with thin coal beds and constitute fining-upward successions (Figs 53, 59). In the Atanikerluk area, the complex sandstone sheets constitute *c.* 40% of the section (Nielsen 2003) whereas their proportion is higher in Saqqaqdalen (Shekhar *et al.* 1982) and at Kussinerujuk (Pulvertaft & Chalmers 1990). The member is characterised by aggradational stacking of the depositional cycles (Figs 57, 58).

The sandstones are pale, friable, medium- to coarse-grained, in places with pebbly channel lags of intraformational mudstone or coal clasts, and are either cross-bedded or structureless, commonly with soft-sediment deformation structures (Midtgaard 1991; Olsen 1991; G.K. Pedersen & Pulvertaft 1992; Jensen 2000; Nielsen 2003; G.K. Pedersen *et al.* 2006). The mudstones are grey, silty, carbonaceous, at several localities with high C/S ratios, and are weakly laminated (Nielsen 2003). The mineralogy is similar to that in the rest of the Atane Formation. The coal beds are interbedded with mudstones with plant debris, sand streaked mudstones and cross laminated sand. Root horizons are seen locally, but preserved tree stumps are rare. A few of the coal beds have been studied in detail (Shekhar *et al.* 1982; Bojesen-Koefoed *et al.* 2001; G.K. Pedersen *et al.* 2006). Coarsening-upward successions of grey mudstones, wave-rippled heterolithic sandstones and fine-grained sandstones with swaley and hummocky cross stratification are especially well developed at Asuk (Fig. 56). The sedimentary structures are enhanced by drapes of comminuted plant (coal)

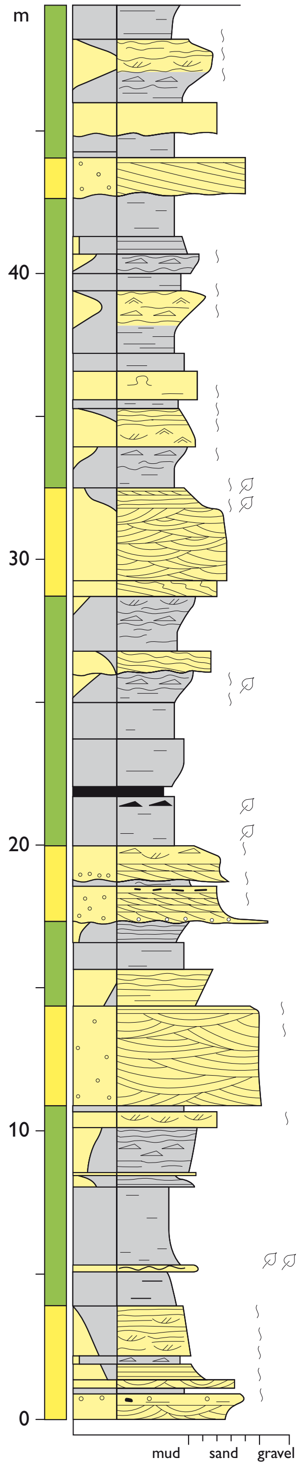
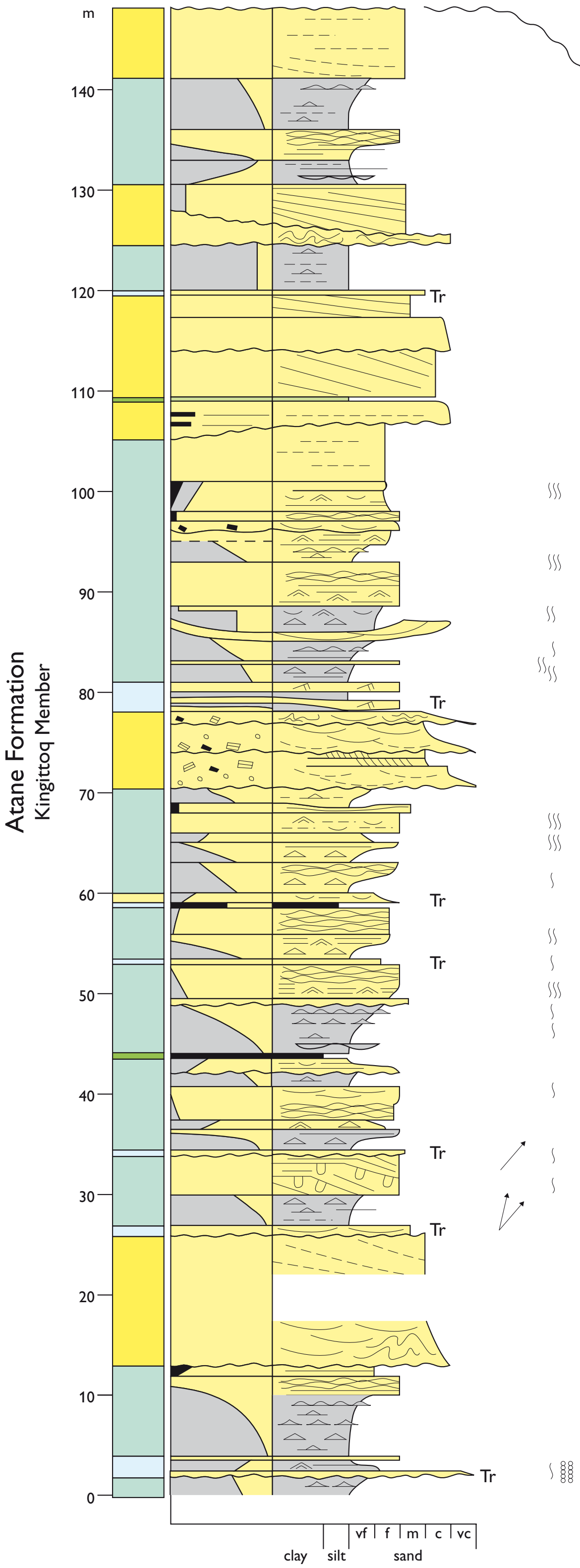


Fig. 54. Reference section of the Kingitoq Member at J.P.J. Ravn Kløft (for location, see Fig. 22). Note the predominance of delta plain facies deposited in shallow lakes, small channels and interdistributary bays. See also Fig. 51A. Base of section at *c.* 650 m a.s.l. For legend, see Plate 1.



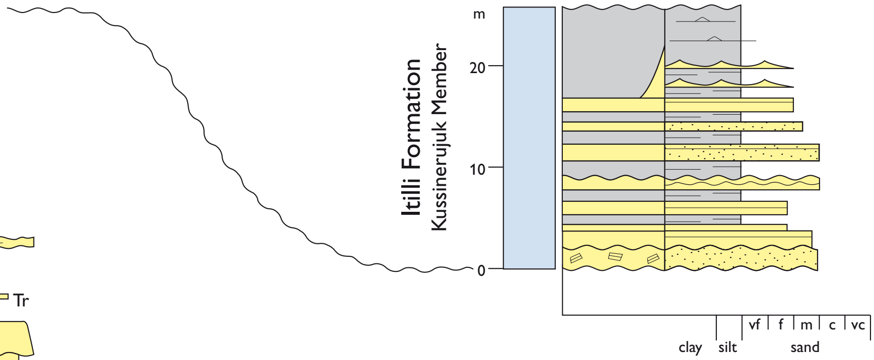


Fig. 55. Reference section of the Kingittoq Member at Asuk, north coast of Disko (for location, see Fig. 2). The section is dominated by stacked delta front deposits and intervals assigned to the delta plain facies association are thin. Note that only one thin coal seam is present (44 m). See also Figs 56, 57 and 80. At this locality, the member is clearly more influenced by marine deposition than at Kingittoq (Fig. 53). **Tr**, transgressive sandstones. For legend, see Plate 1.

debris. Marine fossils are found locally and bioturbation is generally slight. Thin beds of well-sorted, structureless sandstone are seen at Kingittoq, whereas similar beds at Asuk show erosional bases and contain numerous trace fossils, of which *Ophiomorpha nodosa* is prominent (Fig. 55).

Fossils. Plant macrofossils, spores and pollen are known from the Kingittoq Member (Heer 1883a, b; Seward 1926; Ehman *et al.* 1976; Croxton 1978a, b; Lanstorp 1999). Heer (1883b) described plant fossils collected from four outcrops of the Kingittoq Member (Qullissat, Asuk, Qallunnguaq, and Atanikerluk) and referred these to the Atane flora and the Patoot flora.

Marine dinocysts are known from the Kingittoq Member (D.J. McIntyre, personal communication 1997) and finds of rare individuals of three marine invertebrates, *Nucula cancellata*, *Nucula* sp., and *Lucina occidentalis*, were reported from Kingittoq (Ravn 1918). The trace fossils *Ophiomorpha nodosa, Taenidium serpentinum, Teichichnus rectus, Thalassinoides* isp. occur locally in the Kingittoq Member.

Fig. 56. Delta front succession of the Kingittoq Member at Asuk (27–35 m in Fig. 55). Note the upward increase in frequency and thickness of sandstone beds. The well-sorted sandstones with hummocky and swaley cross-stratification (**S**) are indicative of a high-energy depositional environment. The mudstone (**M**) at the top of the section is interpreted as an interdistributary bay deposit. For location, see Fig. 2.

Depositional environment. The Kingittoq Member is interpreted to represent fluvial to deltaic deposits and is referred to four facies associations: the channel and delta plain associations (dominant), the delta front or mouth bar association (subordinate) and the transgressive sand sheet association (rare) (Midtgaard 1991; G.K. Pedersen & Pulvertaft 1992; Dam *et al.* 2000; Jensen 2000; Nielsen 2003; G.K. Pedersen *et al.* 2006). The cross-bedded, medium- to coarse-grained sandstones are interpreted as fluvial channel deposits. The sedimentary structures frequently indicate downstream accretion on bars and rare development of point bars, indicating that the fluvial channels were mostly braided. The complex sheets of coarse-grained sandstones are interpreted as having been deposited as the multi-storey fill of fluvial valleys (Jensen 2000; Jensen & Pedersen in press).

The carbonaceous mudstones, sandstones and coal beds are interpreted to represent the vertical aggradation of subaerial to freshwater lacustrine or swamp deposits. The high C/S ratios indicate that deposition occurred in freshwater environments on the upper delta plain (G.K. Pedersen & Pulvertaft 1992; Nielsen 2003). The coal beds are interpreted as the *in situ* accumulations of plant remains in freshwater environments (Bojesen-Koefoed *et al.* 2001; G.K. Pedersen *et al.* 2006). This facies association is subordinate at Asuk.

The coarsening-upward heteroliths are interpreted as delta front or mouth bar deposits formed during progradation of shelf deltas (G.K. Pedersen & Pulvertaft 1992; Bojesen-Koefoed *et al.* 2001; Nielsen 2003; G.K. Pedersen *et al.* 2006). This facies association is dominant at Asuk. The thin beds of sand with marine trace fossils are interpreted as transgressive sand sheets (Midtgaard 1991). The erosive base constitutes a ravinement surface. In the Kingittoq Member, the transgressive sand sheets are best developed at Asuk. The Kingittoq Member is dominated by stacked upper delta plain deposits in the Atanikerluk area and at Qullissat, and by lower delta plain and stacked delta front deposits at Asuk.

Boundaries. The lower boundary of the Kingittoq Member is exposed on northern Nuussuaq where the Kingittoq Member overlies the Ravn Kløft Member (Fig. 50). Here the boundary is a drowning surface which separates the fluvial sandstones from the overlying delta plain deposits. In the rest of the Nuussuaq Basin, the lower boundary is not exposed.

The upper boundary, corresponding generally to the upper boundary of the Atane Formation in the outcrop area of the member, is everywhere an erosional unconformity overlain by the Itilli, Quikavsak, Atanikerluk and Vaigat Formations (Fig. 16). On the north coast of

Fig. 57. The Kingittoq Member at Asuk showing thick fluvial channel deposits overlying coarsening-upward delta front successions capped by transgressive shoreface sandstones (**ts**). For location, see Fig. 2 and Fig. 55: 44–83 m.

Nuussuaq, the upper boundary of the Kingittoq Member is generally poorly exposed due to landslides and rock glaciers, but east of Ikorfat it is overlain by small outcrops of Campanian–Maastrichtian mudstone (the Itilli Formation) and Paleocene tuffaceous mudstone (the Eqalulik Formation) (Birkelund 1965; A.K. Pedersen *et al.* 2006b) (Fig. 22).

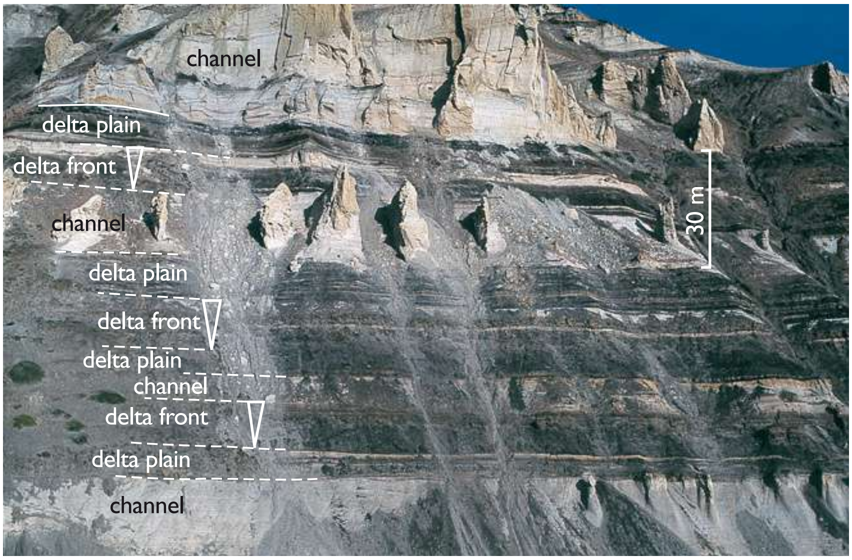
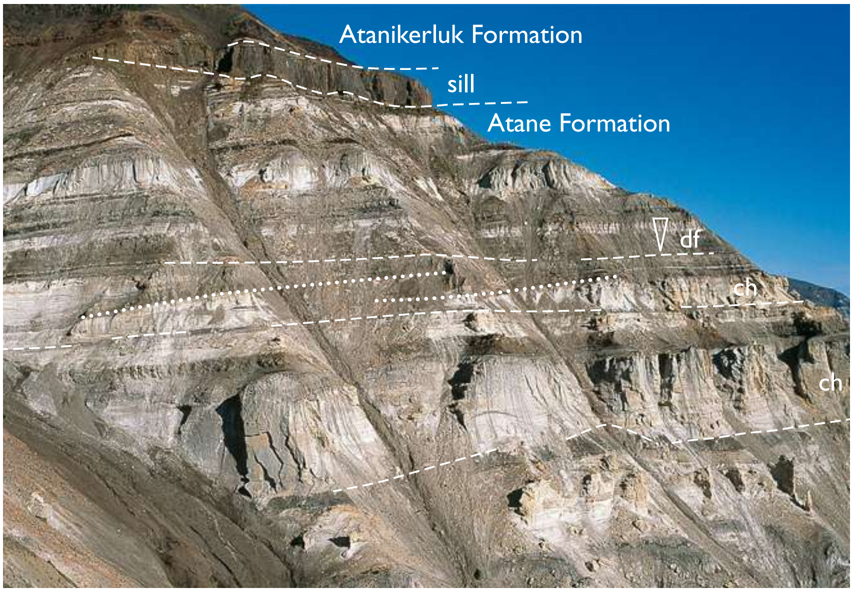


Fig 58. Outcrop of the Kingittoq Member on the eastern slope of the Qallunnguaq valley (for location, see Fig. 40). Delta plain facies constitute a large proportion of the succession and delta front deposits are thin and fine-grained suggesting low-energy depositional environments (lower delta plain with swamps, shallow lakes and interdistributary bays (Nielsen 2003)). The channel sandstone at the top of the photograph is the lowermost fluvial unit in a multi-storey sandstone body studied by Jensen (2000) and Jensen & Pedersen (in press).

Fig. 59. The Kingittoq Member at Kingittoq, see 310–465 m in Fig. 53. Most fluvial channels are braided, but a point bar succession is seen in the centre of the photo with inclined accretionary surfaces (indicated by dotted line); **ch**, fluvial channel; **df**, delta front. For location, see Fig 40.



Geological age. The geological age of the Kingittoq Member ranges from Albian (Tartunaq) to Cenomanian (Atanikerluk, Saqqaqdalen, Kingittoq, Kussinerujuk, Asuk and Ravn Kløft) and into Early Turonian (Saqqaqdalen, Kingittoq and Asuk). The deposits are dated on the basis of spores, pollen and marine dinocysts (Croxton 1978a, b; Lanstorp 1999; McIntyre 1994a, personal communication 1997; this study).

Correlation. The Kingittoq Member is coeval with the Skansen Member (eastern Disko); the Kingittoq Member of southern Nuussuaq may be equivalent the Ravn Kløft Member on northern Nuussuaq (Fig. 16). The Kingittoq Member correlates with the Upernivik Næs Formation on Upernivik Ø, and possibly to the lower part of the Itilli Formation of western Nuussuaq and Svartenhuk Halvø.

Qilakitsoq Member

new member

History. The Qilakitsoq Member includes sediments referred to the Atane Formation on southern and central Nuussuaq, and sediments formerly referred to the now abandoned Pautût (or Patoot) Formation (see above under history of the Atane Formation).

Name. The name is derived from the Qilakitsoq stream, a tributary to the Kuussuaq river which flows through the Aaffarsuaq valley on central Nuussuaq (Fig. 82).

Distribution. The Qilakitsoq Member is the sole representative of the Atane Formation in central Nuussuaq and parts of southern Nuussuaq. Outcrops are found from Agatdalen to Ilugissoq along the north slope of the Aaffarsuaq Valley and along the south coast from Paatuut to Alianaatsunnguaq (Figs 2, 40, 82).

Type section. The type section of the Qilakitsoq Member is along the Qilakitsoq stream on central Nuussuaq (Figs 60, 82). The base of the type section is located at 70°27.97′N, 53°27.13′W.

Reference sections. Reference sections are found at Nuuk Killeq and Ataata Kuua (type section of the Atane Formation; Fig. 43). Two continuously cored boreholes from the Paatuut area (GGU 247701 and GGU 247901) provide reference sections of the Qilakitsoq Member and have been described in detail by Ambirk (2000).

Thickness. The type section documents a minimum thickness of 480 m, but correlation with nearby sections shows that at least 820 m are exposed in the Qilakitsoq area, and *c*. 600 m are known from the well at Ataata Kuua together with nearby outcrops (Fig. 43; A.K. Pedersen *et al*. 2007b).

Lithology. The Qilakitsoq Member is characteristically cyclic, individual cycles typically passing up from mudstones through heteroliths, well-sorted sandstones, coarser grained sandstones with ribbon geometry, and finally into carbonaceous mudstones with coal beds overlain by thin sheets of bioturbated sandstone (Fig. 60; Midtgaard

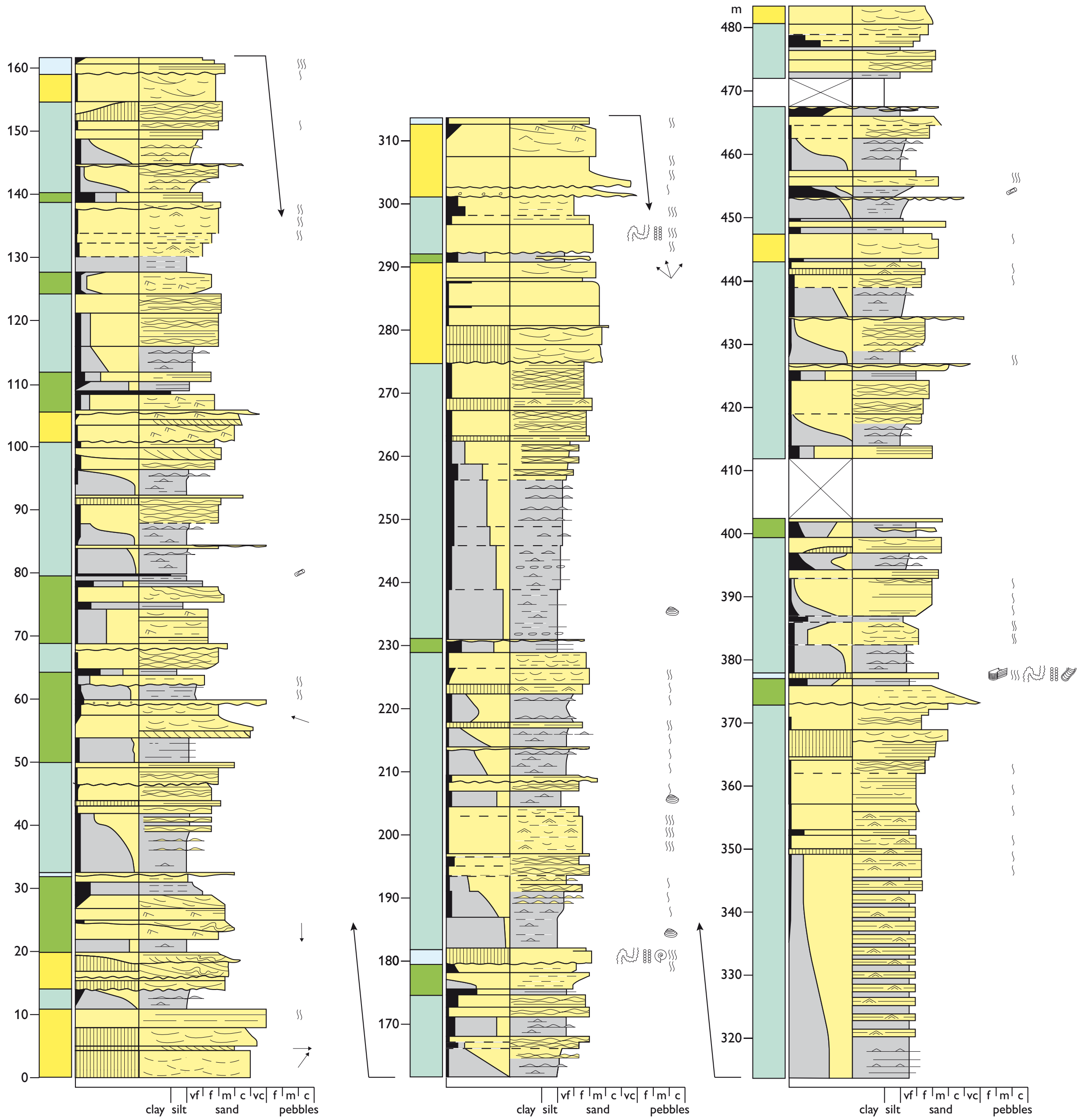


Fig. 60. Type section of the Qilakitsoq Member (Atane Formation) on the western side of the Qilakitsoq stream, central Nuussuaq. Note the higher proportion of delta front deposits compared to the Kingittoq Member (Fig. 53). For location, see Fig. 82; for legend, see Plate 1.

1991; Olsen 1991, 1993; G.K. Pedersen & Pulvertaft 1992; Boyd 1993; Dueholm & Olsen 1993; Ambirk 2000; Dam *et al.* 2000). The coarsening-upward successions are typically 5–25 m thick but may reach up to *c.* 70 m (Fig. 61). They can be traced laterally through closely spaced outcrops for up to 8 km in the Paatuut area (Fig. 46; Olsen 1991, 1993; Dueholm & Olsen1993) and also in the Qilakitsoq area.

The mudstones at the base of the coarsening-upward units are dark grey, silty and weakly laminated, and may contain marine fossils (Olsen & Pedersen 1991; Nøhr-Hansen 1996). These grade up into sand streaked mudstones and heterolithic sandstones, where wave-ripples and swaley- and hummocky cross-stratification are enhanced by drapes of comminuted plant debris (Fig. 60, 33–50 m). The successions are frequently topped by medium-grained, trough cross-bedded sandstones (Fig. 60, 145-158 m). Bioturbation may locally be very intense and totally obscure primary structures.

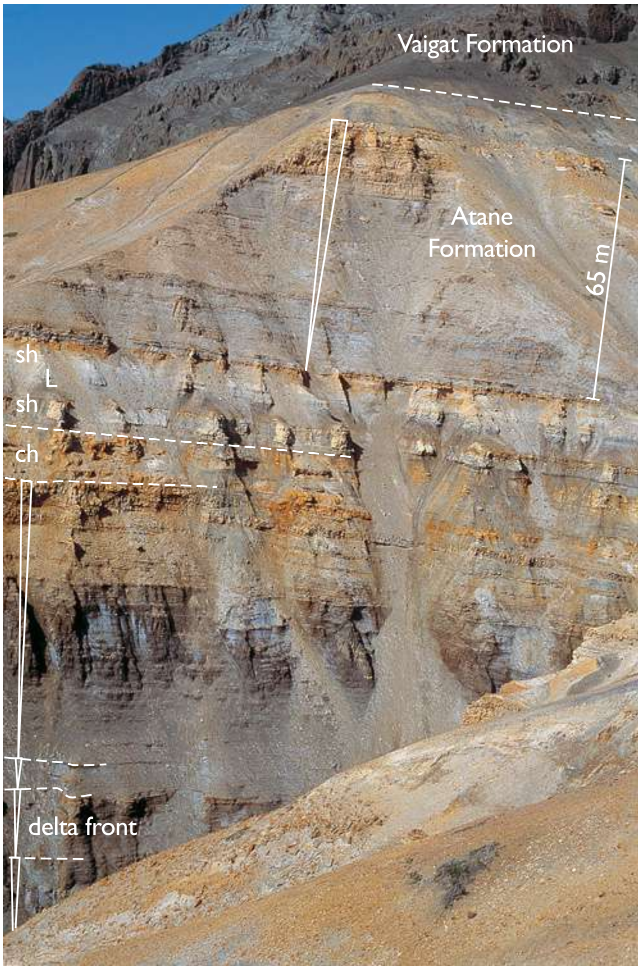


Fig. 61. Outcrop of the Qilakitsoq Member on the western slope of gully immediately west of Qilakitsoq. The member is dominated by stacked delta front successions. The outcrop corresponds to the interval 200–380 m in Fig. 60; **ch**, channel; **L**, lagoon; **sh**, shoreface. Note that the uppermost delta front succession is abnormally thick at this locality. For location, see Fig. 82.

Other sandstones are pale, friable, medium- to coarse-grained, in places with channel lags of pebbles or intraformational clasts of mudstone and coal. These sandstones are cross bedded or structureless, commonly with soft-sediment deformation structures. They form single-storey sandstone ribbons with a width:thickness ratio as low as 6 and a sinuosity of 1.2 (Olsen 1993) (Fig. 60: 0–11 m).

Successions of carbonaceous heteroliths interbedded with cross laminated sand, sand streaked mudstones, mudstones with plant debris and coal seams occur in all outcrops of the Qilakitsoq Member. Their dark grey to black colour reflects the abundance of comminuted plant debris. Locally, root horizons or rare tree stumps are present. Numerous coal beds at Paatuut and Ataa are more than 0.8 m thick. Concretions and 'coal balls' are observed in several horizons, as well as silicified wood. Dirt bands in coal beds are common, mainly consisting of carbonaceous mudstones (Fig. 60: 20–32 m).

Sheets of structureless or strongly bioturbated sandstone with an erosional base occur in most outcrops of the Qilakitsoq Member. They range from thin (*c*. 0.05 m) fine-grained sandstones to thick (*c*. 3 m) medium- to coarse-grained sandstones. Upwards, these sandstones may pass gradually into mudstones (Fig. 60, 180–182 m).

Fossils. Plant macrofossils, spores and pollen are known from the Qilakitsoq Member (Heer 1883a, b; Seward 1926; Ehman *et al*. 1976; Croxton 1978a, b; Boyd 1990, 1992, 1993, 1994). Heer (1883b) described plant fossils collected from three outcrops of the Qilakitsoq Member (Alianaatsunnguaq, Ataa, and Paatuut) and referred these to the Atane and Patoot floras. Boyd (1992, 1993) recognised three or more floral communities (nearshore lacustrine, backswamp, levee and riparian vegetation) in the fossil flora from the Paatuut area (the Paatuut flora).

Marine dinocysts have been identified in samples from the Qilakitsoq Member (D.J. McIntyre, personal communications 1997, 1999; Nøhr-Hansen 1996). The sparse marine invertebrates include ammonites (*Clioscaphites saxitonianus septentrionalis* (Birkelund), *Clioscaphites* sp. aff. *saxitonianus* (McLearn), *Scaphites ventricosus, Scaphites* cf. *Svartenhukensis*, and *Baculites codyensis* (Reeside)) (Birkelund 1965; Dam *et al*. 2000); bivalves (*Sphenoceramus patootensis, S. pinniformis, Oxytoma tenuicostata*) and echinoderms (Ravn 1918; Olsen & Pedersen 1991; Boyd 1993).

Trace fossils are common in the Qilakitsoq and Nuuk Killeq areas. Burrows such as *Planolites* isp., *Teichichnus* isp., *Dactyolidites ottoi*, and *Helminthopsis horizontalis* occur in the coarsening-upward successions, whereas *Ophiomorpha nodosa* and *O. irregulaire* are seen in the sandstone sheets (Fig. 62; G.K. Pedersen & Rasmussen 1989; Dam *et al*. 2000; G.K. Pedersen & Bromley 2006). The trace fossil assemblages indicate the presence of both suspension and deposit feeders.

Depositional environment. The Qilakitsoq Member is interpreted as being constructed of aggradational deltaic deposits referred to four facies associations: the marine delta front association, the distributary channel association, the delta plain association and the transgressive sand sheet association (Midtgaard 1991; Olsen 1991, 1993; G.K. Pedersen & Pulvertaft 1992; Dueholm & Olsen 1993; Dam *et al*. 2000).

Fig. 62. The trace fossil *Ophiomorpha irregulare* is characteristic of transgressive shoreface sandstones in the Qilakitsoq Member, especially at Qilakitsoq and Nuuk Killeq. For location, see Fig. 2.

The marine delta front association comprises coarsening-upward units where mudstones with marine fossils deposited below storm-wave base are overlain by heterolithic mudstones and sandstones which pass up into shallower water facies. These units are interpreted as the result of delta front progradation of shelf deltas.

The distributary channel association consists of cross-bedded, medium- to coarse-grained sandstones, which are interpreted as having been deposited within almost straight to slightly sinuous fluvial channels (Olsen 1991, 1993). Small fluvial channels are included in the delta plain association, which is characterised by carbonaceous mudstones, sandstones and coal beds, interpreted as having formed through vertical aggradation of subaerial to freshwater lacustrine or swamp deposits on the lower and upper delta plain. The coal beds are interpreted as the *in situ* accumulations of plant remains in both fresh- and brackish-water environments. The transgressive sand sheet association includes thin beds of sand with erosive bases and often with numerous marine trace fossils, indicating deposition on a marine shoreface (G.K. Pedersen & Rasmussen 1989; Midtgaard 1991; Olsen 1991; Olsen & Pedersen 1991; G.K. Pedersen & Pulvertaft 1992; G.K. Pedersen & Bromley 2006). The erosional bases represent ravinement surfaces.

Boundaries. The lower boundary of the Qilakitsoq Member is not exposed. The upper boundary, which corresponds to the upper boundary of the Atane Formation, is everywhere an erosional unconformity. Different units overlie the member throughout the region; these include the Itilli, Kangilia, Quikavsak and Atanikerluk Formations as well as volcanic rocks of the Vaigat Formation (Fig. 16).

Geological age. The geological age of the Qilakitsoq Member is Middle Turonian to Santonian at Ataata Kuua, Coniacian at Alianaatsunnguaq (Birkelund 1965), Santonian – earliest Campanian at Paatuut, Nuuk Killeq and on central Nuussuaq (Koch 1964; Boyd 1990, 1992; Olsen & Pedersen 1991; G.K. Pedersen & Pulvertaft 1992; Nøhr-Hansen 1996; D.J. McIntyre, personal communication 1997). Stable carbon isotopes in wood fragments suggest a Middle to Late Santonian age (Ambirk 2000).

Correlation. The Qilakitsoq Member correlates with part of the Itilli Formation (western Nuussuaq and Svartenhuk Halvø).

Subdivision. The Qilakitsoq Member includes the Itivnera Bed in the Aaffarsuaq valley near Tunoqqu.

Itivnera Bed

revised bed

History. The Itivnera beds were described by Dam *et al.* (2000) as fluvial sandstones incised into the top of the Qilakitsoq Member (Atane Formation) at two widely separated localities: Itivnera and Ataata Kuua (Figs 40, 82). The erosional, lower boundary was interpreted as a sequence boundary. At Itivnera, the fluvial deposits are

Fig. 63. Type locality of the Itivnera Bed in central Nuussuaq (for location, see Fig. 82). The bed comprises three channellised sandstone units up to 38 m thick that cut down into Santonian deltaic deposits of the Qilakitsoq Member (Atane Formation). The Itivnera Bed is overlain by submarine fan deposits of the Itilli Formation (Aaffarsuaq Member). The sandstone cliffs are about 16 m high and the spacing between the valleys is less than 100 m (see Dam *et al.* 2000).

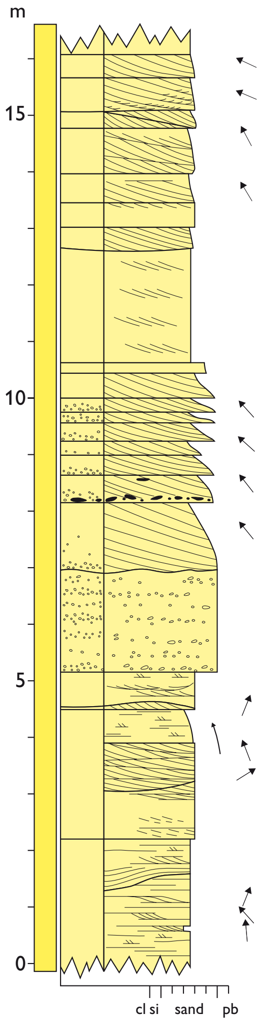


Fig. 64. Type section of the Itivnera Bed. Neither the base nor the top of the fluvial sandstone unit is exposed (from Dam *et al.* 2000). For legend, see Plate 1; for location, see Fig. 82.

overlain by deep marine deposits belonging to the Aaffarsuaq Member of the Itilli Formation. At Ataata Kuua, a valley incised into the Atane Formation is filled by turbidite mudstones, sandstones and conglomerates referred to the late Maastrichtian to earliest Paleocene Kangilia Formation; the Itilli Formation is not present at Ataata Kuua (Figs 14, 15, 16). The Qilakitsoq Member here is of Turonian–Santonian age. Fine-grained organic-rich sediments preserved in the top of a small fluvial channel contain palynomorphs indicating a Coniacian age.

The fluvial channel deposits at Ataata Kuua that were previously referred to as Itivnera beds are now assigned to the Qilakitsoq Member on the basis of photogrammetric mapping (A.K. Pedersen *et al.* 2007b) and dating of the fine-grained channel fill, which lies within the age range of the Qilakitsoq Member at this locality. The presence of Early Campanian fluvial deposits at Ataata Kuua cannot be demonstrated.

The Itivnera beds sensu Dam *et al.* (2000) constituted the basal part of the Itilli Formation. In the present paper, this unit is restricted to the cemented channel sandstones at Itivnera which are defined here as the Itivnera Bed of the Qilakitsoq Member.

Name. The strata are named after the saddle feature named Itivnera between Nalluarissat and Tunoqqu (Fig. 82). The name was derived from a nearby locality shown on the geodetic map from 1966 (Geodætisk Institut 1966); the spelling has not been changed to modern Greenlandic orthography because the locality is not shown on later geodetic maps.

Type section. The strata exposed on the south-facing slope of Nalluarissat between Aaffarsuaq and Kangersooq, just west of Itivnera, are designated as the type section (Figs 63, 64). The type section is located at 70°29.50′N, 53°08.87′W.

Distribution. The bed has only been recognised on the south-facing slope of Nalluarissat between Aaffarsuaq and Kangersooq (Fig. 82).

Thickness. The bed is up to 38 m thick and confined to lensoid bodies up to 100 m wide.

Lithology. The bed consists of cross-bedded coarse-grained sandstones, arranged in fining-upward successions form lensoid bodies arranged like pearls on a string (Figs 63, 64). Basement pebble conglomerates are locally present. The sediments between the cemented sandstone bodies are covered by scree (Dam *et al*. 2000).

Fossils. Macrofossils have not been found.

Depositional environment. The sandstones of the Itivnera Bed were deposited in fluvial channels (Dam *et al*. 2000).

Boundaries. The Itivnera Bed erosively overlies deltaic deposits of the Qilakitsoq Member (Atane Formation). In the type section, the fluvial sandstones are succeeded by turbiditic mudstones and sandstones of the Aaffarsuaq Member (Itilli Formation). The lower boundary is no longer interpreted as a sequence boundary because there is insufficient evidence that a sea-level fall preceded the rise in sea level that marks the transition to the deep-water deposits of the Aaffarsuaq Member.

Geological age. At Nalluarissat, just west of Itivnera, the Qilakitsoq Member is Late Santonian in age, and at Tunoqqu, immediately east of Itivnera, the Aaffarsuaq Member is of Early to Middle Campanian age (Nøhr-Hansen 1996). Deposition of the fluvial sandstone bodies at Itivnera is therefore well constrained to the Early Campanian.

Itilli Formation

new formation

History. The strata exposed in river sections in the Itilli valley on western Nuussuaq were informally assigned to the Itilli formation by J.M. Hansen (1980b). The Itilli Formation is here extended to include the unnamed Upper Turonian to Campanian marine strata on Svartenhuk Halvø and Nuussuaq (cf. Birkelund 1965; Henderson *et al*. 1976; J.G. Larsen & Pulvertaft 2000). Furthermore, on northern Disko at Kussinerujuk and Asuk, outcrops previously correlated with the Paleocene Kangilia Formation (J.M. Hansen 1980b; Pulvertaft & Chalmers 1990) are here assigned to the Itilli Formation (see below). The Itivnera beds of the Itilli Formation (Dam *et al*. 2000) are, however, now redefined as the Itivnera Bed of the Qilakitsoq Member (Atane Formation).

On Itsaku (Svartenhuk Halvø), the ?Upper Campanian/Maastrichtian to Paleocene succession has been suggested to be equivalent either to both the Itilli and Kangilia Formations (i.e. Campanian to Paleocene) or to the Kangilia Formation alone (i.e. upper Maastrichtian to Paleocene), based on correlation of two major conglomerate horizons with tectonic events recognised on Nuussuaq (J.G. Larsen & Pulvertaft 2000). Based on zircon provenance data, this succession is here assigned to the Kangilia Formation (see below).

Name. After Itilli, a major valley transecting Nuussuaq from north-west of Marraat on the south coast to west of Niaqornat on the north coast (Figs 2, 65).

Distribution. The Itilli Formation is exposed in the Itilli valley (Fig. 65) and on the north coast of Nuussuaq in the ravines between Ikorfat and Niaqornat (Fig. 74) where it has been drilled in the shallow wells GGU 400705, GGU 400706, and GGU 400407 (Christiansen *et al*. 1994a), and the formation is probably also present in the FP94-11-02, FP94-11-04 and FP94-11-05 wells (Dam & Nøhr-Hansen 1995). It is also well exposed on central Nuussuaq along the slopes of the valley of Aaffarsuaq between Qilakitsoq and Tunoqqu, along the slopes of the valley Kangersooq (Fig. 82), and in the valley of Agatdalen including the shallow well GGU 400702 (Fig. 113; Nøhr-Hansen 1996; Dam *et al*. 2000). On Disko, the formation is exposed at Asuk and Kussinerujuk.

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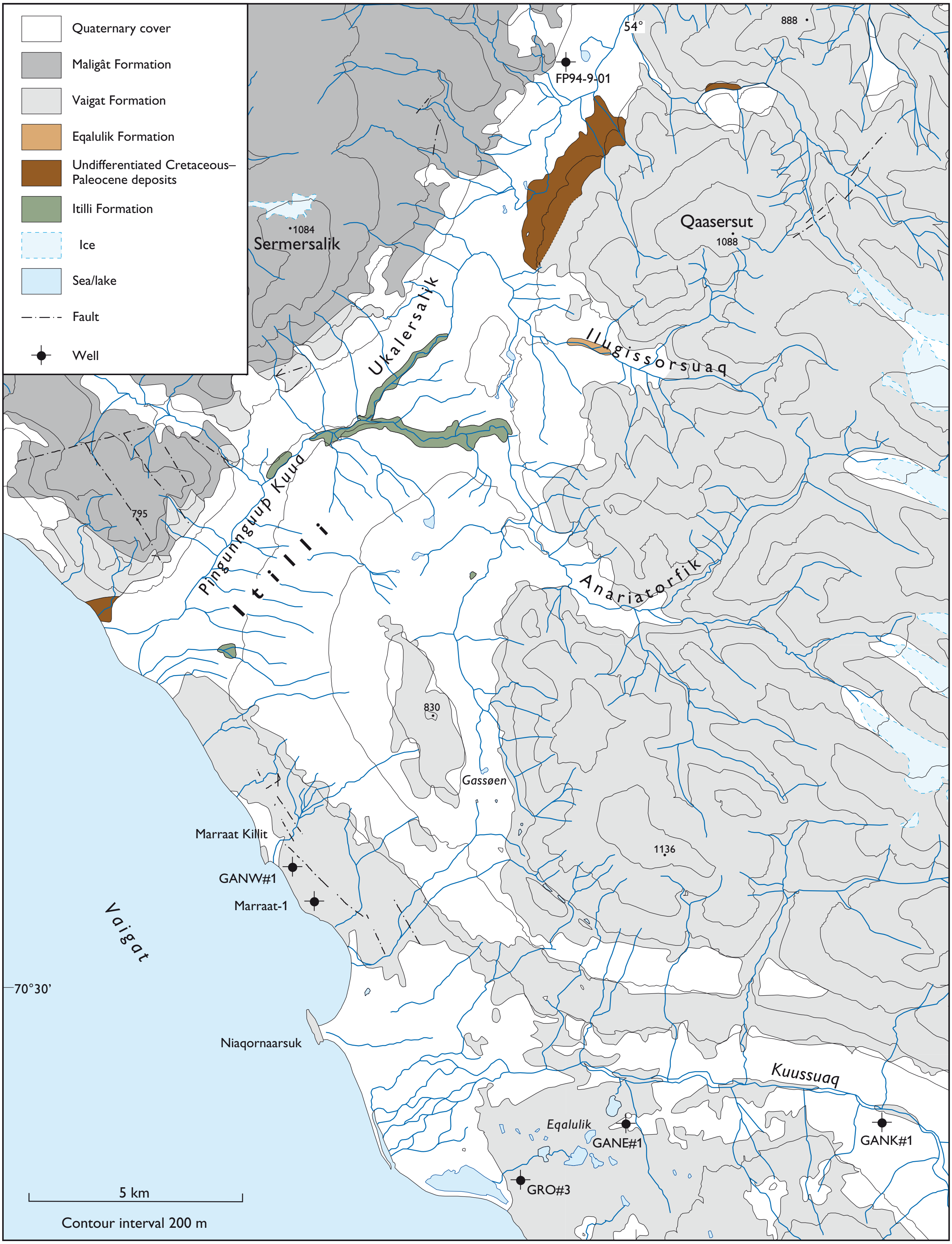
Fig. 65. Map of the southern part of the Itilli valley showing outcrops of the Itilli Formation (Anariartorfik Member) and the Eqalulik Formation and location of the wells Marraat-1, GANW#1, GANE#1, GANK#1 GRO#3 and FP94-9-01. Based on Rosenkrantz *et al*. (1974) and Hald (1976). Contour interval 200 m. For location, see Fig. 2.


Quaternary cover
Maligât Formation
Vaigat Formation
Eqalulik Formation
Undifferentiated Cretaceous–Paleocene deposits
Itilli Formation
Ice
Sea/lake
Fault
Well
54°
888
FP94-9-01
Qaasersut
1088
1084
Sermersalik
Ukalersalik
Ilugissorsuaq
Pingunnguup Kuua
795
Itilli
Anariartorfik
830
Gassøen
1136
Marraat Killit
GANW#1
Marraat-1
Vaigat
70°30'
Niaqornaarsuk
Kuussuaq
Eqalulik
GANE#1
GANK#1
GRO#3
5 km
Contour interval 200 m

The Itilli Formation is also exposed in the eastern part of the Svartenhuk Halvø area (Fig. 73; J.G. Larsen & Pulvertaft 2000) where it was cored in the Umiivik-1 well (Dam *et al.* 1998b).

On Nuussuaq, the lower part of the formation (Early Campanian and older) is only present west of the Kuugannguaq–Qunnilik Fault (Chalmers *et al.* 1999 fold-out 2) where it is exposed in the Itilli valley area. In this area, the formation was cored in the FP94-9-01 (Fig. 65; Madsen 2000) and GANT #1 wells (Fig. 74; Dam 1996a).

Type section. The type section of the Itilli Formation is located in the southern part of the Itillli valley along the Pingunnguup Kuua river and its tributaries, Ukalersalik and Anariatorfik (Figs 65, 66, Plate 2). The type section was described briefly by J.M. Hansen (1976, 1980a) and in detail by Dam & Sønderholm (1994). Neither the base nor the top of the formation is exposed in the type section. The base of the type section is located at 70°36.35´N, 54°13.79´W.

Reference sections. Reference sections showing the lower boundary with the Atane Formation are exposed at Kussinerujuk and Asuk on the north coast of Disko (Figs 55, 77) and in the Aaffarsuaq valley on central Nuussuaq (Fig. 83). The upper boundary towards the Kangilia Formation is located on the north coast of Nuussuaq around Kangilia (Figs 72, 74, 87; Birkelund 1965; Rosenkrantz 1970; Henderson *et al.* 1976). The upper boundary towards the Eqalulik Formation is exposed at Qilakitsoq on central Nuussuaq (Figs 82, 83).

Well reference sections are available from the fully cored boreholes FP94-9-01 (Madsen 2000), Umiivik-1 (Dam 1997), and GANT#1 (Dam 1996a). The formation was drilled but not cored in the GRO#3 well (Fig. 67; Kristensen & Dam 1997). For details on these wells, see below under description of members.

Thickness. The formation is more than 1400 m thick at the type locality where the base and top of the formation are not exposed (Plate 2). In the nearby GRO#3 well, the formation is more than 2000 m thick (Fig. 67). The formation thins dramatically eastwards across the

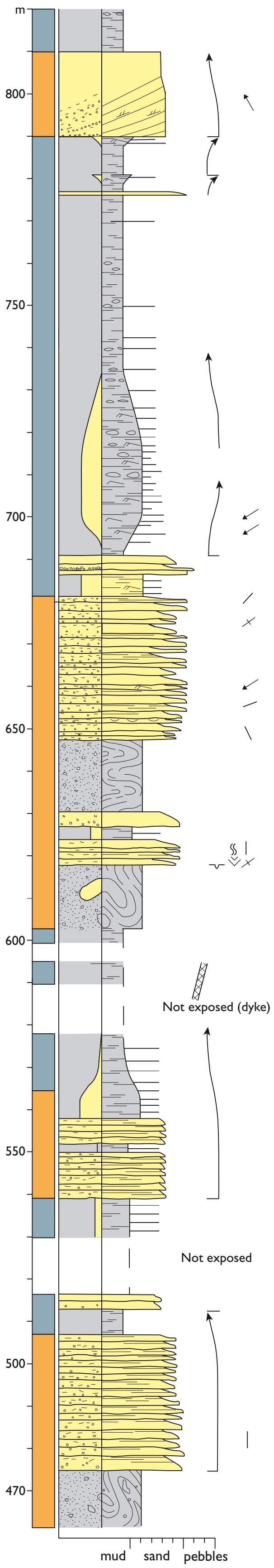


Fig. 66. Expanded sedimentological log showing a representative portion of the Itilli Formation in the type section along the Pingunnguup Kuua river; the entire section, at a smaller scale, is shown in Plate 2. For legend, see Plate 1; for location, see Fig. 65. From Dam & Sønderholm (1994).

Kuugannguaq–Qunnilik Fault and is only 240 m thick along the northern slopes of the Aaffarsuaq valley between Qilakitsoq and Tunoqqu. At Kangilia, on the north coast of Nuussuaq, the formation is at least 250 m thick (Fig. 87), and the nearby GANT#1 well penetrated 645 m of the formation without reaching the base of the formation. On Svartenhuk Halvø, the drilled and cored part of the formation is 960 m thick (excluding twenty-two Paleocene dolerite intrusions with a total thickness of 240.2 m), but the base of the formation was not reached (Fig. 75). At Kussinerujuk on the north coast of Disko, the measured part of the formation is 42 m thick (Fig. 77; Pulvertaft & Chalmers 1990).

Lithology. In the type section, the Itilli Formation comprises mudstones, thinly interbedded sandstones and mudstones, chaotic beds, amalgamated beds of coarse-grained to very coarse-grained sandstone, and giant-scale cross-bedded sandstones (Figs 66, 68, 69, 70, Plate 2; Dam & Sønderholm 1994). These lithological contrasts are reflected in the blocky pattern in the petrophysical logs of the GRO#3 well (Fig. 67; Kristensen & Dam 1997).

In the Aaffarsuaq area, the Itilli Formation comprises mudstones, thinly interbedded sandstones and mudstones, and amalgamated sandstone and conglomerate units together with chaotic beds comparable to those in the Itilli valley (Dam *et al.* 2000). The main differences between the Itilli and Aaffarsuaq areas are that most of the channellised amalgamated sandstone and conglomerate units in Aaffarsuaq are separated from the underlying deposits by major erosional surfaces or minor angular unconformities and that they are generally coarser-grained than their Itilli counterparts. Furthermore, the chaotic beds in Aaffarsuaq occur at many levels in the section and are not restricted to a position immediately underlying a channellised sandstone unit, and the interbedded sandstone and mudstone units often show an overall thinning-upward trend.

The amalgamated sandstone and conglomerate units of the Aaffarsuaq area consist of very coarse- to medium-grained sandstone and conglomerate beds grading upward into thinly interbedded sandstones and mudstones. These coarse-grained units are up to 50 m thick, extend laterally beyond the extent of outcrop (several hundred metres)

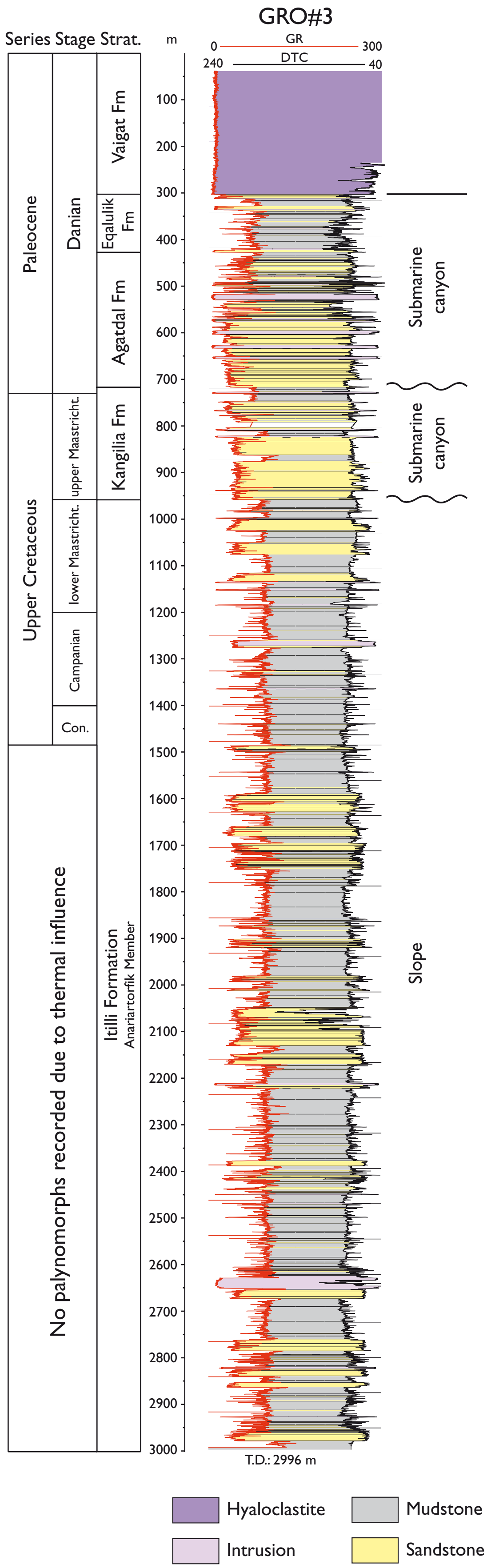


Fig. 67. Lithological log of the GRO#3 well interpreted from petrophysical data. **GR**, Spectral gamma-ray log; **DTC**, Sonic log; **Con.**, Coniacian; **Maastricht.**, Maastrichtian; **Strat.**, lithostratigraphy; T.D., total depth. Modified from Christiansen *et al.* (1999). For location, see Fig. 65.

Fig. 68. Outcrop of the Itilli Formation in the type locality in the Anariartorfik gorge showing amalgamated sandstones and thinly interbedded sandstones and mudstones (prominent sandstone unit is approximately 30 m thick). Anariartorfik section 930–1010 m (Plate 2). For location, see Fig. 65.

Fig. 69. Thinly interbedded sandstones and mudstones of the Itilli Formation in the Anariartorfik section (1070–1150 m; Plate 2). For location, see Fig. 65.

Fig. 70. Amalgamated sandstones of the Itilli Formation (Anariartorfik Member) deposited from turbidity currents in slope channels overlying contorted mudstones (at river level). Pingunnguup Kuua section 460–510 m (Plate 2). The amalgamated sandstone unit is approximately 30 m thick and is cut by a dyke. For location, see Fig. 65.

and include clasts of intraformational mudstone, sandstone (probably derived from the underlying Atane Formation), redeposited concretions and basement lithologies.

On the north coast of Nuussuaq and on Svartenhuk Halvø, the formation is dominated by mudstones, thinly interbedded sandstones and mudstones, and bioturbated thinly interbedded sandstones and mudstones. These lithologies are arranged in coarsening-upward successions 10–50 m thick (Fig. 75).

At Kussinerujuk on the north coast of Disko, the formation consists of sandstones and conglomerates with angular cobbles and boulders of mudstone, sandstone, or interbedded sandstone and mudstone. Other clasts consist of rounded pebbles of quartz and clay ironstone (Fig. 77; Pulvertaft & Chalmers 1990, fig. 6). At Asuk, the formation consists of a basal sandstone or conglomerate bed succeeded by sand-streaked mudstones (Fig. 55).

Fossils. Ammonites, belemnites, inoceramid bivalves (Fig. 71) and rare crustaceans and corals are present in the formation at several localities on Nuussuaq and Svartenhuk Halvø (Birkelund 1965; Rosenkrantz 1970; Dam *et al*. 2000). However, most of these are not found *in situ* in the outcrops and may furthermore be reworked intraformationally or derived from older deposits. Dinocysts, spores and pollen occur throughout in small numbers but cannot be determined neither in the lower part of the Umiivik-1 and GRO#3 wells nor from the outcrops in the Itilli valley. Burrows are occasionally present at the top of sandstone beds. Details of fossil contents are presented under the description of individual members.

Depositional environment. The Itilli Formation was primarily deposited in slope and submarine fan environments. In the type area the amalgamated sandstones were deposited in slope channels initiated during sea level lowstands whereas the mudstones and the thinly interbedded sandstones and mudstones were deposited in interchannel slope areas (Dam & Sønderholm 1994). Details on the depositional environment are presented under the description of individual members.

Boundaries. On the north coast of Nuussuaq, the Itilli Formation overlies the Atane Formation in a small and poorly exposed section at high altitude immediately east of the Ikorfat Fault (Fig. 22; A.K. Pedersen *et al*. 2006b). The boundary with the underlying Atane Formation is well exposed on central Nuussuaq along the northern slope of the Aaffarsuaq valley between Qilakitsoq and Tunoqqu (Fig. 82; Nøhr-Hansen 1996; Dam *et al*. 2000) and on northern Disko at Kussinerujuk and Asuk (Fig. 2). In Aaffarsuaq, the lower boundary is placed at the unconformity between the Santonian deltaic deposits of the Atane Formation and the first turbidite sandstone or mudstone deposits of the Campanian Aaffarsuaq Member (Fig. 83). At Kussinerujuk and Asuk, the lower boundary is an erosional unconformity between the deltaic deposits of the Atane Formation and the slope deposits of the Itilli Formation (Figs 55, 77, 78, 79).

The upper boundary is well exposed on northern Nuussuaq where it is defined at a major unconformity with the upper Maastrichtian – Lower Paleocene Annertuneq Conglomerate Member of the Kangilia Formation (Figs 72, 76, 87). However, in areas outside the distribution of the Annertuneq Conglomerate Member, there

Fig. 71. Giant inoceramid bivalves on top of a turbidite sandstone bed of the Itilli Formation (Aaffarsuaq Member) in the second ravine east of Qilakitsoq. For location, see Fig. 82.

Fig. 72. Unconformity between the Itilli Formation (Umiivik Member) and the overlying Kangilia Formation with the resistant pale-weathering Annertuneq Conglomerate Member at the base. North coast of Nuussuaq, at Annertuneq. Base of conglomerate is at *c.* 300 m a.s.l. For location, see Fig. 74.

is no lithological contrast at the boundary between the Itilli and Kangilia Formations and in these areas biostratigraphic data may be essential for the distinction between the Turonian to lower Maastrichtian Itilli Formation and the mainly Danian Kangilia Formation. On Svartenhuk Halvø, the formation is overlain by hyaloclastite of the Vaigat Formation or, as observed on the east slope of Firefjeld, by a conglomeratic unit that may be correlated with either the Agatdal Formation or with the Quikavsak Formation. The upper boundary of the Itilli Formation is not exposed on northern Disko.

On the north coast of Nuussuaq and in the GANT#1 and GRO#3 wells, the Itilli Formation is unconformably overlain by the Kangilia Formation (Figs 67, 72, 87). Along the Aaffarsuaq valley, the upper boundary is ambiguous and can be difficult to identify. East of Qilakitsoq, however, Campanian deposits of the Itilli Formation are overlain by a Paleocene conglomerate/sandstone unit referred to the Eqalulik Formation (Fig. 83) thus indicating a major unconformity. At Nassaat, a tributary on the south-eastern side of Agatdalen, the presence of Upper Santonian mudstones with *Sphenoceramus* was reported by Rosenkrantz (1970); this succession is now referred to the Itilli Formation. At this locality, the mudstones are overlain by pebbly sandstones and bituminous mudstones, a unit that referred to the Agatdal Formation by Rosenkrantz (1970 fig. 4c) but to the Upper Atanikerdluk Formation (Quikavsak Formation of this paper) by Koch (1959 fig. 37). No new data are available from this outcrop.

Geological age. A ?Late Turonian to early Maastrichtian age range for the formation is indicated by the ammonite fauna (Fig. 16). Palynomorph data are generally in accordance with the ammonite data, but local discrepancies occur, probably due to redeposition of ammonites from the underlying deposits.

At Asuk and Kussinerujuk on northern Disko, the Itilli Formation is of Cenomanian–Turonian age (Fig. 16; Bojesen-Koefoed *et al.* 2007) whereas on Svartenhuk Halvø, the formation is of Turonian to Early Campanian age (Fig. 16; Nøhr-Hansen 1996, unpublished data; Dam *et al.* 1998b). Strata of Campanian age referred to the Hilli Formation are also exposed on Nuussuaq (Itilli, Aaffarsuaq, Agatdalen; Birkelund 1965; Sønderholm e*t al.* 2003). The Maastrichtian part of the formation is only known from Kangilia and Aaffarsuaq (Birkelund 1965; Rosenkrantz 1970; Nøhr-Hansen 1996) and has been dated in the GRO#3 well (Sønderholm *et al.* 2003). Detailed information on the age of the various members is found in the description of the members below.

Correlation. The pre-Early Campanian part of the formation is coeval with the Atane and Upernivik Næs Formations (Fig. 16).

Subdivision. Four members are recognised, the Anariartorfik, Umiivik, Kussinerujuk, and Aaffarsuaq Members, of which the Anariartorfik Member is found only west of the Kuugannguaq–Qunnilik Fault. The Anariartorfik Member consists of interbedded turbidite channel sandstones and mudstones deposited in a fault-controlled slope environment. The Umiivik Member is the northernmost representative of the Itilli Formation. It is finer grained than the Anariartorfik Member, and dominated by major coarsening-upward successions deposited in a base-of-slope and basin-floor fan environment. Both the Anariartorfik and Umiivik Members record deposition from probably the Cenomanian to the Maastrichtian. The Kussinerujuk Member is only exposed on northern Disko at Asuk and Kussinerujuk and represents a Cenomanian transgressive event on top of the Atane Formation. The Aaffarsuaq Member crops out east of the Kuugannguaq–Qunnilik Fault on central Nuussuaq and comprises a relatively thin wedge of Lower to Middle Campanian strata that are distinctly different from the Anariartorfik Member with regard to their large content of intraformational clasts, the overall lack of fine-grained mudstones and the lenticular shapes of the thinly interbedded sandstone and mudstone units. The sediments of the Aaffarsuaq Member were deposited in a deep marine, channellised footwall fan system.

Anariartorfik Member

new member

History. Strata referred here to the Anariartorfik Member were described informally as the Itilli Formation by J.M. Hansen (1980b). Detailed studies of strata assigned to the Anariartorfik Member were published by Dam & Sønderholm (1994) and Madsen (2000).

Name. The member is named after the Anariartorfik valley leading into the Itilli valley (Fig. 65).

Distribution. The Anariartorfik Member is exposed in the Itilli valley and is present in the subsurface west of the Kuuganguaq–Qunnilik Fault in the western part of Nuussuaq (Fig. 11).

Type section. The type section is the same as for the Itilli Formation in the southern part of the Itilli valley (Figs 65, 66, Plate 2). The base of the type section is located at 70°36.35´N, 54°13.79´W.

Reference sections. Well-exposed reference sections are located in the northern part of the Itilli valley and in the adjoining Tunorsuaq valley (Figs 2, 65, 74).

The member was cored in the FP94-9-01 borehole between 32 and 522 m in the central part of the Itilli valley (Fig. 65; Madsen 2000); the cores are stored at GEUS in Copenhagen. The member was drilled but not cored in the GRO#3 well between 959 m and 2996 m (Figs 65, 67; Kristensen & Dam 1997).

Thickness. The member has a thickness (including intrusions) of at least 2037 m in the GRO#3 well. Approximately 1400 m are exposed in two incomplete sections in the Itilli valley (Fig. 65, Plate 2).

Lithology. In the type section, the Anariartorfik Member is dominated by mudstones and thinly interbedded sandstones and mudstones, chaotic beds, amalgamated beds of coarse-grained to very coarse-grained sandstones, and giant-scale cross-bedded sandstones (Figs 66, 68, 69, 70, Plate 2; Dam & Sønderholm 1994). These lithological contrasts create a characteristic blocky pattern in the petrophysical log of the GRO#3 well (Fig. 67; Kristensen & Dam 1997).

The mudstones are dark grey to black, show parallel lamination and occur in intervals up to 15 m thick in the type section. Persistent layers of early diagenetic ankerite concretions occur in most mudstone intervals.

The thinly interbedded sandstone and mudstone units comprise laterally extensive graded laminae and beds of fine- to very coarse-grained sandstone capped by parallel-laminated mudstones; this facies forms successions several tens of metres in thickness (Plate 2). The sandstone beds range in thickness from less than 1 cm to 80 cm, have flat, locally scoured bases and show normal grading; the beds may be structureless near their base or may be parallel- or cross-laminated throughout. The sandstone beds are laterally persistent at outcrop scale (> 100 m) and there is generally no systematic variation in thickness. Convolute bedding and slump structures are common. Early diagenetic ankerite concretions are common in the mudstone units.

The chaotic beds are up to 30 m thick and consist of contorted, laminated mudstone, thinly interbedded sandstone and mudstone, and homogenised mudstone with scattered sand grains, reworked early diagenetic ankerite concretions, semi-indurated mudstone and sandstone clasts and occasional basement clasts. The chaotic beds invariably underlie a thick unit of amalgamated sandstone beds and are often associated with sandstone dykes (Fig. 66, Plate 2).

The amalgamated sandstone beds form up to 50 m thick channel-shaped bodies that can be followed for 1–2 km along strike (Figs 66, 68, 70, Plate 2). The sandstone units are erosionally based and locally show well-developed flute casts and channel-shaped scours at the base. The sandstone units may show a thinning-upward trend and have a gradational or sharp, but non-erosional contact to the overlying interbedded sandstone and mudstone units. Internally, the sandstone units are dominated by amalgamated, normally graded, medium-grained

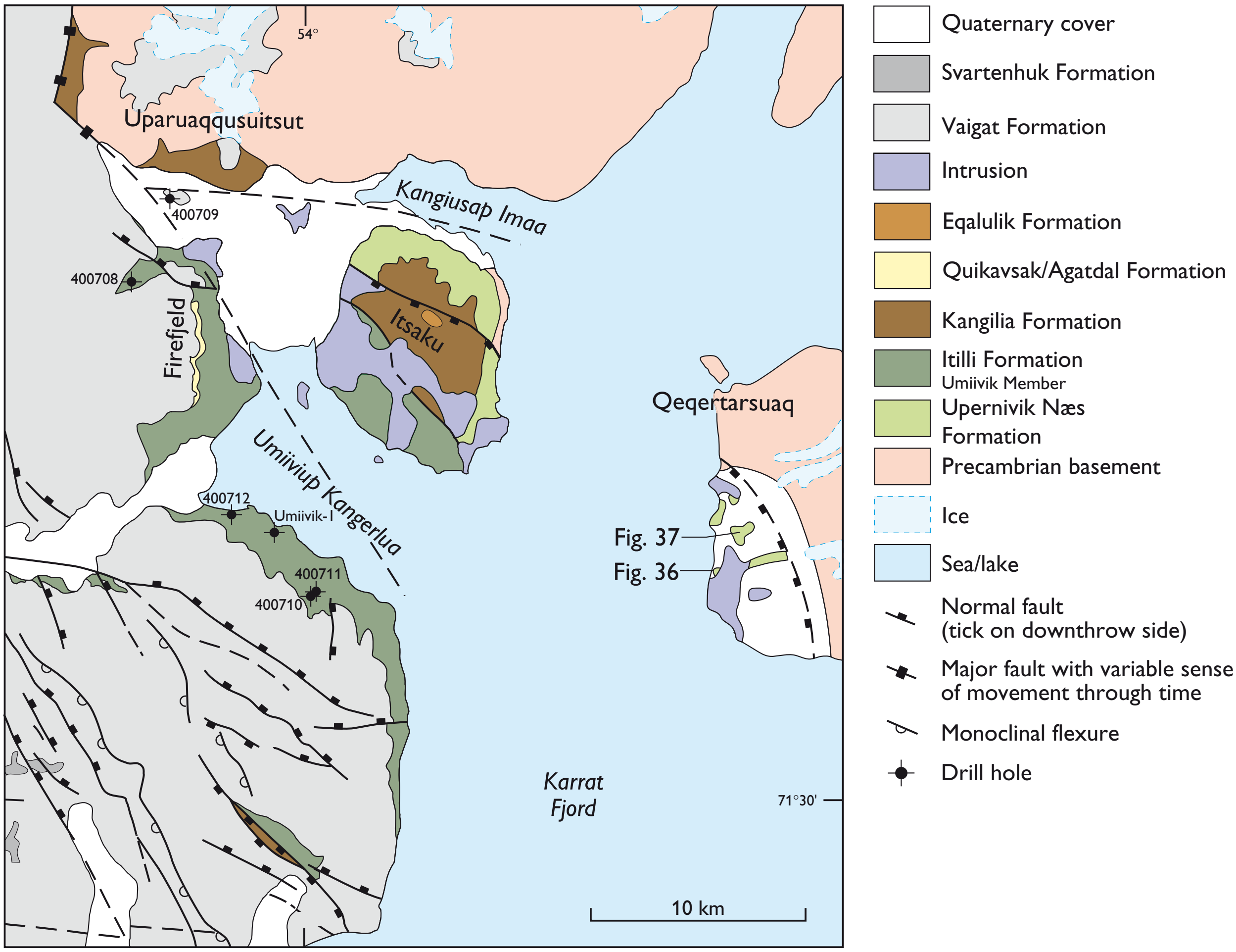


Fig. 73. Geological map of the south-eastern part of Svartenhuk Halvø and the west coast of Qeqertarsuaq showing the location of the Umiivik-1 well (type section of the Umiivik Member of the Itilli Formation) and the position of shallow wells drilled by GGU in 1992 (GGU 400708–400712). Reference sections of the Upernivik Næs Formation on Qeqertarsuaq are indicated (see Figs 36, 37). For location, see Fig. 2. Modified from J.G. Larsen & Grocott (1991) and J.G. Larsen & Pulvertaft (2000).

to pebbly, very coarse-grained sandstone beds (0.1–3.5 m thick) or, less commonly, show planar and trough cross-bedding. The graded beds have planar, erosional bases and can be followed laterally for more than 140 m without major variations in thickness (Figs 66, 68, 70). Angular mudstone clasts, ranging from a few millimetres to 45 cm across and rounded basement pebbles up to 8 cm across are common in the graded beds. In some cases, the uppermost part of the graded sandstone beds show well-developed parallel lamination, with parting lineation and tool marks, trough cross-bedding, low-angle cross-bedding and climbing ripple lamination. The graded sandstone beds are commonly separated by thin mudstone beds or units of thinly interbedded mudstone and sandstone.

Giant-scale cross-bedded sandstone units occur as channel-shaped bodies at a few levels in the type section. The units comprise 7–15 m thick low-angle, cross-bedded sets dominated by coarse- to medium-grained sandstone; the sets can be followed for approximately 150 m in a dip direction. At one locality, a single set fills out a large channel-shaped erosional depression that is approximately 300 m wide (Plate 2 at 800 m; Dam & Sønderholm 1994).

Fossils. Macrofossils have not been found in this member, but burrows are locally present at the top of the sandstone beds. They include common *Ophiomorpha* isp., *Thalassinoides* isp., escape burrows, and rare *Helminthopsis* isp. (Dam & Sønderholm 1994). Identifiable palynomorphs are very rare in the area of the type sec-

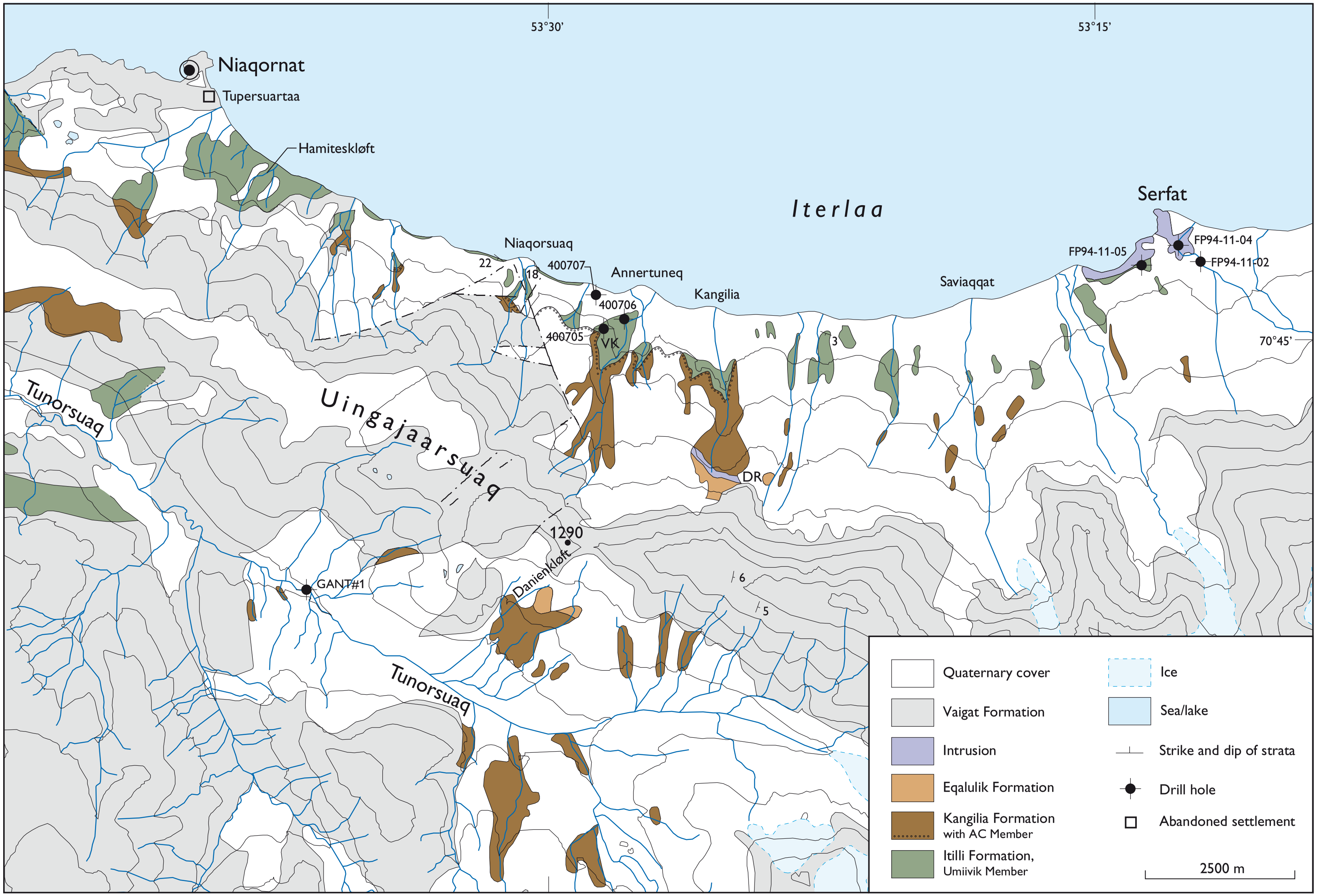


Fig. 74. Geological map of the north coast of Nuussuaq showing outcrops of the Itilli and Kangilia Formations. The wells FP94-11-02, -04 and -05 are located near Serfat. The shallow wells drilled by GGU in 1992 (GGU 400705–400707) are located at Annertuneq. The GANT#1 well is in the Tunorsuaq valley. **DR**, Danienrygge; **AC**, Annertuneq Conglomerate Member. Contour interval is 200 m. For location, see Fig. 2. Modified from Rosenkrantz *et al.* 1974.

tion, but are abundant in the cuttings from the middle and upper part of the GRO#3 well (Nøhr-Hansen 1997c).

Depositional environment. Deposition of the Anariartorfik Member took place in a fault-controlled slope environment (Dam & Sønderholm 1994). Most of the channellised amalgamated turbidite sandstone beds were deposited from high-density turbidity currents in confined low-sinuosity channels, although a few examples of giant-scale, cross-bedded sandstones are interpreted as the products of lateral accretion in meandering slope channels.

The thinly interbedded sandstones and mudstones are interpreted as having been deposited from traction currents and from fall-out processes associated with various sedimentation stages within waning low-density currents. The lateral continuity and the lack of systematic vertical thickness variations in the thinly interbedded sandstones and mudstones suggest that these deposits were not confined by channel-levee systems, but most likely represent interchannel slope deposits.

Where present, the chaotic beds always underlie undisturbed channel sandstones. This suggests that the channels were initially excavated by retrogressive slumping of unstable sediments on the slope followed by channel excavation by scouring (Dam & Sønderholm 1994).

Boundaries. The lower and upper boundaries of the Anariartorfik Member are not exposed. The upper boundary was drilled in the GRO#3 well but not cored (Fig. 67). An erosional unconformity between the Anariartorfik Member and the overlying Kangilia Formation was suggested by Kristensen & Dam (1997).

Geological age. Palynomorphs in the GRO#3 well indicate a ?Coniacian/Santonian – early Maastrichtian age for the uppermost *c.* 525 m of the Anariartorfik Member. In the lowermost 1510 m of the well, the organic material is degraded due to thermal maturation and this part of the formation cannot be dated (Nøhr-Hansen 1997c).

Umiivik Member

new member

History. Outcrops of marine Upper Cretaceous strata referred to the Umiivik Member on Svartenhuk Halvø and northern Nuussuaq have only been briefly described by earlier workers since their main focus was on the collection of fossils (Rosenkrantz *et al.* 1942; Birkelund 1956, 1965; Rosenkrantz 1970). Later studies in connection with mapping by the Geological Survey and drilling of stratigraphic wells in the Umiivik area of Svartenhuk Halvø have been reported by Christiansen (1993), Dam *et al.* (1998b), Christiansen *et al.* (2000) and J.G. Larsen & Pulvertaft (2000). On northern Nuussuaq, extensive stratigraphic studies have been carried out at Annertuneq and Kangilia (Christiansen *et al.* 1992; Christiansen 1993; Christiansen *et al.* 1994) and at Serfat in connection with drilling of mineral exploration wells (Dam & Nøhr-Hansen 1995).

Name. The member is named after the stretch of shore located south-east of Firefjeld in the inner part of the Umiiviup Kangerlua bay, eastern Svartenhuk Halvø (Fig. 73).

Distribution. On Svartenhuk Halvø, the Umiivik Member is locally exposed in the north-western part of the peninsula (Fig. 2), and more extensively in the low-lying coastal outcrops around the bay of Umiiviup Kangerlua, and *c.* 5 km north-west of the south-eastern corner of the peninsula (Fig. 73). On Nuussuaq, exposures are found along the north coast between Niaqornat and Ikorfat and in the Tunorsuaq valley (Figs 2, 74).

On Svartenhuk Halvø, the member has been cored in five shallow wells (GGU 400708–712; Christiansen 1993; Christiansen *et al.* 1994a) and in the deep Umiivik-1 well (Fig. 73; Christiansen *et al.* 1994; Nøhr-Hansen 1996; Christiansen *et al.* 1997; Dam 1997; Nøhr-Hansen 1997a; Dam *et al.* 1998b).

On the north coast of Nuussuaq the member has been penetrated in six shallow boreholes: GGU 400705–707 and FP4-11-02, FP94-11-04 and FP94-11-05 (Christiansen *et al.* 1994; Dam & Nøhr-Hansen 1995), and in the deep GANT#1 well (Fig. 74; Christiansen *et al.* 1996c; Dam 1996a; Dahl *et al.* 1997; Nøhr-Hansen 1997b; Kierkegaard 1998).

Type section. The most complete section of the member is available in the Umiivik-1 core drilled on the southern shore of Umiiviup Kangerlua on Svartenhuk Halvø (GGU 439301; Figs 73, 75). Neither the base nor the top of the member is, however, seen in this well. The cores are stored at GEUS in Copenhagen. The Umiivik-1 well is located at 71°36.70′N, 54°02.52′W.

Reference sections. The best-exposed outcrops of the Umiivik Member are found below the Kangilia Formation (Annertuneq Conglomerate Member) at Annertuneq and Kangilia on the north coast of Nuussuaq (Figs 72,

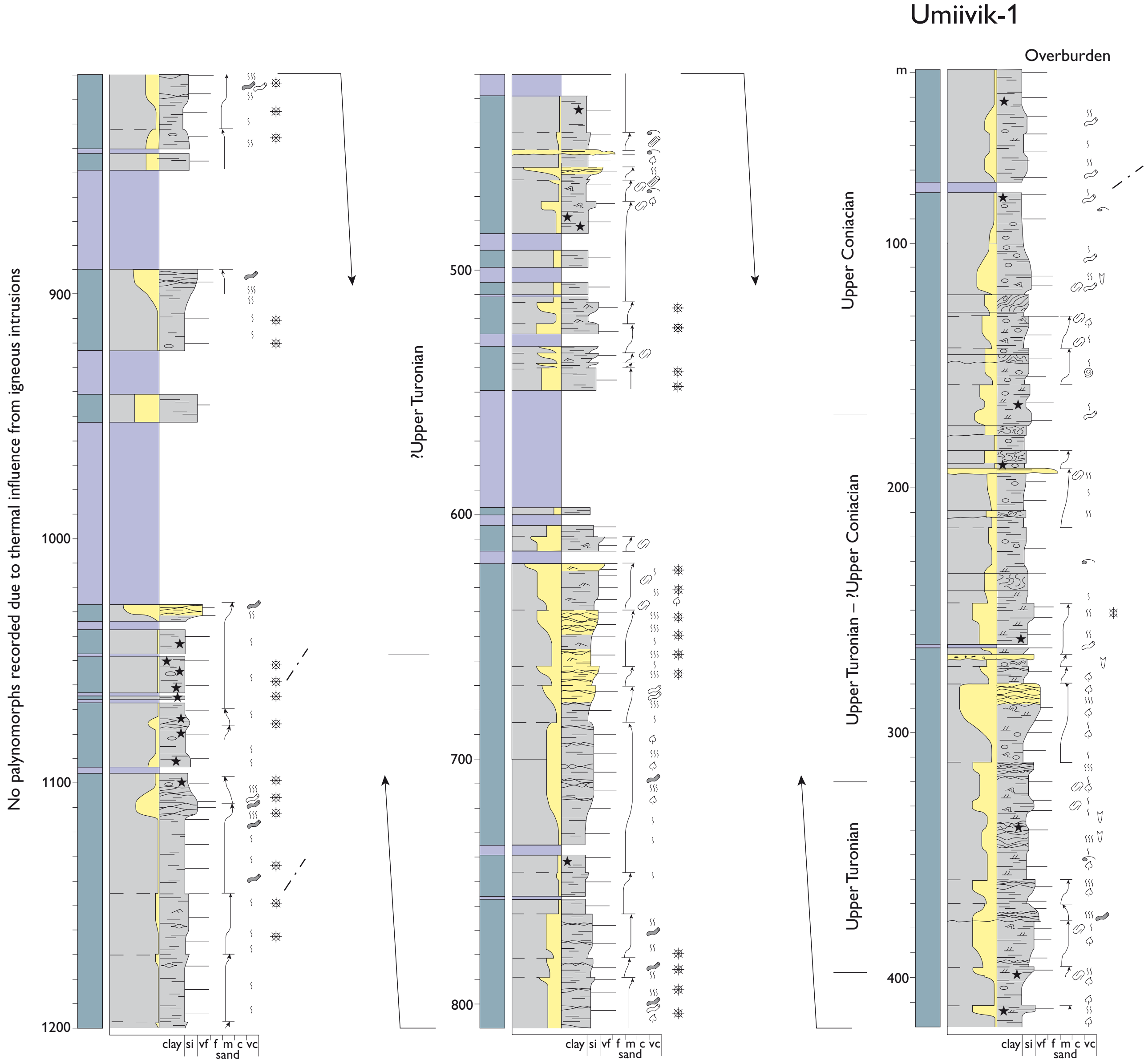
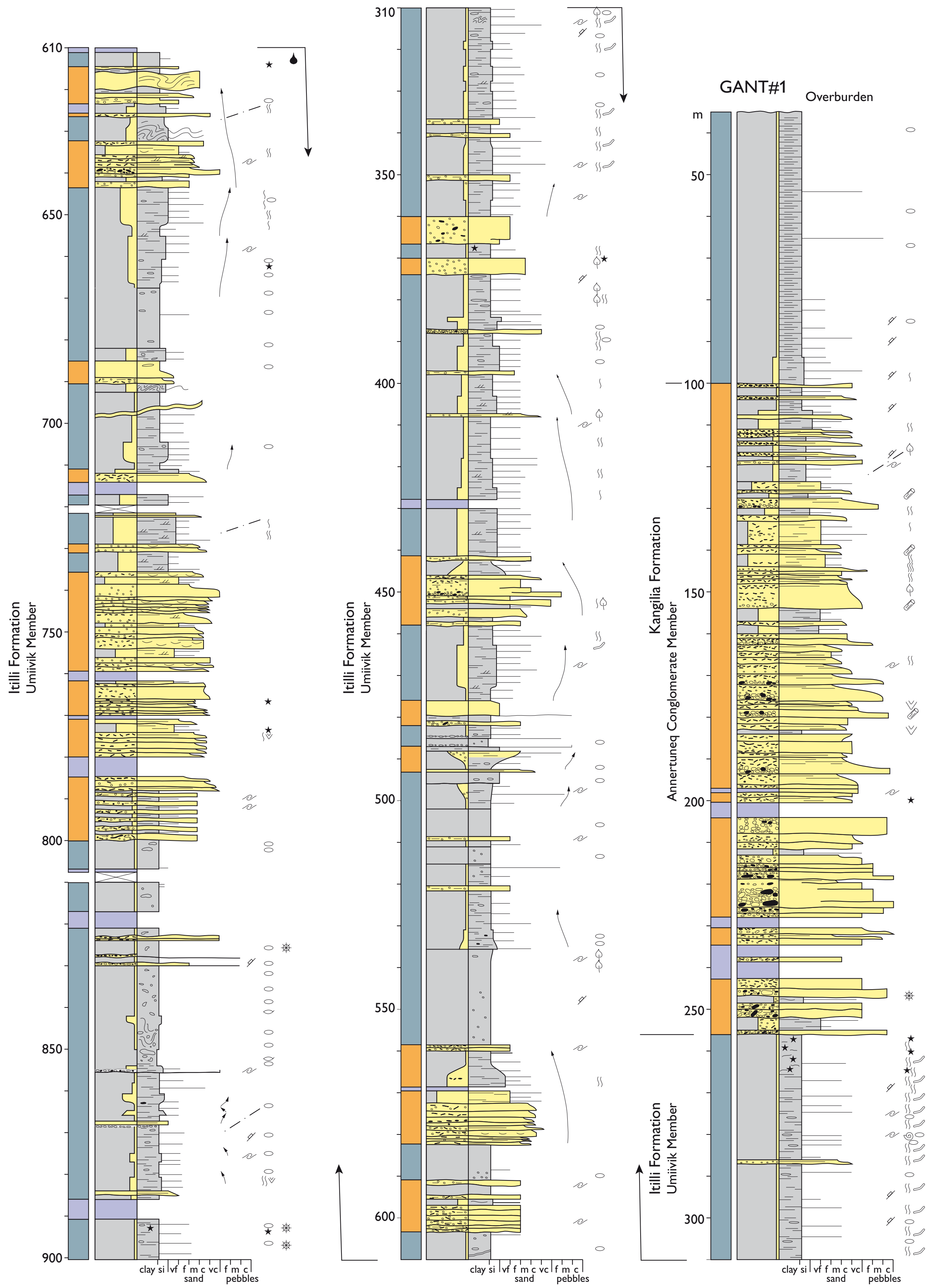


Fig. 75. Sedimentological log showing type section of the Umiivik Member (Itilli Formation) in the Umiivik-1 well. For location, see Fig. 73; for legend, see Plate 1. Modified from Dam *et al.* (1998b).

87). At Annertuneq, the GGU cores 400705–707 were drilled to supplement the outcrop studies (Fig. 74; Christiansen *et al.* 1994). In the GANT#1 well, the interval from 255.8 m to 900.6 m (Fig. 76) is assigned to the Umiivik Member (Dam 1996a). The cores are stored at GEUS in Copenhagen.

Thickness. The total thickness of the Umiivik Member is unknown, but in the Umiivik-1 well on Svartenhuk Halvø it is at least 960 m thick (excluding a total of 22 dolerite intrusions with a cumulative thickness of 240.2 m). In the slopes behind the Umiivik-1 drill site, approximately 185 m of poorly exposed mudstone is present below the base of the hyaloclastic volcanic rocks of the Vaigat Formation – this part of the succession is partly penetrated by the cores 400710–711 (Fig. 73; Christiansen *et al.* 1994). In the GANT#1 well, on northern Nuussuaq, 620 m have been cored (excluding intrusions).

Lithology. The Umiivik Member is dominated by black mudstones intercalated with laminae and thin beds of sandstone; carbonate concretions are common (Figs 75,



GANT#1
Overburden
m
Kangilia Formation
Annertuneq Conglomerate Member
Itilli Formation
Umiivik Member
610
650
700
750
800
850
900
310
350
400
450
500
550
600
50
100
150
200
250
300
clay si vf f m c vc f m c
sand
pebbles

76). Heavily bioturbated interbedded sandstones and mudstones, chaotic beds, and structureless, muddy sandstones also occur. Indistinct thickening- and coarsening-upward cycles, 2–85 m thick, can be seen in the Umiivik-1, FP94-11-02 and FP94-11-04 wells (Fig. 75; Dam & Nøhr-Hansen 1995). A cobble conglomerate composed of lithified sandstone clasts in a mudstone matrix is exposed in stream gullies on the south side of Uparuaqqusuitsut on north-eastern Svartenhuk Halvø (Fig. 73; Christiansen *et al.* 2000).

In the GANT#1 core, chaotic beds, muddy sandstones and sandy mudstones alternate with thick, sharp-based fining-upward successions (Fig. 76; Dam 1996a). The fining-upward successions consist of amalgamated sandstone beds grading upward into thinly interbedded sandstones and mudstones. Thin coarsening-upward successions also occur. The amalgamated sandstones consist of normally graded, medium- to coarse-grained sandstone beds with scattered basement pebbles and mudstone intraclasts. The sandstone beds are generally structureless, but parallel and cross-lamination occurs towards the top of some beds. A thin mudstone layer usually caps the sandstone beds.

The thinly interbedded sandstones and mudstones consist of sharp-based, graded laminae and beds of fine-grained to very coarse-grained sandstone alternating with black parallel-laminated mudstones. The sandstones are well-sorted and may show parallel and cross-lamination; small mudstone rip-up clasts frequently occur throughout the sandstone beds.

Fossils. Ammonites from the Umiivik Member have been described from several localities on Svartenhuk Halvø and include *Scaphites mariasensis umivikensis* (Birkelund), *Scaphites preventricosus svartenhukensis* (Birkelund), *Clioscaphites* sp. aff. *saxitonianus* (McLearn), *Scaphites cobbani* (Birkelund), *Scaphites rosenkrantzi* (Birkelund), *Scaphites* cf. *corvensis* (Cobban), *Clioscaphites saxitonianus septentrionalis* (Birkelund), ammonites of the genus *Haresiceras* and inoceramids of the steenstrupi group (Birkelund 1965). Belemnites from Svartenhuk Halvø include *Actinocamax* cf. *primus* (Arkhangelsky) and *Actinocamax* sp. (Birkelund 1956). Unidentified teleost fish remains have also been found in strata yielding Coniacian ammonites (Bendix-Almgreen 1969).

Ammonites occur at several localities along the north coast of Nuussuaq in the Umiivik Member, including *Pseudophyllites skoui* (Birkelund), *Scaphites (Hoploscaphites), S. (H.) greenlandicus* (Donovan), *S. (H.) ravni* (Birkelund), and *S. (H.) ikorfatensis* (Birkelund). The belemnites *Actinocamax groenlandicus* (Birkelund) and *Actinocamax* aff. *groenlandicus* (Birkelund), and an indeterminate solitary corallum have also been collected (Birkelund 1956, 1965; Floris 1972).

Dinocysts are abundant in the Umiivik Member (Dam & Nøhr-Hansen 1995; Nøhr-Hansen 1996, 1997a; Dam *et al.* 1998b).

Depositional environment. The Umiivik Member records deposition from low-density and high-density turbidity currents, debris flows, slumping and fall-out from suspension. Deposition of the mudstones and intercalated mudstones and sandstones took place in a base-of-slope and basin-floor fan environment. The succession in the GANT#1 well, which is situated close to the Kuuganguaq–Qunnilik Fault, reflects a fault-controlled base-of-slope environment with major and minor distributary feeder channels, small turbidite lobes and interdistributary channel areas.

Boundaries. The Umiivik Member unconformably overlies the Atane Formation on the north coast of Nuussuaq in a small and poorly exposed section at high altitude immediately east of the Ikorfat Fault (Fig. 22; A.K. Pedersen *et al.* 2006b).

West of the Ikorfat Fault, the lower boundary of the Umiivik Member is not exposed and has not been drilled. On northern Nuussuaq, the member is unconformably overlain by the Kangilia Formation (Figs 72, 74, 87). At most localities on Svartenhuk Halvø, it is unconformably overlain by Paleocene hyaloclastic rocks of the Vaigat Formation (Fig. 73). At Firefjeld, however, a thin Paleocene conglomeratic unit that may be correlated with either the Agatdal Formation or the Quikavsak Formation is present between the Umiivik Member and the volcanic succession.

Geological age. The age of the Umiivik Member is based on dinocyst and ammonite data (Birkelund 1965; Nøhr-Hansen 1996, 1997a). The ammonites from Svartenhuk Halvø indicate a ?Late Turonian – Early Campanian age for the Umiivik Member in this area (Fig. 16). Dinocysts

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Fig. 76. Sedimentological log of the Umiivik Member (Itilli Formation) and the Annertuneq Conglomerate Member (Kangilia Formation) in the GANT#1 well. For location, see Fig. 74; for legend, see Plate 1. Modified from Dam (1996a).

from the Umiivik-1 well indicate a ?Late Turonian – Late Coniacian age for the uppermost 659 m of the well; below this palynomorphs are not preserved due to severe alteration of the mudstones by the Paleocene dolerite intrusions. It is likely, however, that the core includes Cenomanian–Turonian strata (Nøhr-Hansen 1997a; Dam *et al.* 1998b). Dinocysts from outcrops and from the three shallow wells (GGU 400710, 400711, 400712) along the southern shore of Umiiviup Kangerlua on Svartenhuk Halvø indicate a Santonian to Early Campanian age (Nøhr-Hansen 1996).

On the north coast of Nuussuaq, the ammonites indicate the presence of Upper Campanian and Maastrichtian strata which is in accordance with palynostratigraphic dating (Birkelund 1965; Nøhr-Hansen 1996).

Kussinerujuk Member

new member

History. On northern Disko at Kussinerujuk and Asuk, local outcrops of conglomerate, sandstone and mudstone unconformably overlying the Atane Formation have previously been correlated with the Paleocene Kangilia Formation (J.M. Hansen 1980b; Pulvertaft & Chalmers 1990). Later, these beds were included in the Asuup Innartaa Member of the Danian Quikavsak Formation (Dam 2002). On the basis of new biostratigraphic data, however, these are here assigned to the Kussinerujuk Member of Cenomanian–Turonian age (Bojesen-Koefoed *et al.* 2007).

Name. The member is named after Kussinerujuk on the north coast of Disko, where it is exposed in narrow gorges (Fig. 2).

Distribution. The member is only known from the north coast of Disko around Kussinerujuk and Asuk.

Type section. The type section of the member is in the ravines at Kussinerujuk (Figs 2, 77, 78). The type section is located at 70°13.10´N, 53°27.68´W.

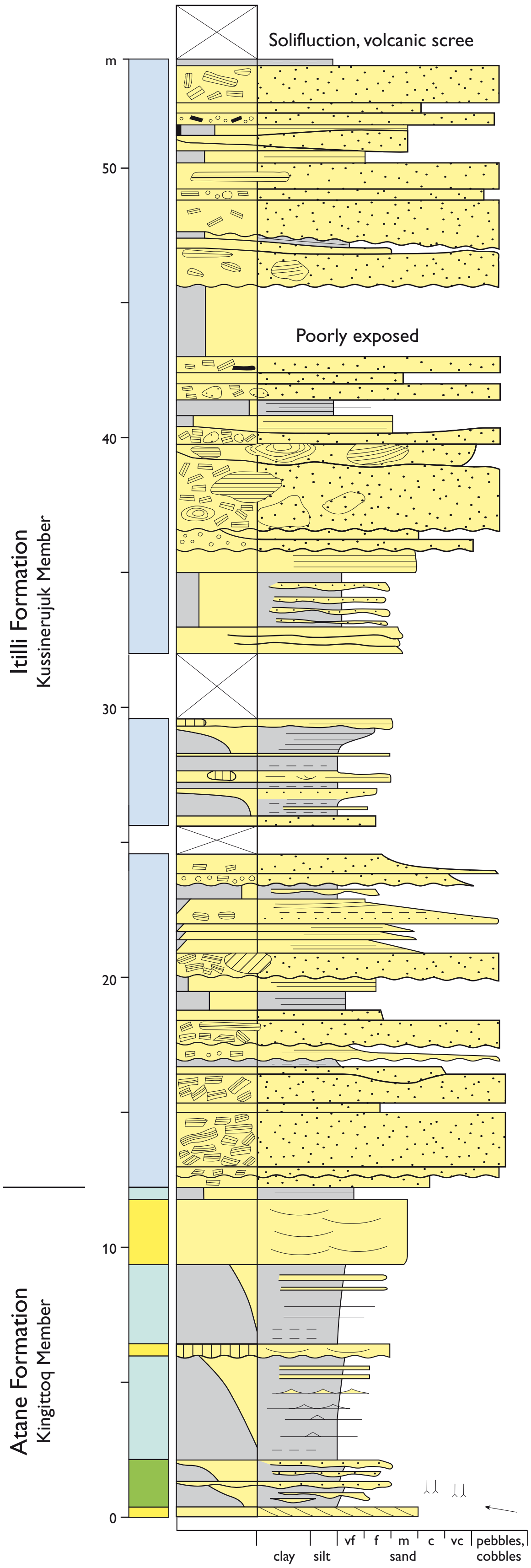
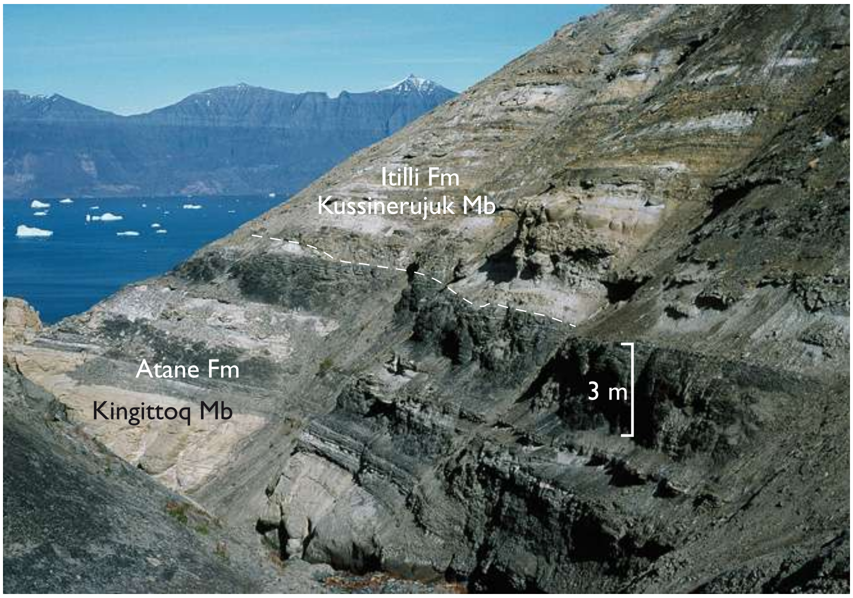


Fig. 77. Type section of the Kussinerujuk Member (Itilli Formation) at Kussinerujuk, north coast of Disko. For location, see Fig. 2; for legend, see Plate 1. Base of section is *c.* 450 m a.s.l.

Fig. 78. Type locality of the Kussinerujuk Member (Itilli Formation) at Kussinerujuk. Note the basal erosional boundary with the Atane Formation beneath; the uppermost depositional unit underlying the Kingittoq Member is a dark grey, delta front mudstone. The Kussinerujuk Member is dominated by mud-clast conglomerates with a matrix of sand (see Fig. 77). For location, see Fig. 2.



Reference sections. Reference sections are found in the coastal cliffs east of Asuk (Figs 55, 79). The lithologies here differ from those of the type section but are locally affected by complicated deformation resulting from landslides obscuring the stratigraphic relationships (Bojesen-Koefoed *et al.* 2007).

Thickness. At Kussinerujuk the measured part of the formation is at least 42 m thick (Fig. 77; see also Pulvertaft & Chalmers 1990) but the member may be up to a couple of hundred metres thick.

Lithology. The Kussinerujuk Member comprises thinly interbedded mudstones and sandstones, and mudstone clast conglomerates, first described by Pulvertaft & Chalmers (1990 fig. 6).

At Kussinerujuk the member consists of mud-clast conglomerates of varying thicknesses, with angular clasts of cobble to boulder size, interbedded with medium- to coarse-grained sandstone (Fig. 77). In some conglomerate beds, the clasts are imbricated whereas other conglomerates appear to be disorganised. Pebble-sized clasts consist of rounded quartz and clay ironstone while angular cobbles and boulders consist of mudstone, sandstone, or interbedded sandstone and mudstone.

At Asuk, the Atane Formation is overlain by mudstones and sandstones that are referred to the Kussinerujuk Member. These sediments occur in three separate outcrops. The westernmost of these is seen in Fig. 79, the central outcrop is seen in Fig. 80, and the eastern is seen in the coastal cliff adjacent to the huge alluvial fan at Qorlortorsuaq. The western outcrop is overlain by volcanic breccias and lavas of the Asuk Member (lower part of the Vaigat Formation; Bojesen-Koefoed *et al.* 2007). The volcanic rocks are part of a major landslide, and the complicated relationships seen in Fig. 79 suggest that the sediments at this locality are also affected by sliding; their stratigraphic relationships with the central and eastern outcrops are thus uncertain.

A simplified sedimentological log from the central outcrop is shown in Fig. 55. Here a basal conglomerate of mudstone and sandstone clasts in a matrix of coarse-grained sand erosionally overlies the Atane Formation and is succeeded by parallel-laminated sandstones interbedded with sand-streaked mudstones (Figs 55, 80).

The western, landslipped outcrops comprise a unit of parallel-laminated, sand-streaked mudstone, locally with small-scale load structures (Fig. 81A). Other units consist of strongly erosional, channellised sandstones that cut into mudstones (Fig. 81 B); thicker sandstone beds are fine- to medium-grained and show parallel lamination and ripple cross-lamination. Other sandstone beds are structureless and have erosional bases with sole-marks.

Fossils. Brackish to marine dinocysts occur in the member and are relatively abundant at Asuk (McIntyre 1994a, b) noted that rich pollen and spore assemblages dominated by bisaccate conifer pollen are present in the type section whereas dinocysts are very rare.

Depositional environment. The Kussinerujuk Member records a transgressive event on top of a variably incised

Fig. 79. Outcrops of the Itilli Formation at the western end of the coastal cliff section at Asuk. Outcrops of the Atane Formation are seen farthest to the east (left); for detail, see Fig. 57. The pale sandstones (centre-left) are impregnated with hydrocarbons (see Bojesen-Koefoed *et al.* 2007).The dark grey mudstones in the centre of the photograph are referred to the Kussinerujuk Member as are the sandstones to the west. The dark-weathering rocks cropping out above these sandstones are referred to the volcanic Asuk Member (Vaigat Formation). These volcanic rocks are part of a major landslide, and the complicated structural relationships between the pale sandstones and the mudstones of the Itilli Formation suggest that the coastal exposures may be affected by landslides. The height of the cliff is *c.* 30 m. For location, see Fig. 2.

surface capping the Atane Formation east of the Kuuganguaq–Qunnilik Fault. The genetic relationships between the two outcrop areas of the member are, however, poorly understood. The conglomerates at the type locality at Kussinerujuk were deposited from channellised sediment gravity flows at unknown water depths possibly generated by slope failure in a deeply incised channel. Farther east, at Asuk and Qorlortorsuaq, the mudstone-dominated succession is tentatively interpreted to be deposited in a marine environment during transgression. Deposition occurred below storm wave base on a gently sloping sea floor from low-energy unconfined turbidity currents or distal storm-generated flows.

Boundaries. The lower boundary, as exposed at Kussinerujuk, Asuk and Qorlortorsuaq (Fig. 2), is an erosional unconformity where mudstones or mud-clast conglomerates sharply overlie deltaic sandstones of the Atane Formation (Kingittoq Member; Figs 16, 55, 77). The upper boundary is not exposed, but is probably an erosional unconformity overlain by Paleocene hyaloclastite breccias of the Vaigat Formation.

Geological age. Spores, pollen and dinocysts indicate a Cenomanian to Late Turonian age for the member at Kussinerujuk (McIntyre 1994a, b; this study). Dinocysts indicate a Cenomanian age at Asuk (Fig. 16; Bojesen-Koefoed *et al.* 2007).

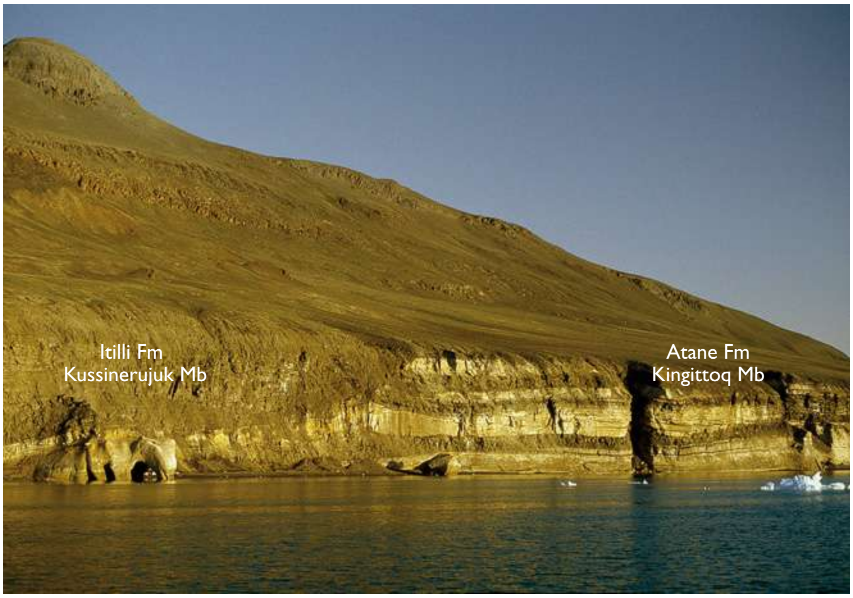


Fig. 80. Erosional unconformity between the Atane Formation and the Itilli Formation (see Fig. 55) in the coastal cliff east of Asuk. The coastal cliff is *c.* 30 high. For location, see Fig. 2.

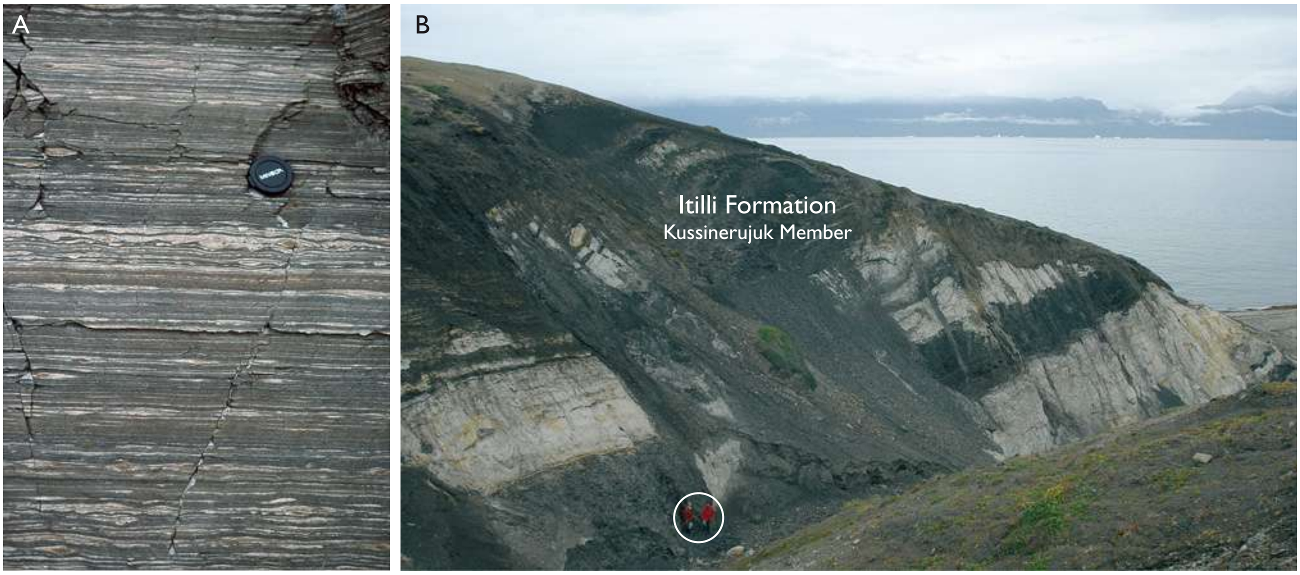


Fig. 81. **A**: Silt-streaked mudstone with small-scale load structures in the Kussinerujuk Member (Itilli Formation) at Asuk. Lens cap for scale. **B**: Land-slipped deposits of erosionally based sandstones interbedded with mudstones at Asuk are assigned to the Kussinerujuk Member of the Itilli Formation. Encircled persons for scale; for location, see Fig. 2.

Correlation. The Kussinerujuk Member is coeval with parts of the Umiivik and Anariartorfik Members of the Itilli Formation.

Aaffarsuaq Member

new member

History. The un-named Upper Cretaceous marine sandstones and shales exposed on central Nuussuaq that were informally referred to the Aaffarsuaq member by Dam *et al*. (2000), are mainly known for the remarkable discoveries in 1952 of huge specimens of Upper Santonian – Lower Campanian inoceramid (*Sphenoceramus*) bivalve shells (Fig. 71; Rosenkrantz 1970).

Name. The member is named after the Aaffarsuaq valley on central Nuussuaq (Fig. 82).

Distribution. The member is found on central Nuussuaq where it is well exposed along the south-facing slopes of Aaffarsuaq between Qilakitsoq and Tunoqqu. Minor exposures are present in a stream section on the north-facing slope of Aaffarsuaq, south of Nalluarissat, in Kangersooq (Fig. 82) and in Turritelladal at Scaphitesnæsen, and in Agatdalen where the Teltbæk fault crosses the Agatdalen river (Figs 82, 113; Dam *et al*. 2000).

Type section. The type section is located in the second ravine east of Qilakitsoq on the northern slopes of Aaffarsuaq (Figs 82, 83). The base of the type section is located at 70°28.70′N, 53°21.97′W.

Reference sections. Well-exposed reference sections occur in ravines on the northern side of Aaffarsuaq along Nalluarissat, between Qilakitsoq and Tunoqqu (Fig. 82).

Thickness. In the main outcrop area, the thickness of the member decreases eastward from *c*. 250 m in the type section to 65 m at Tunoqqu.

Lithology. The Aaffarsuaq Member is characterised by amalgamated sandstone and rip-up mudstone and sandstone clast conglomerate units alternating with thinly interbedded sandstones and mudstones, dark, sand-streaked mudstones, and chaotic beds of homogeneous mudstone commonly cut by sandstone dykes and synsedimentary faults (Figs 83, 84, 85, 86; Dam *et al*. 2000).

The amalgamated sandstone and conglomerate units of the Aaffarsuaq Member consist of very coarse- to medium-grained sandstone and conglomerate beds grading upwards into thinly interbedded sandstones and mudstones. These coarse-grained units are up to 50 m thick and extend laterally beyond the extent of outcrop (several hundred metres) or occasionally form lenticular bodies. Individual beds have planar erosional bases and internally show normal grading. Beds are from <25 cm

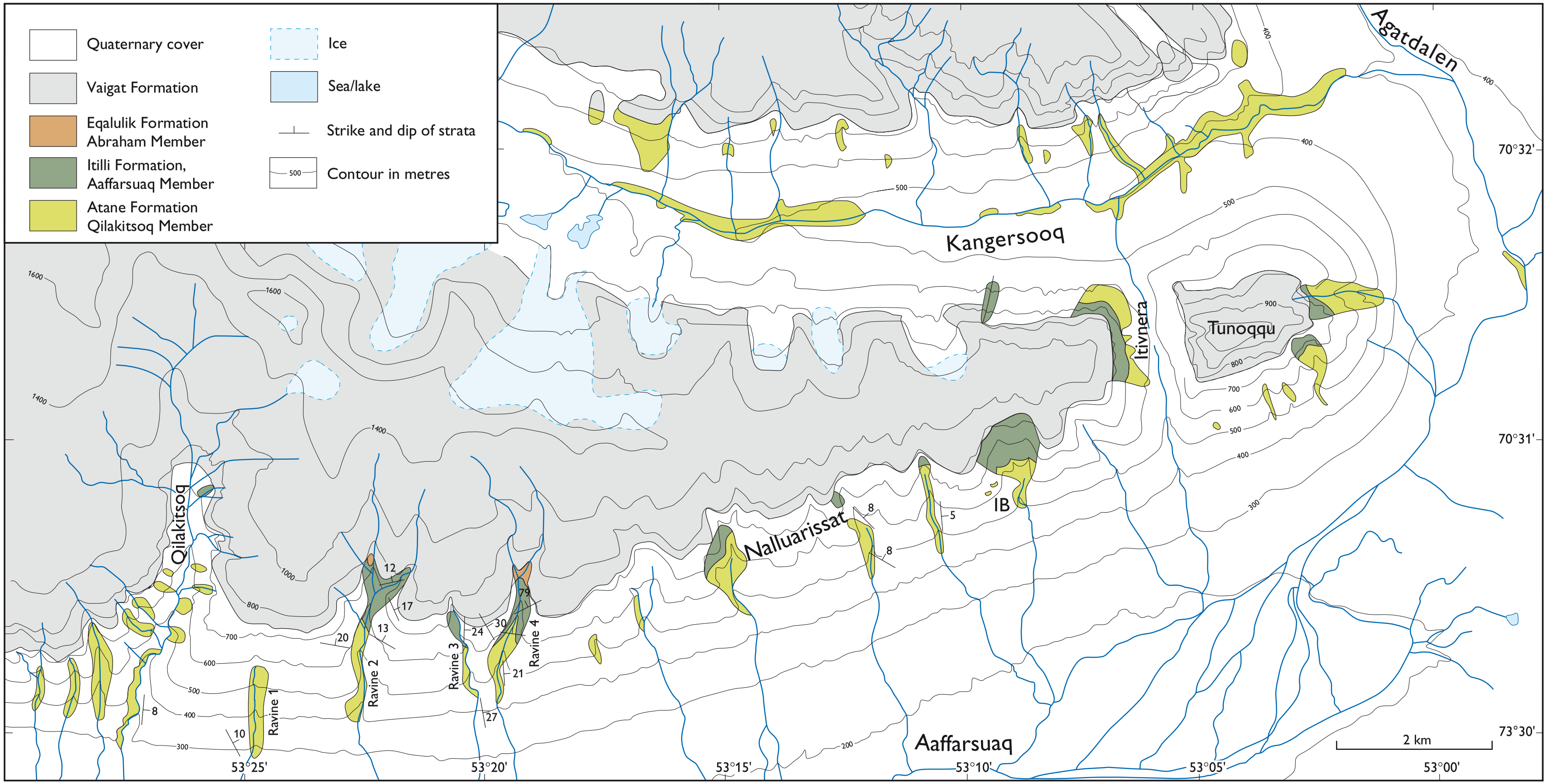


Fig. 82. Geological map of the north side of the Aaffarsuaq valley between Qilakitsoq and Agatdalen. The type section of the Qilakitsoq Member (Atane Formation) is located along Qilakitsoq, and the type section of the Aaffarsuaq Member (Itilli Formation) is located in Ravine 2. **IB**, type section of the Itivnera Bed. Contour interval is 100 m in the sedimentary outcrops, 200 m in the Vaigat Formation. Modified from Rosenkrantz *et al.* (1974).

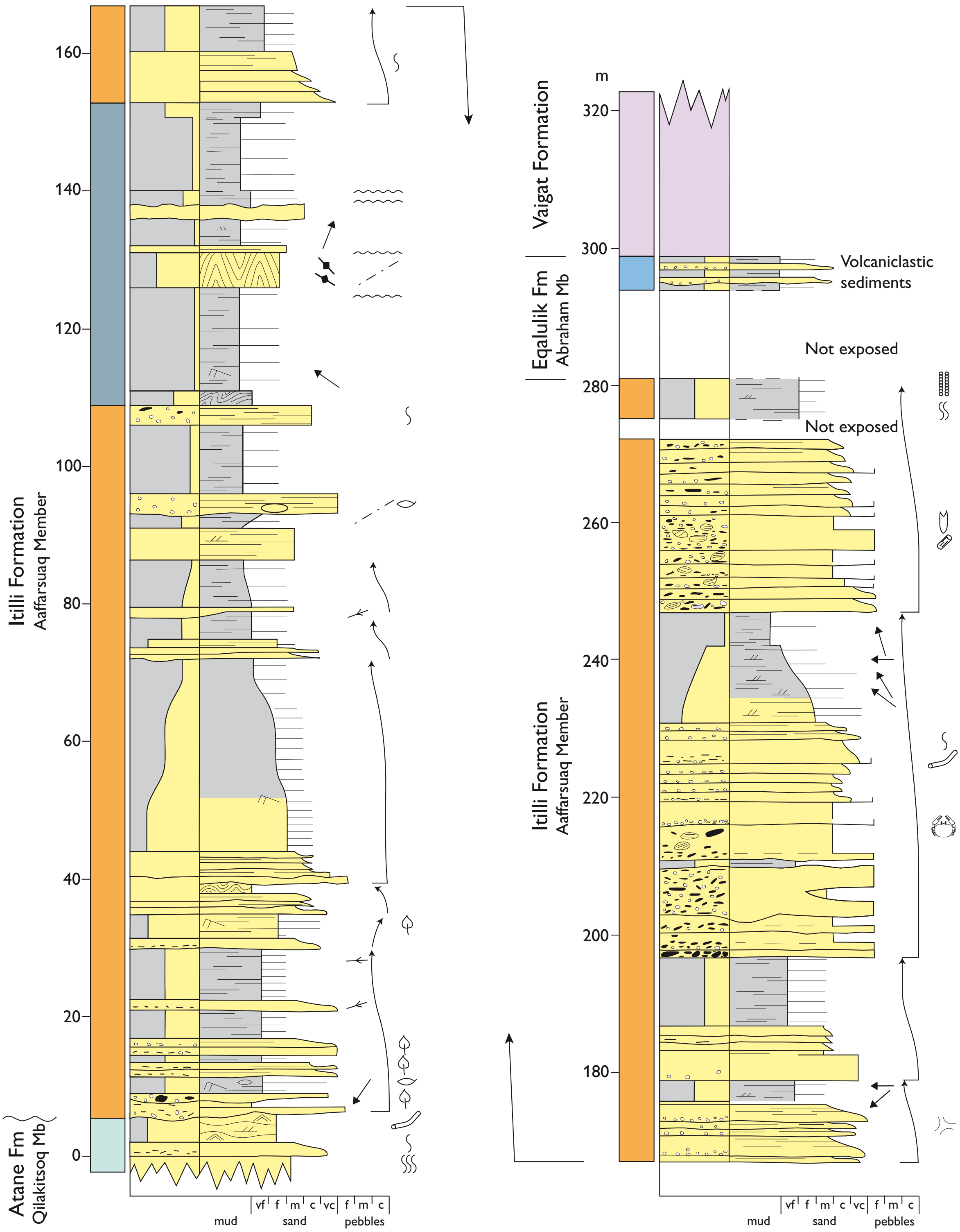


Fig. 83.Type section of the Aaffarsuaq Member (Itilli Formation), second ravine east of Qilakitsoq, compare with Fig. 85. For location, see Fig. 82; for legend, see Plate 1. Modified from Dam *et al.* (2000).

Fig. 84. Unconformity between Santonian deltaic deposits of the Atane Formation (Qilakitsoq Member) and Campanian turbidite sandstones and conglomerates of the Aaffarsuaq Member (Itilli Formation). East-side of Tunoqqu. For location, see Fig. 82.

to more than 5 m thick and are commonly separated by thin mudstone beds (Figs 83, 85). The sandstones are mostly structureless, whereas the conglomerates show considerable lateral variation, are poorly sorted, and always have a coarse-grained sandy matrix. Both matrix- and clast-supported conglomerates occur. The clasts consist of intraformational mudstone, sandstone (probably derived from the underlying Atane Formation), concretions and basement lithologies (Dam *et al.* 2000).

The amalgamated sandstone and conglomerate units are overlain by thinly interbedded sandstone and mudstone units with either a gradational or a sharp contact. These units are up to 30 m thick and show a general thinning- and fining-upward trend (Figs 83, 85). They consist of laterally persistent, normally-graded, <1–40 cm thick beds of fine- to medium-grained sandstone capped by parallel-laminated mudstone.

Mudstones with thin (<2 cm), laterally persistent sandstone streaks form monotonous successions 10–30 m thick. The mudstones are finely laminated and laminae are usually normally graded. The sandstone laminae are normally graded, parallel- or cross-laminated throughout and constitute less than 25% of the succession.

Up to 15 m thick units of strongly contorted, thinly interbedded sandstones and mudstones and chaotic beds of homogeneous mudstone with evenly scattered coarse sand grains, mudstone intraclasts, transported early diagenetic concretions and basement clasts occur both within the mudstone-dominated successions and directly beneath the thick units of amalgamated sandstones and conglomerate.

Fossils. Ammonites have been found at Scaphitesnæsen in Turritellakløft and include *Pseudophyllites skoui* (Birkelund), *Baculites obtusus* (Meek), *Baculites* cf. *haresi* (Reeside), *Scaphites cobbani* (Birkelund) and *Scaphites rosenkrantzi* (Birkelund) (Birkelund 1965). Reworked ammonites including *Scaphites* cf. *svartenhukensis* (Birkelund 1965) have been found at Tunoqqu (Dam *et al.* 2000).

Well-preserved inoceramids are commonly found at the top of turbidite sandstone beds, suggesting only little transportation (Fig. 71). Bryozoans fixed to inoceramid bivalve shells have been reported. A single, nearly complete capitulum of the cirripid *Eskimolepas gregersi* Rosenkrantz (Rosenkrantz 1970) has also been found. Dinocysts and pollen belonging to the *Aquilapollenites* interval have been reported from Scaphitesnæsen and Tunoqqu (Nøhr-Hansen 1996; Dam *et al.* 2000).

Depositional environment. The Aaffarsuaq Member exhibits a characteristic suite of thick units of amalgamated sandstone and conglomerate beds, interpreted to represent deposition mainly from gravity flows in a channellised, footwall fan system. Deposition of the amalgamated sands was confined to major turbidite channels. The intervening thinly interbedded sandstone and mudstone units were deposited mainly from low-density turbidity currents confined to minor channels. The sand-streaked, mudstone-dominated units were deposited by waning low-density turbidity currents in an interchannel slope setting. The contorted, thinly interbedded sandstones and mudstones probably formed by downslope displacement of semi-consolidated sediment (Dam *et al.* 2000).

In the Aaffarsuaq Member, the chaotic beds are not invariably associated with turbidite channel deposits, as

Fig. 85. Mudstones and conglomeratic sandstones of the upper part of the Aaffarsuaq Member (Itilli Formation) in the type section in the second ravine east of Qilakitsoq, see Fig. 83, *c*. 175–300 m. For location, see Fig. 82.

observed in the Anariartorfik Member, suggesting that downslope failure could also be associated with seismic activity (Dam *et al*. 2000).

Geological age. The ammonites at Scaphitesnæsen indicate an Early Campanian age (*Baculites obtusus* Zone) for the Aaffarsuaq Member. The mudstones are generally almost barren of palynomorphs but a rich flora is locally

Fig. 86. Conglomerate at the top of the type section of the Aaffarsuaq Member (Itilli Formation); note the predominance of sedimentary clasts. Ruler is 120 cm long. For location, see Fig. 82.

present that suggest an Early–Middle Campanian age for the member (Nøhr-Hansen 1996; Dam *et al.* 2000).

Boundaries. The lower boundary is an angular unconformity. Tilted strata of the deltaic Qilakitsoq Member (Atane Formation) were truncated during the transgression recorded by the Aaffarsuaq Member (Dam *et al.* 2000). Along the Aaffarsuaq valley, the Aaffarsuaq Member is unconformably overlain by Paleocene hyaloclastites of the Vaigat Formation (A.K. Pedersen *et al.* 2002). However, in two ravines along Aaffarsuaq, it is overlain by Paleocene mudstones and volcaniclastic sandstones referred to the Eqalulik Formation (Figs 82, 83, see below).

Kangilia Formation

revised formation

History. The Kangilia Formation was established by Rosenkrantz (1970) to encompass the Danian (Lower Paleocene) conglomerate-based, marine mudstone-dominated succession that overlies Upper Cretaceous mudstones (Itilli Formation of this paper) with an angular unconformity on northern and central Nuussuaq. Based largely on the content of fossils, he divided the formation into four members, from base to top: the Conglomerate Member, a conspicuous coarse-grained, clast-supported conglomerate unit, *c.* 50 m thick, the Fossil Wood Member, comprising black mudstones with a sandstone unit in the lower part, *c.* 425 m thick, the *Thyasira* Member consisting of sandstones and black mudstones with tuff beds, *c.* 35 m thick and the *Propeamussium* Member made up of black mudstones, locally with intercalated sandstones, *c.*100 m thick.

Without providing details, Rosenkrantz (*in* Henderson 1969 fig. 4) included the entire 300 m thick mudstone-dominated succession at Ataata Kuua (near Atâ) in the Kangilia Formation. Furthermore, the distribution of the Kangilia Formation was shown in a schematic section through the Nuussuaq Basin that was presented by Henderson *et al.* (1976 fig. 303). The two upper members of the formation were also reported from Alianaatsunnguaq, Tupaasat and Ataa on the south coast of Nuussuaq (Rosenkrantz 1970).

The Kangilia Formation including the basal conglomeratic member (Annertuneq Conglomerate Member) is formally defined here. The 'Oyster-Ammonite Conglomerate' (Birkelund 1965) is formally defined as the Oyster–Ammonite Conglomerate Bed. The Fossil Wood, *Thyasira* and *Propeamussium* Members are abandoned. The strata previously assigned to the latter two are now included in the new Eqalulik Formation (see below). On central Nuussuaq, Dam *et al.* (2000) mapped a unit in the Kangilia Formation that was informally termed the Danienrygge member; this unit is not formally recognised here.

On Itsaku, Svartenhuk Halvø, J.G. Larsen & Pulvertaft (2000) suggested that the poorly dated ?Upper Campanian/Maastrichtian to Paleocene succession may be equivalent either to both the Itilli and Kangilia Formations (i.e. Campanian to Paleocene) or to the Kangilia Formation alone (i.e. upper Maastrichtian to Paleocene), on account of a tentative correlation of two major conglomerate horizons with two discrete tectonic events recognised on Nuussuaq. Zircon provenance data show that the detrital zircon population of this succession has a distinct and narrow age range peaking at 1870 Ma whereas ages of zircons in the underlying sediments of the Upernivik Næs Formation show a greater spread with a distinct peak at 2750 Ma (Scherstén & Sønderholm 2007). Since there was only one major change in zircon provenance in the section involving a shift to a unique, single point source at the boundary between the Upernivik Næs and the overlying deposits, the suggestion is that only one tectonic event is recorded in the section. The entire ?Upper Campanian/Maastrichtian to Paleocene succession on Itsaku may thus be assigned to the Kangilia Formation.

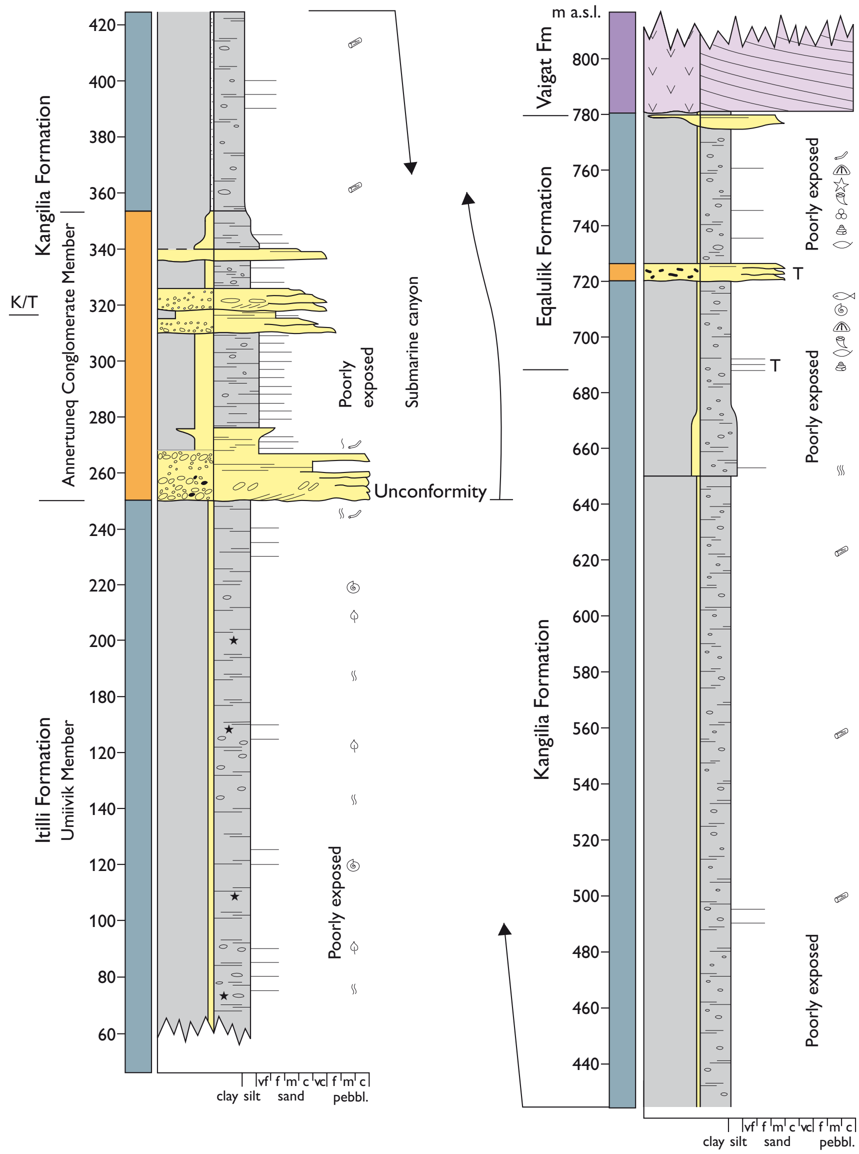
Name. After the headland of Kangilia on the north coast of Nuussuaq (Fig. 74).

Distribution. The formation is exposed at Ataata Kuua, Ivisaannguit, Tupaasat, Nuuk Killeq and Alianaatsunnguaq on the south coast of Nuussuaq (Figs 2, 6, 40; A.K. Pedersen *et al.* 1993), in the northern part of Agatdalen on central Nuussuaq (Fig. 113), in the Tunorsuaq valley on western Nuussuaq (where it has also been drilled in the GANT#1 well) and along the north coast of Nuussuaq (Fig. 74), and on Itsaku on eastern Svartenhuk Halvø (Fig. 73). The formation has been drilled on western Nuussuaq in the GRO#3 well (Fig. 65).

Type section. The exposures at Kangilia on the north coast of Nuussuaq are designated as the type section (Figs 87, 88). The base of the type section is located at 70°44.90′N, 53°25.33′W.

Reference sections. Well-exposed reference sections occur at Annertuneq (Fig. 72; Nøhr-Hansen & Dam 1997),

Fig. 87. Type section of the Kangilia Formation at Kangilia on the north coast of Nuussuaq. The log is generalised due to intermittent exposures of the mudstone intervals. Top of section is at Danienrygge; for location, see Fig. 74. **K/T**, Cretaceous–Palaeogene boundary. See also Figs 88 and 118. For legend, see Plate 1.



Ataata Kuua (Figs 14, 89; Dam & Nøhr-Hansen 2001) and at Ivisaannguit west of Ataata Kuua. The formation was drilled and cored in the GANT#1 well in Tunorsuaq between 35 m and 256 m (Fig. 76) and drilled in the GRO#3 well between 728 m and 959 m (Fig. 67).

Thickness. The Kangilia Formation varies in thickness from 440 m at Kangilia (Fig. 87) to *c*. 400 m at Ataata Kuua (Fig. 15), 230 m in the GRO#3 well (Fig. 67), to just 75 m on central Nuussuaq (H.J. Hansen 1970).

Lithology. On northern Nuussuaq the Kangilia Formation comprises a basal approximately 85–140 m thick conglomeratic unit overlain by a mudstone-dominated succession. The conglomeratic unit is here formally established as the Annertuneq Conglomerate Member. In the lower part it is composed of amalgamated conglomerate beds that towards the top become finer-grained and separated by mudstone intervals (Figs 72, 76, 87; for detailed description, see below).

The succession overlying the basal conglomerate unit consists mainly of dark mudstones with thin beds of fine- to coarse-grained sandstone (Figs 76, 87, 88). The mudstones are weakly laminated; locally some of the laminae are graded. The sandstone beds have sharp bases and are usually normally graded. The sandstones are structureless or parallel-laminated. Ferroan carbonate concretions and fragments of fossil wood are common at various levels.

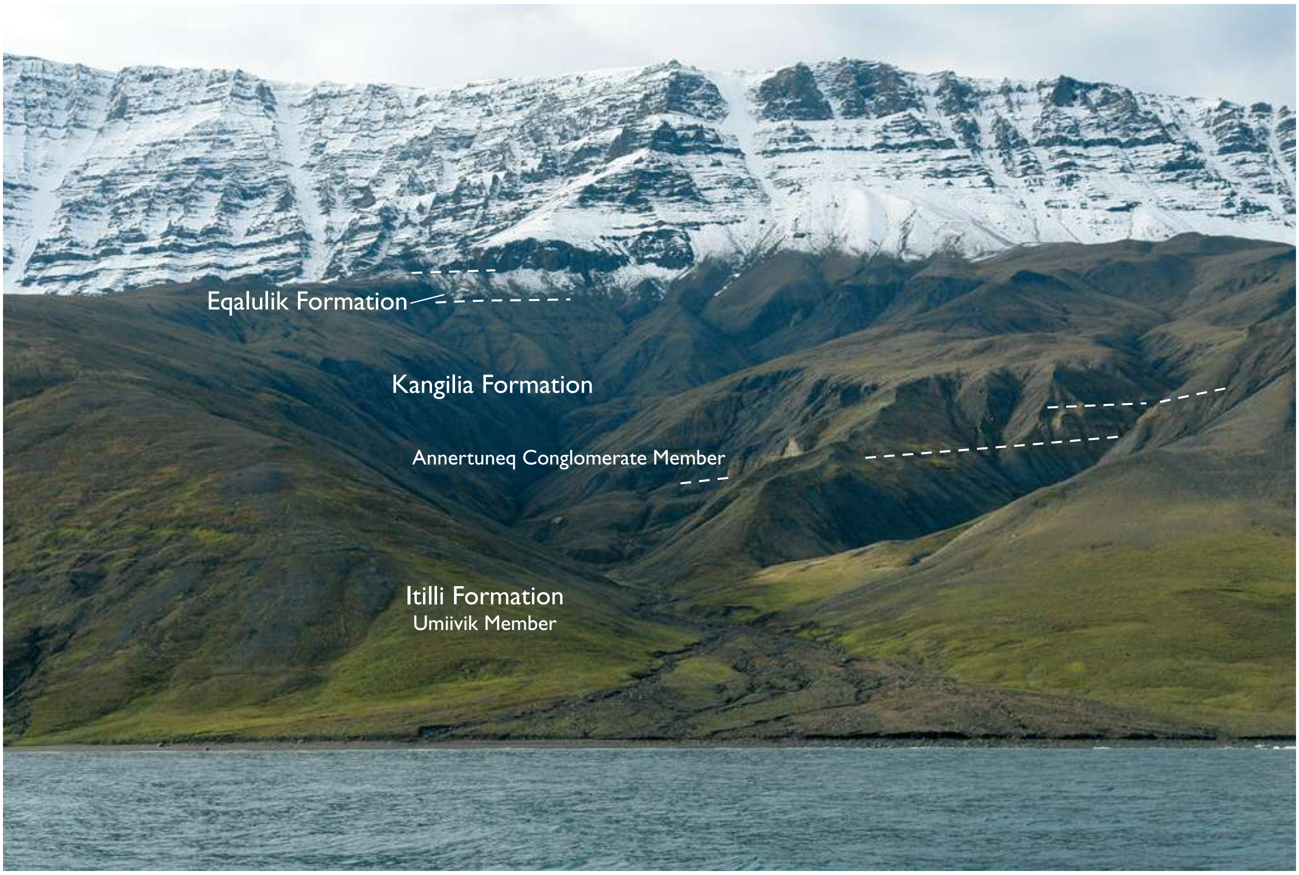


Fig. 88. Outcrop of the Itilli, Kangilia and Eqalulik Formations at Kangilia. The snowline at *c.* 800 m corresponds roughly to the base of the volcanic Vaigat Formation. For location, see Fig. 74.

At Ataata Kuua on the south coast of Nuussuaq, a basal sandstone unit with scattered mudstone clasts and transported concretions up to 1.5 m in diameter rests on a deeply eroded surface above lowest Campanian and older Atane Formation (Figs 14, 15). The unit forms the base of a 107 m thick fining-upward succession; the sandstone unit grades up into thinly interbedded sandstones and mudstones that are capped by mudstones with scattered basement pebbles interbedded with sandstone lenses and layers (Fig. 89; Pulvertaft & Chalmers 1990; Dam & Nøhr-Hansen 2001). The sandstones are largely structureless, but may grade into parallel- and cross-laminated sandstone. Convolute bedding is developed locally.

The sandstones occur as sheets in composite bedsets in the basal 11 m of the succession, or as single beds that fill wide shallow scours in the middle and upper part (Fig. 89). The composite sandstone bedsets are succeeded by approximately 50 m of interbedded sandstones and mudstones consisting of sharply based laminae and beds that grade upwards from coarse-grained to fine-grained sandstone capped by silty mudstone (Fig. 89). These lithologies may form sharply based fining-upward units up to 1.5 m thick, restricted to lenticular bodies a few tens of metres wide (Fig. 89). Erosional discordances are common within the lenticular bodies and internally they are made up of small amalgamated fining-upward successions.

The interbedded sandstones and mudstones are succeeded by a 56 m thick unit dominated by massive mudstone containing scattered sand grains and few pebble- and cobble-sized basement clasts (Fig. 89). The mudstone beds are interbedded with laminated mudstones with sand streaks (Fig. 90). Conglomerates and sandstones form an up to 40 m thick unit in the middle of the Ataata Kuua exposure (Figs 14, 15, 89), with sedimentary facies very similar to that seen in the prominent conglomerate unit on the north coast of Nuussuaq. This unit is overlain by approximately 250 m of generally poorly exposed mudstone (Fig. 14).

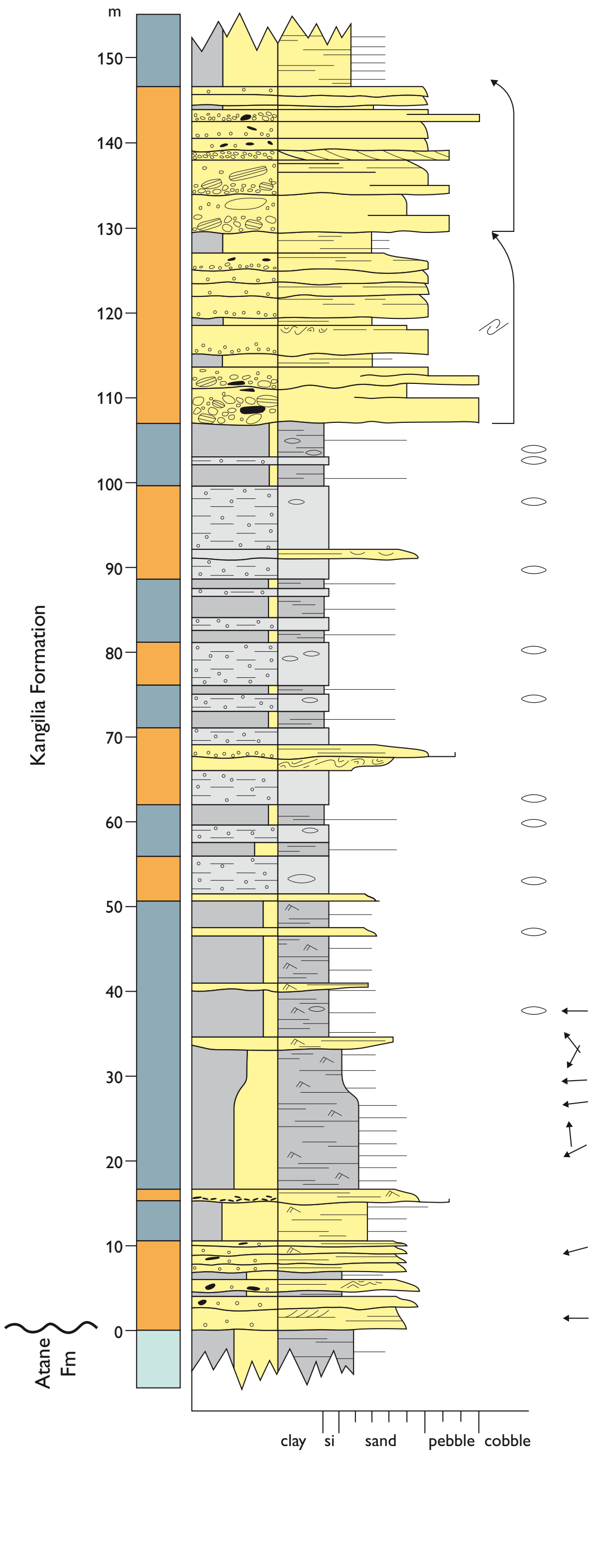


Fig. 89. Sedimentological log showing the lower part of the Kangilia Formation at Ataata Kuua. Slightly modified from Dam & Nøhr-Hansen (2001), see also Fig. 15. For location of section, see Fig. 40; for legend, see Plate 1.

Fig. 90. Dark grey mudstones interbedded with thin sandstone beds of the Kangilia Formation at Ataa (for location, see Fig. 40). The illustrated section is *c*. 5 m thick.

Just west of Ataata Kuua, several levels of coarse-grained sandstones and conglomerates are present within the upper mudstone succession (Fig. 91). Larger clasts include sandstone and mudstone intraclasts, clay ironstone concretions and kaolinised gneiss clasts. Dykes of injected sand are also seen. Farther west these coarse-grained levels disappear.

In Agatdalen on central Nuussuaq, the formation is generally poorly exposed and dominated by mudstones. A Paleocene conglomerate unit about 5 m thick was described as the Oyster-Ammonite Conglomerate by Birkelund (1965) and Rosenkrantz (1970). It is mainly composed of derived, highly fossiliferous concretions and is here formally established as the Oyster–Ammonite Conglomerate Bed.

Fossils. Along the north coast of Nuussuaq, fossils are rare in the Kanglia Formation apart from *Teredo-bored* fossil wood (Mathiesen 1961; Rosenkrantz 1970). A very

Fig. 91. Mudstones interbedded with sandstone and channellised conglomerates (arrows point to base of conglomerate-filled channels). The Kangilia Formation at Ataa; for location, see Fig. 40. Height of the section is *c*. 50 m.

small number of *in situ* ammonites (*Hoploscaphites* aff. *H. angmartussutensis*) and echinoderms have been found in a sandstone bed in the lower part of the formation and in scattered concretions (Nøhr-Hansen & Dam 1997; Kennedy *et al*. 1999). Palynomorphs are common and are referred to five zones from the *Wodehouseia spinata* Zone to the *Palaeocystodinium bulliforme* Zone (Nøhr-Hansen 1997b; Nøhr-Hansen *et al*. 2002).

The Oyster–Ammonite Conglomerate Bed in Agatdalen is made up of highly fossiliferous concretions containing a mainly Maastrichtian fauna of ammonites although concretions with Campanian and Danian species are also present. The matrix of the conglomerate contains Danian oysters and other bivalves, gastropods, crustaceans and rare specimens of other fossils (Birkelund 1965; Rosenkrantz 1970).

On the south coast of Nuussuaq, fossils are very scarce in the Kangilia Formation and only indeterminate thin-shelled bivalves and gastropods have been found in the mudstones at Ivisaannguit. The trace fossil *Planolites* isp. and escape burrows occur locally in the sandstone beds.

Depositional environment. The presence of dinocysts, echinoderms and ammonites indicates a marine depositional environment and the mudstones and sandstones dominating the formation are interpreted to have been deposited from waning, low-density turbidity currents whereas the conglomeratic units were deposited from channellised, high-density currents. Some of the mudstones may also have been deposited from suspension.

The conglomerates and sandstones at the base of the Kangilia Formation exhibit a characteristic suite of facies that indicate deposition from catastrophic flows related to high-density, turbidity currents and debris flows. On the north coast of Nuussuaq deposition took place in a slope environment, probably in a major submarine canyon setting (Figs 76, 87).

At Ataata Kuua, the lower part of the formation was deposited in a submarine canyon (Figs 15, 92) whereas the mudstones in the upper part were deposited by dilute turbidity currents in an unconfined slope setting. The basal erosional unconformity represents a transverse section through the submarine canyon (Figs 15, 92; Dam & Nøhr-Hansen 2001). The thin lenticular fining-upward successions are interpreted as minor turbidite channel deposits. Dinocysts and macrofossils suggest general marine conditions during deposition. Along the south coast of Nuussuaq, at Ataata Kuua and Ivisaannguit, no marine palynomorphs have been recorded (McIntyre 1993), suggesting a dominant terrestrial input.

Boundaries. The lower boundary is an erosional unconformity that separates the Kangilia Formation from the underlying Atane Formation on southern Nuussuaq (Fig. 15) and from the Itilli Formation on western, central and northern Nuussuaq (Figs 14, 87, 88). Along the north coast of Nuussuaq, in the GANT#1 and GRO#3 wells and at Ataata Kuua, the lower boundary is picked at the base of a thick conglomerate unit that cuts down into the underlying deposits of the Itilli and Atane Formations. At all these localities, the lower boundary marks the base of a major submarine canyon system (Fig. 92; Dam & Nøhr-Hansen 2001). Where the basal conglomerate is absent, the unconformity between the Itilli and Atane Formations is difficult to locate using lithological criteria (mudstone overlying mudstone) and has to be picked on the basis of biostratigraphic data.

On Itsaku (Svartenhuk Halvø), there is an angular unconformity between the Kangilia Formation and the underlying sediments of the Upernivik Næs Formation. At this locality, a thick conglomerate unit occurs at the base of the formation. Elsewhere on Svartenhuk Halvø, the formation locally onlaps the basement or is in faulted contact with the Umiivik Member of the Itilli Formation (Fig. 73; J.G. Larsen & Pulvertaft 2000).

The Kangilia Formation is overlain by the Eqalulik Formation on northern and western Nuussuaq (Figs 87, 118), the Agatdal Formation on central Nuussuaq and possibly on Itsaku (Fig. 113), and by the Quikavsak Formation on southern Nuussuaq (Fig. 99A).

Geological age. The dinocyst flora suggest a late Maastrichtian to Danian age for the Kangilia Formation on the north coast of Nuussuaq and a Danian age in the central part of Nuussuaq (Fig. 16; J.M. Hansen 1970; Nøhr-Hansen 1996, Nøhr-Hansen & Dam 1997; Nøhr-Hansen *et al*. 2002).

The type section of the Kangilia Formation provides a well-exposed section across the Cretaceous–Tertiary (K/T) boundary in a clastic, deep-water setting (Fig. 87; Nøhr-Hansen & Dam 1997). Ammonites in the lowermost part of the formation indicate a late Maastrichtian age (Kennedy *et al.* 1999) and coccoliths indicate that most of the section above the K/T boundary has a nanofossil NP3–4 Zone age and consequently that NP2 and

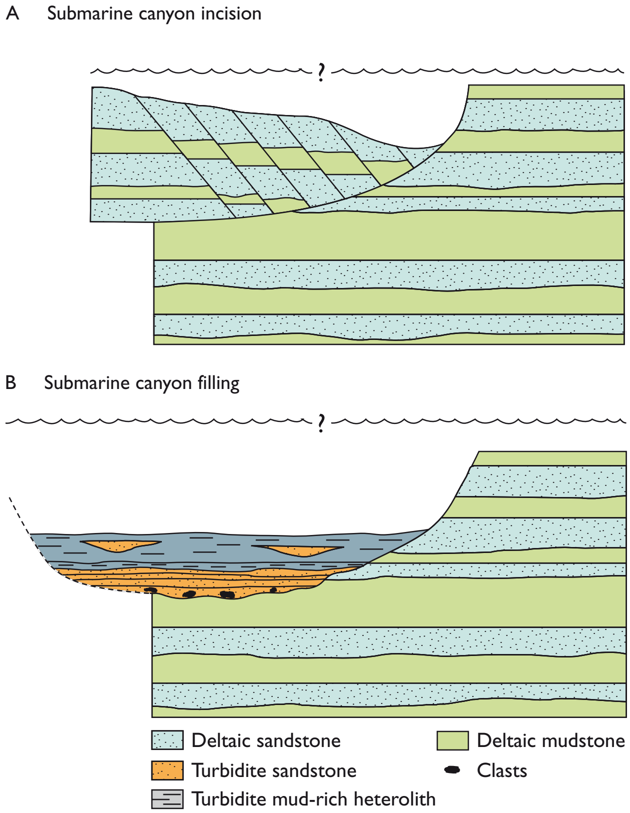


Fig. 92. Conceptual model for the formation of the submarine canyon fill of the Kangilia Formation at Ataata Kuua. From Dam & Nøhr-Hansen (2001 fig. 4). The canyon formed in response to listric faulting, detachment and collapse of the hanging wall (**A**). The steeply dipping part of the detachment surface of the footwall acted as the canyon wall and seems not to have been eroded to an appreciable extent. During a subsequent transgression, the canyon was filled with turbidite deposits (**B**). Colours reflect interpreted depositional environments (see Plate 1).

part of the NP1 zone are probably missing or very condensed (Nøhr-Hansen *et al.* 2002). The K/T boundary was also cored by the GANT#1 well (Fig. 76).

On central Nuussuaq, Danian bivalves and gastropods in the matrix of the Oyster–Ammonite Conglomerate Member indicate that this part of the formation cannot be older than Danian.

On the south coast of Nuussuaq at Ataata Kuua, palynomorphs (mainly spores and pollen) suggest a late Maastrichtian – Early Paleocene age for the formation (McIntyre 1993).

Correlation. The upper, Paleocene part of the Kangilia Formation is coeval with the Agatdal and Quikavsak Formations (Fig. 16).

Subdivision. At the type locality of the Kangilia Formation, the Annertuneq Conglomerate Member forms the basal unit of the formation (Figs 76, 87). In Agatdalen, a conglomerate unit containing abundant, derived concretions, the so-called 'Oyster-Ammonite Conglomerate' of Birkelund (1965), is now formally established as the Oyster–Ammonite Conglomerate Bed.

Annertuneq Conglomerate Member

redescribed member

History. This coarse-grained unit was established by Rosenkrantz (1970) as the Conglomerate Member – the basal member of the Danian Kangilia Formation in the type section on the north coast of Nuussuaq (Figs 72, 93, 94). Rosenkrantz (1970) correlated it with his basal Danian conglomerate in Agatdalen, a unit also referred to as the Oyster-Ammonite Conglomerate by Birkelund (1965) and H.J. Hansen (1970). Based on new data from the north coast of Nuussuaq and subsurface data from the GANT#1 well, a more thorough and formal description is presented here. The member is retained for the sake of continuity and also because this impressive unit is distinctive as one of the relatively few conglomerates in the Nuussuaq Basin.

Name. The name is derived partly from the reference locality close to the type section and partly from its historical name based on the lithology of the unit.

Distribution. The Annertuneq Conglomerate Member forms a conspicuous unit along the north coast of Nuussuaq between Niaqorsuaq and Kangilia. It has been drilled in the GANT#1 well in the Tunorsuaq valley (Figs 74, 76), and is assumed to be present locally in the subsurface at the base of the Kangilia Formation.

Type section. The type section of the Annertuneq Conglomerate Member is the same as for the Kangilia Formation (Figs 74, 87, 88). The base of the member is located at 70°44.54′N, 53°25.11′W.

Reference sections. A well-exposed section of the lower part of the member is accessible in the western gully leading to Annertuneq, a few kilometres west of Kangilia (Figs 72, 93, 94). The member was cored in the GANT#1 well, from 256.0 m to 100.0 m (Fig. 76).

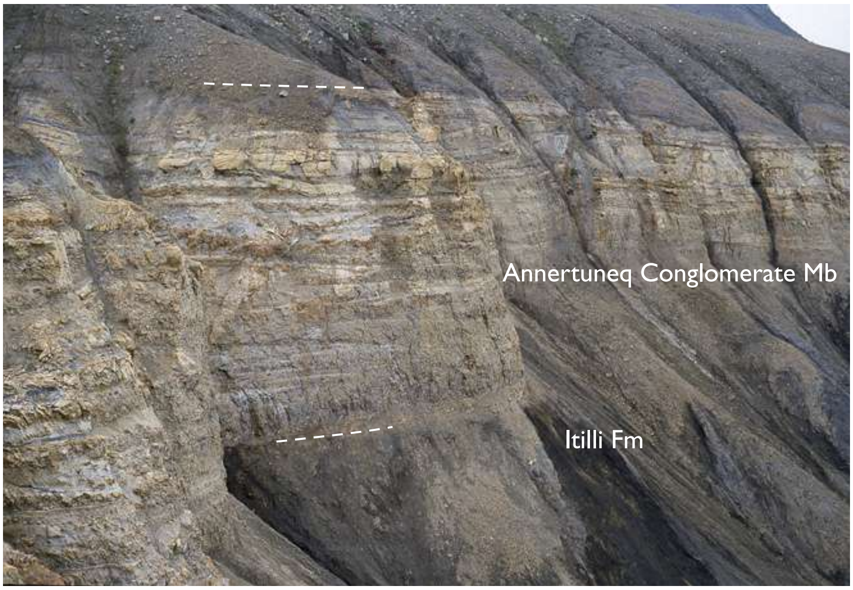


Fig. 93. The Annertuneq Conglomerate Member (*c.* 40 m thick) of the Kangilia Formation at Annertuneq. For location, see Fig. 74.

Thickness. The Annertuneq Conglomerate Member varies in thickness from *c*. 85 m on the north coast of Nuussuaq (Fig. 87) to 140 m (excluding igneous intrusions) in the GANT#1 well (Fig. 76; see also A.K. Pedersen *et al.* 2006b).

Lithology. At the reference section at Annertuneq, the lower part of the conglomerate unit is composed of amalgamated up to 8 m thick lenticular beds containing pebble- to boulder-sized clasts up to 2 m in diameter (Fig. 94). Clasts include quartz (40%), quartzitic grey sandstones (35%), intraformational mudstones and concretions (10%), quartzitic red sandstones (7%), chert (3%) and others (5%); 'others' include Precambrian gneiss and granite clasts, and clasts of silicified limestone that may be pisolitic or contain Ordovician gastropods. The conglomerates also include coalified wood fragments and poorly preserved marine bivalves and gastropods. Individual conglomerate beds can be divided into structureless, structureless to normally graded, or inversely graded, clast-supported conglomerate facies. The conglomerates are poorly sorted and always contain a matrix of medium to very coarse-grained sandstone or sandy mudstone. The sandstones are predominantly structureless, but in some cases the uppermost parts of the beds show well-developed parallel lamination and cross-lamination. Dish structures and escape burrows are common.

In the type section at Kangilia, the lower part of the member consists of a 20 m thick unit of amalgamated conglomerate beds comprising pebble- to boulder-sized clasts in a poorly sorted medium- to very coarse-grained sandstone matrix. The conglomerate units fine upwards and sandstone becomes the dominant lithology towards the top (Fig. 87, 95).

Fossils. Scarce, strongly worn bivalves and gastropods and occasional, coalified wood fragments are present in the member.

Depositional environment. Both at the type section and in the GANT#1 well, the conglomerates were deposited from debris flows and high density turbidite currents and sandstones from high- and low-density turbidity currents. It has previously been suggested that deposition took place in a fluvial environment (H.J. Hansen 1970), but the depositional facies and inferred processes, the upward transition into fully marine deposits and the presence of marine dinocysts in the interbedded mudstones (Nøhr-Hansen 1997b) indicate a marine depositional environment. The considerable increase in the thickness of the member in the GANT#1 well compared to the exposures situated at Annertuneq and Kangilia, *c*. 6 km to the north, suggests that deposition took place in a major submarine canyon and that the GANT#1 well is situated in a more axial position than the north coast exposures.

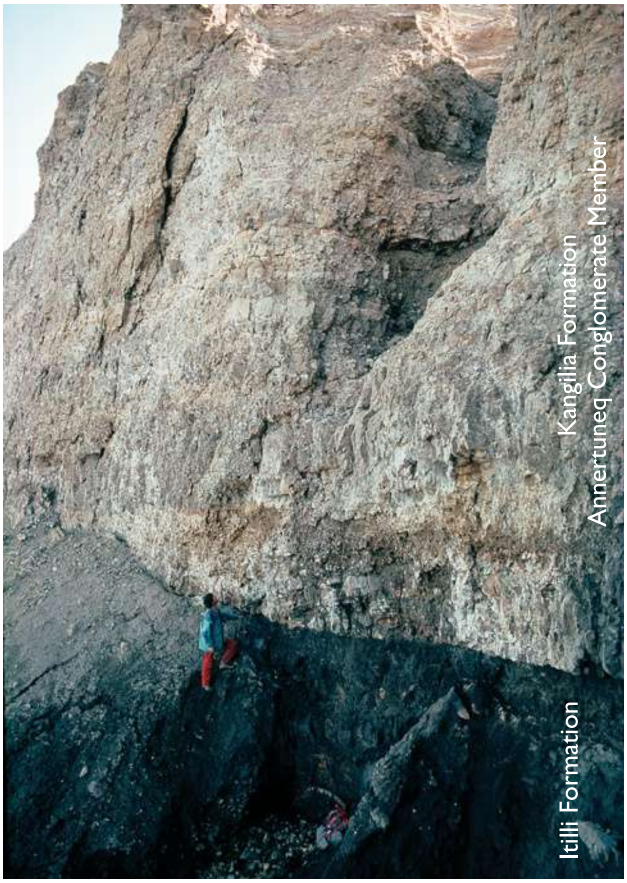


Fig. 94. Close-up of the sharp, erosional base of the Annertuneq Conglomerate Member at Annertuneq. Person for scale. For location, see Fig. 74.

Boundaries. The lower boundary of the Annertuneq Conglomerate Member is developed as a major erosional unconformity. On the north coast of Nuussuaq,this separates mudstones of the Itilli Formation below from the conglomerates of the Annertuneq Conglomerate Member above (Fig. 72). The upper boundary is gradational at all localities and is placed at the top of the uppermost, very coarse-grained sandstone bed (Figs 76, 87, 93, 95).

Geological age. The Annertuneq Conglomerate Member does not contain fossils of biostratigraphic significance. The age of the member is, however, constrained by its position between marine mudstones. The Umiivik Member of the Itilli Formation (below) has a Late Campanian

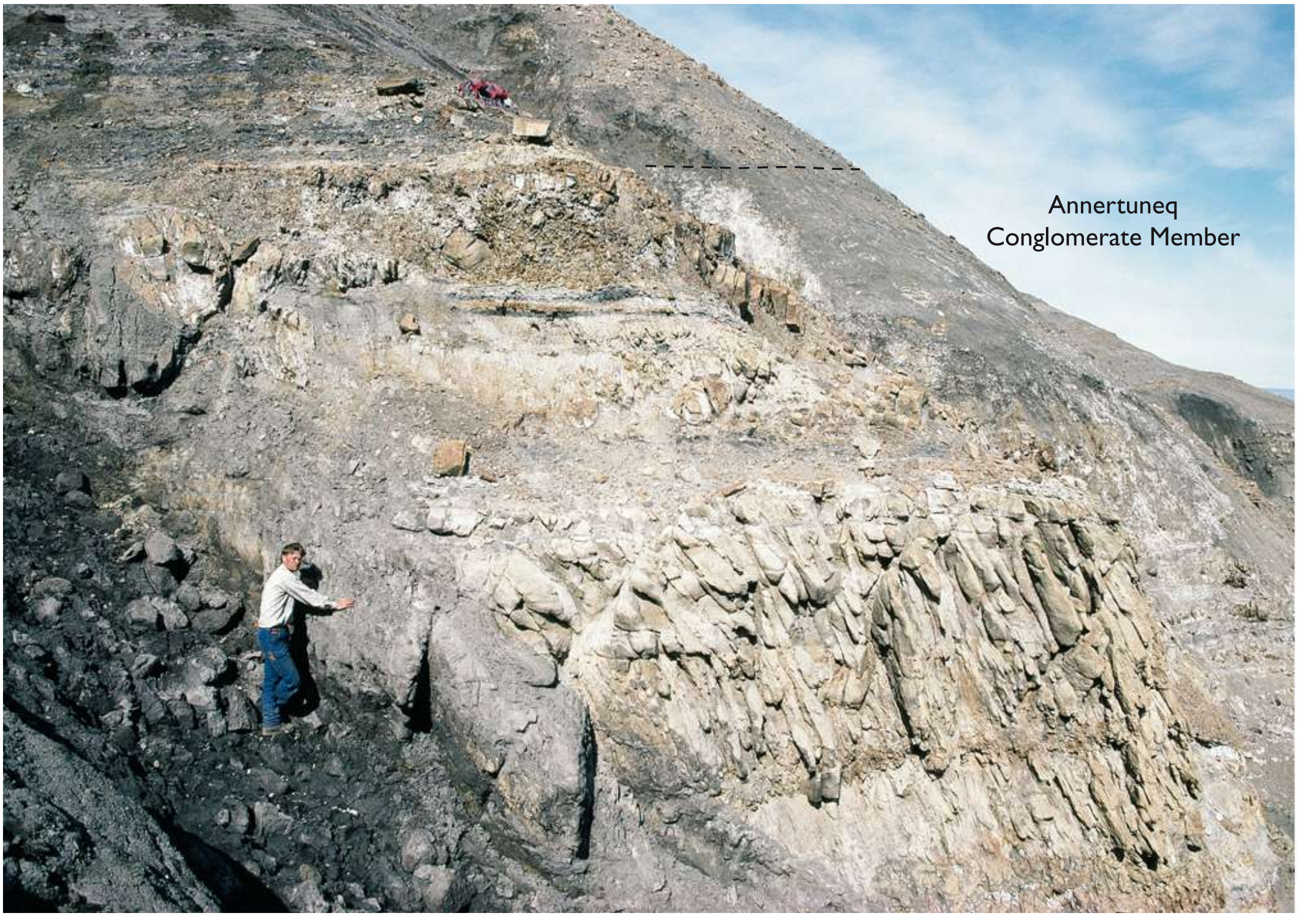


Fig. 95. Upper boundary (dashed line) of the Annertuneq Conglomerate Member of the Kangilia Formation at Kangilia showing a gradual transition from conglomerates and sandstones to mudstones. For location, see Fig. 74; person for scale.

age (J.M. Hansen 1980b; Nøhr-Hansen 1996, 1997b; Dam *et al*. 1998c; Nøhr-Hansen *et al*. 2002). The mudstones of the remaining Kangilia Formation (above) are of late Maastrichtian – Paleocene age. The position of the Maastrichtian–Paleocene boundary within the Kangilia Formation varies between localities, from 210 m above the base of the Annertuneq Conglomerate Member (Nøhr-Hansen & Dam 1997), *c*. 70 m above the base of the member at Kangilia (Fig. 87), to a position close to the top of the member in the GANT#1 well (Nøhr-Hansen 1997b). This suggests an ?early to late Maastrichtian age for the member.

Oyster–Ammonite Conglomerate Bed

new bed

History. In Agatdalen on central Nuussuaq, a conglomerate of Danian age containing a huge number of derived concretions has been referred to as the Oyster-Ammonite Conglomerate (e.g. Birkelund 1965). H.J. Hansen (1970) referred this conglomerate to the *Thyasira* Member of Rosenkrantz (1970). For historical reasons and in order to distinguish this fossiliferous conglomerate unit from the Annertuneq Conglomerate Member, it is now formally established as a bed and named the Oyster–Ammonite Conglomerate Bed.

Name. The bed is named after the rich occurrence of reworked oysters and ammonites in the conglomerate.

Distribution. The bed has only been described from three localities in Agatdalen (Fig. 113).

Type locality. The bed is best exposed in the western river bank of the Agatdalen river, south-east of Sill Sø (Figs 96, 113). The type locality is located at 70°34.62´N, 53°04.50´W.

Thickness. The bed is approximately 5 m thick (Rosenkrantz 1970).

Fig. 96. **A**: Type locality of the Oyster–Ammonite Conglomerate Bed on the western bank of the Agatdalen river. For location, see Fig. 113. **B**: Clast in the polymodal, matrix-supported conglomerate (paraconglomerate) in the Oyster–Ammonite Conglomerate Bed. Hammer (encircled) for scale.

Lithology. The Oyster–Ammonite Conglomerate Bed is a clast-supported conglomerate dominated by numerous, calcareous concretions and dark mudstone boulders eroded from Maastrichtian and Campanian deposits (Fig. 96; H.J. Hansen 1970). The matrix consists of sandy mudstone containing Danian oysters and bivalves (see below). In places, calcareous concretions have been formed within the conglomerate (Floris 1972).

Fossils. The fossils in the concretions are reworked and include ammonites, oysters and other bivalves, gastropods, crustaceans and corals (Birkelund 1965; Rosenkrantz 1970; Floris 1972). They show that the concretions were eroded from Maastrichtian deposits and represent a rich fauna including *Hypophylloceras (Neophylloceras) groenlandicum* Birkelund 1965, *Saghalinites wrighti* Birkelund 1965, *Baculites* cf. *B. meeki* Elias 1933, *Scaphites (Discoscaphites) waagei* Birkelund 1965, and *S. (D.) angmartussutensis* Birkelund 1965 (*Hoploscaphites* Nowak 1911 according to Kennedy *et al.* 1999). In addition *Scaphites (Hoploscaphites)* cf. *S. (H.) ravni* Birkelund 1965, *S. (H.)* cf. *S. (H.) greenlandicus* Donovan 1953, *S. cobbani* Birkelund 1965 and *S. rosenkrantzi* Birkelund 1965 occur very occasionally and indicate that some concretions were derived from the Campanian (Kennedy *et al.* 1999). Corals include *Stephanocyathus* sp. and *Caryophyllia agatdalensis* (Floris 1972). The mudstone matrix includes oysters and other bivalves that have also been described from the lower part of the overlying Eqalulik Formation on the north coast of Nuussuaq (*Thyasira* Member of Rosenkrantz (1970)). Dinocysts are present in both the reworked concretions and the matrix of the conglomerate.

Depositional environment. Deposition took place from debris flow(s) in a marine environment.

Boundaries. The lower and upper boundaries of the bed are not well exposed. The lower boundary is inferred to be an erosional unconformity separating the conglomerate from underlying mudstones of the Campanian Itilli

Formation. The conglomerate is overlain by black bituminous mudstones of the Kangilia Formation (Fig. 113).

Geological age. The oysters and other bivalves in the matrix of the conglomerate indicate a Danian age (Birkelund 1965). The fauna has species in common with the *Thyasira* Member of the Kangilia Formation of Rosenkrantz (1970), here defined as the Eqalulik Formation, and the conglomerate was referred to the Lower to Middle Danian by Rosenkrantz (1970). Dinocysts from the mudstone matrix also suggest a Danian age. Kennedy *et al.* (1999) referred the ammonites to the early Maastrichtian. The age of the Oyster–Ammonite Conglomerate Bed is constrained by its Danian fossils and the early Late Danian age of the Agatdal Formation, which overlies the Kangilia Formation.

Correlation. The bed is referred to the Kangilia Formation based on the general Danian age and the lack of volcaniclastic material (the presence of which characterises the Eqalulik Formation) in both the conglomerate and the overlying mudstone.

Quikavsak Formation

new formation

History. The strata comprising the Quikavsak Formation as defined here were briefly described by Steenstrup (1874 p. 79) and later in detail by Koch (1959) who included them in his Quikavsak Member of the Tertiary Upper Atanikerdluk Formation. The strata are now established as a separate formation. A major, fluvial channellised sandstone unit that Koch (1959 fig. 5) previously included in the top of the Atane Formation at Quikassaap Kuua is now tentatively also included in the Quikavsak Formation. At Nassaat, a tributary on the south-eastern side of Agatdalen, a poorly exposed conglomerate unit that had been assigned to the Sonja member (Agatdal Formation) by Rosenkrantz (1970) and to the Quikavsak Member by Koch (1959) is here re-assigned to the Quikavsak Formation.

Dam (2002) suggested a division of the Quikavsak Formation into four members reflecting various depositional stages during infill and drowning of the incised valley system. Dam's three lower members – the Tupaasat, Nuuk Qiterleq and Paatuutkløften Members – are defined formally below. The Asuup Innartaa Member is no longer recognised, and the deposits on Nuussuaq are now included in either the Eqalulik or the Atanikerluk Formations whereas the deposits on Disko are now referred to the Kussinerujuk Member of the Itilli Formation (see below).

Name. The member is named after the stream of Quikavsaup kûa (now spelled Quikassaap Kuua) near Atanikerluk (Fig. 40). The spelling of the name is taken from Koch (1959).

Distribution. The formation is exposed along the south coast of Nuussuaq, from Nuuk Killeq in the west to Saqqaqdalen in the east. On central Nuussuaq, the formation is exposed at Nassaat (Fig. 2).

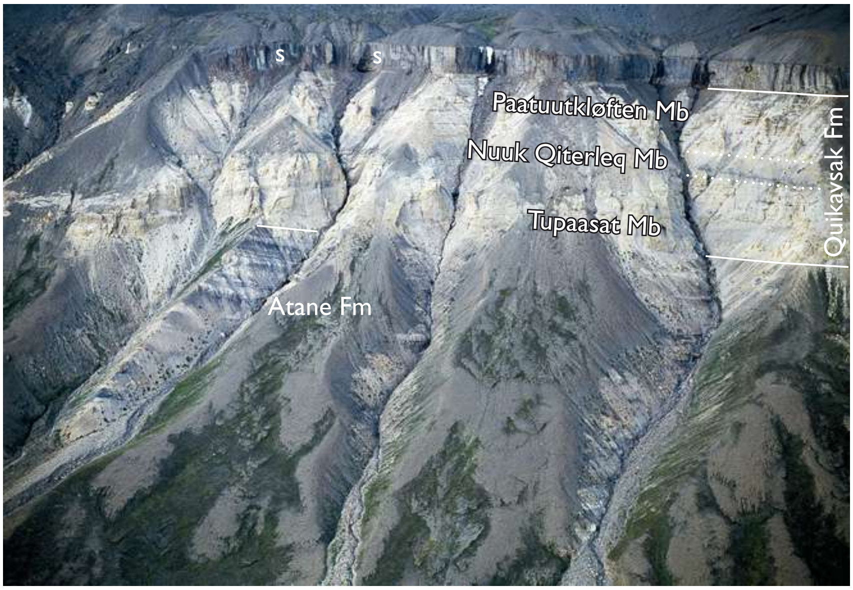


Fig. 97. The type locality of the Quikavsak Formation, east of Nuuk Qiterleq on the south coast of Nuussuaq (for location, see Figs 2, 40). The Quikavsak Formation overlies the Atane Formation and is overlain by a very thin Eqalulik Formation and hyaloclastite breccias of the Vaigat Formation. A volcanic sill (**S**) has been intruded between the Quikavsak and the Eqalulik Formations. The thickness of the Quikavsak Formation in this outcrop is *c.* 180 m.

On Svartenhuk Halvø, on the east slope of Firefjeld, a thin (30 m) Paleocene conglomeratic unit is present between the Itilli Formation and the hyaloclastic rocks of the Vaigat Formation (Fig. 73; J.G. Larsen & Pulvertaft 2000). This unit may be correlated with either the Agatdal Formation or the Quikavsak Formation.

Type section. Originally, Koch (1959) chose the exposures at the stream of Quikassaap Kuua as the type locality for his Quikavsak Member (Fig. 40). At this locality, however, only two of the members of the Quikavsak Formation are exposed (Tupaasat and Nuuk Qiterleq Members) and the formation has an atypical appearance (Fig. 100). The best exposures and the most complete development of the formation occur between Paatuut and Nuuk Killeq, south Nuussuaq. The type section is located on the coastal slope just east of Nuuk Killeq below the mountain Point 1580 (Figs 6, 97, 98, 99A; A.K. Pedersen *et al.* 1993). The type section is located at 70°20.75´N, 53°08.75´W.

Reference sections. Reference sections occur at Ivisaannguit, Paatuut and Quikassaap Kuua (Figs 40, 99B, 100, 108).

Thickness. The channellised nature of the deposits forming the Quikavsak Formation results in highly variable thicknesses. The formation is up to 180 m thick at the type locality. At Ivisaannguit it is up to 116 m thick, on the west side of Ataata Kuua it is up to 135 m, on the east side of Ataata Kuua below the mountain of Ivissussat Qaqqaat it is more than 100 m, at Paatuut up to 162 m and at Quikassaap Kuua it is up to 70 m thick. Between these sections, the formation is only a few metres thick or is absent altogether.

Lithology. Along the south coast of Nuussuaq the formation is divided into three lithological units that are given the rank of members (Dam & Nøhr-Hansen 2001; Dam

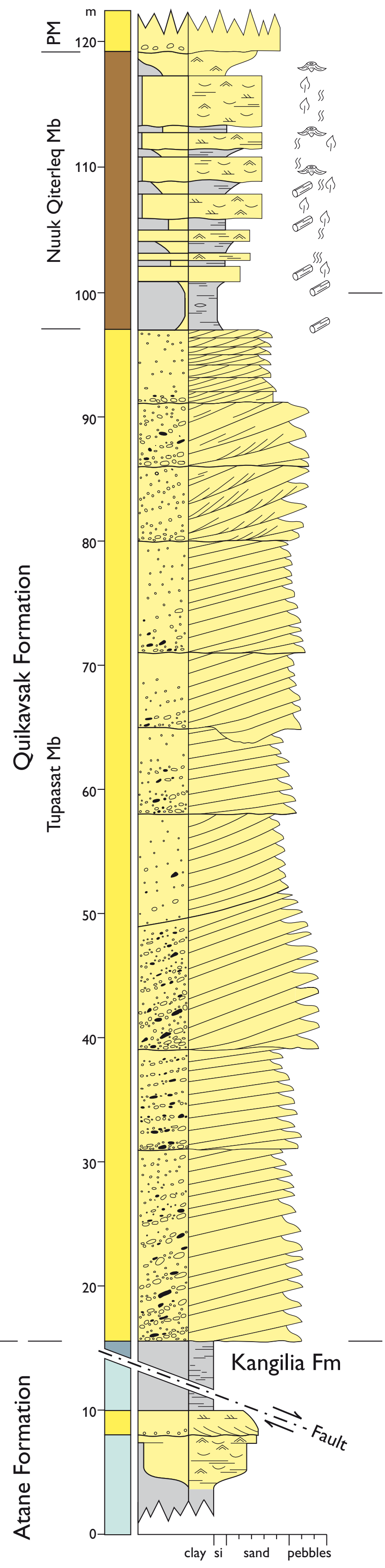


Fig. 98. Type section of the Quikavsak Formation (and the Tupaasat and Nuuk Qiterleq Members) at Tupaasat, east of Nuuk Qiterleq; for location, see Figs 2, 6, 97. The upper member of the formation (**PM**, Paatuutkløften Member) has not been measured at this locality. The lenticular mud-rich body illustrated on Fig. 99A just south-east of the section line is absent in this section, probably due to erosion at the charred base at 39 m. Modified from Dam & Nøhr-Hansen (2001). Note that the position of this section was erroneously stated to be at Ivisannguit in Dam (2002). For legend, see Plate 1.

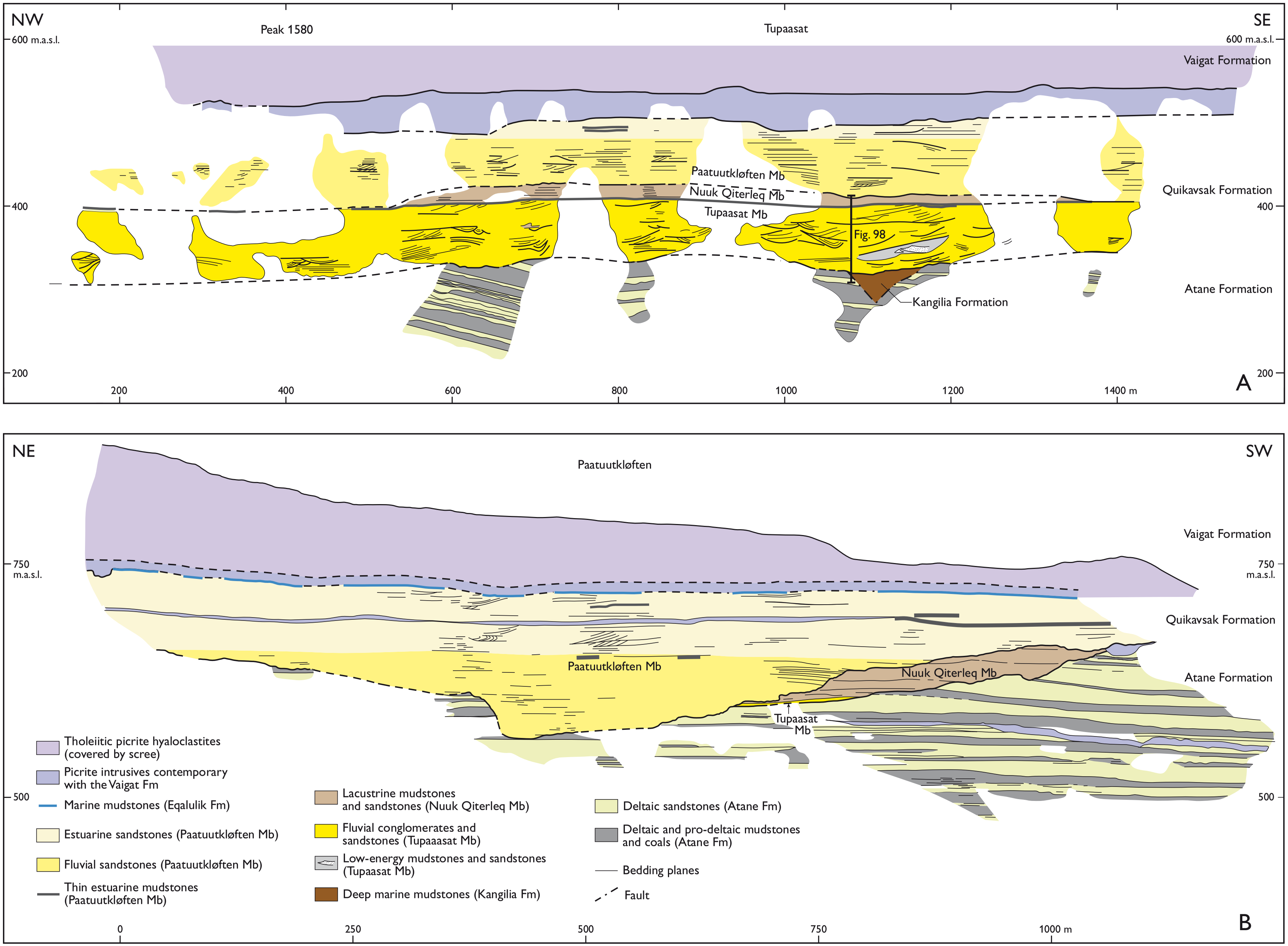

NW
SE
Peak 1580
Tupaasat
600 m.a.s.l.
400
200
Vaigat Formation
Quikavsak Formation
Atane Formation
Paatuutkløften Mb
Nuuk Qiterleq Mb
Tupaasat Mb
Fig. 98
Kangilia Formation
200
400
600
800
1000
1200
1400 m
A
NE
SW
Paatuutkløften
750 m.a.s.l.
500
Vaigat Formation
Quikavsak Formation
Atane Formation
Paatuutkløften Mb
Nuuk Qiterleq Mb
Tupaasat Mb
Tholeiitic picrite hyaloclastites (covered by scree)
Picrite intrusives contemporary with the Vaigat Fm
Marine mudstones (Eqalulik Fm)
Estuarine sandstones (Paatuutkløften Mb)
Fluvial sandstones (Paatuutkløften Mb)
Thin estuarine mudstones (Paatuutkløften Mb)
Lacustrine mudstones and sandstones (Nuuk Qiterleq Mb)
Fluvial conglomerates and sandstones (Tupaaasat Mb)
Low-energy mudstones and sandstones (Tupaasat Mb)
Deep marine mudstones (Kangilia Fm)
Deltaic sandstones (Atane Fm)
Deltaic and pro-deltaic mudstones and coals (Atane Fm)
Bedding planes
Fault
0
250
500
750
1000 m
B

Fig. 100. Reference locality of the Quikavsak Formation at Quikassaap Kuua (see Fig. 40 for location). This locality was selected by Koch (1959) as the type locality of his Quikavsak Member. The channellised sandstone is now referred to the Tupaasat Member of the Quikavsak Formation (for explanation, see text).

2002). The lower, markedly erosional unit dominated by coarse-grained sandstones succeeded by a middle unit comprising sand- and silt-streaked mudstones and sandstones with numerous *in situ* and drifted remains of trees. The upper unit also has an erosional base and consists of medium- to coarse-grained sandstones arranged in an overall fining- and thinning-upward succession, locally with a basal boulder conglomerate bed. For detailed descriptions, see members below.

Fossils. The sandy parts of the formation are rich in coal fragments and pieces of coalified wood. The fine-grained parts of the formation are rich in clay ironstone with plant fossils, sideritic silty shale with plant fossils, mostly as impressions, and *in situ* coalified tree trunks. Plant fossils belong to the 'Upper Atanikerdluk A' flora of Heer (1883a, b); fossil insects and ostracods have also been described (Koch 1959). At the top of the section at Paatuut, about 5 m below the basalts, a few marine molluscs have been found (Koch 1959). Early Paleocene oysters (*Ostrea* sp.) have been reported immediately west of Paatuutkløften and east of Nuuk Killeq (Koch 1959). Palynomorphs are common, but only few marine dinocysts are present.

Depositional environment. The Quikavsak Formation represents fluvial to estuarine deposition in a series of fault-controlled, incised valley systems that formed during two phases of uplift of the Nuussuaq Basin (Dam & Sønderholm 1998; Dam & Nøhr-Hansen 2001; Dam 2002). The mudstone member overlying the basal sandstone member in the type section (Fig. 98) is probably related to a quiescent period between the tectonic events resulting in the development of low-energy depositional (lacustrine) areas within the valleys.

Boundaries. The lower boundary of the formation is a major erosional unconformity formed during valley incision, cutting at least 190 m down into the underlying deposits (Figs 99, 109). East of Ataata Kuua, the unconformity separates Turonian – Lower Campanian deltaic sandstones and mudstones of the Atane Formation from the coarse-grained deposits of the Quikavsak Formation. The contact with the underlying Atane Formation is generally easily recognised with the exception of the locality at Quikassaap Kuua where the boundary relationships are somewhat enigmatic (see below under Tupaasat Member). On the west slope of Ataata Kuua and westwards to Ivisaannguit and in the type section,

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Fig. 99. Photogrammetrically measured sections of the incised valley fills of the Quikavsak Formation. **A**: Longitudinal section of the Tupaasat and Paatuukløften incised valleys in the area around the type section (see Figs 97, 98). **B**: Cross-section of the Paatuutkløften incised valley from Paatuutkløften (see Fig. 105). Note that the Kangilia Formation is bounded by faults, and that the Atane Formation is also faulted. Most of the Tupaasat Member and the Nuuk Qiterleq Member were removed by erosion prior to deposition of the Paatuutkløften Member. For location of sections, see Figs 2, 40. Modified from Dam (2002; it should be noted that the figure captions for figs 3B and 4 in this paper are switched).

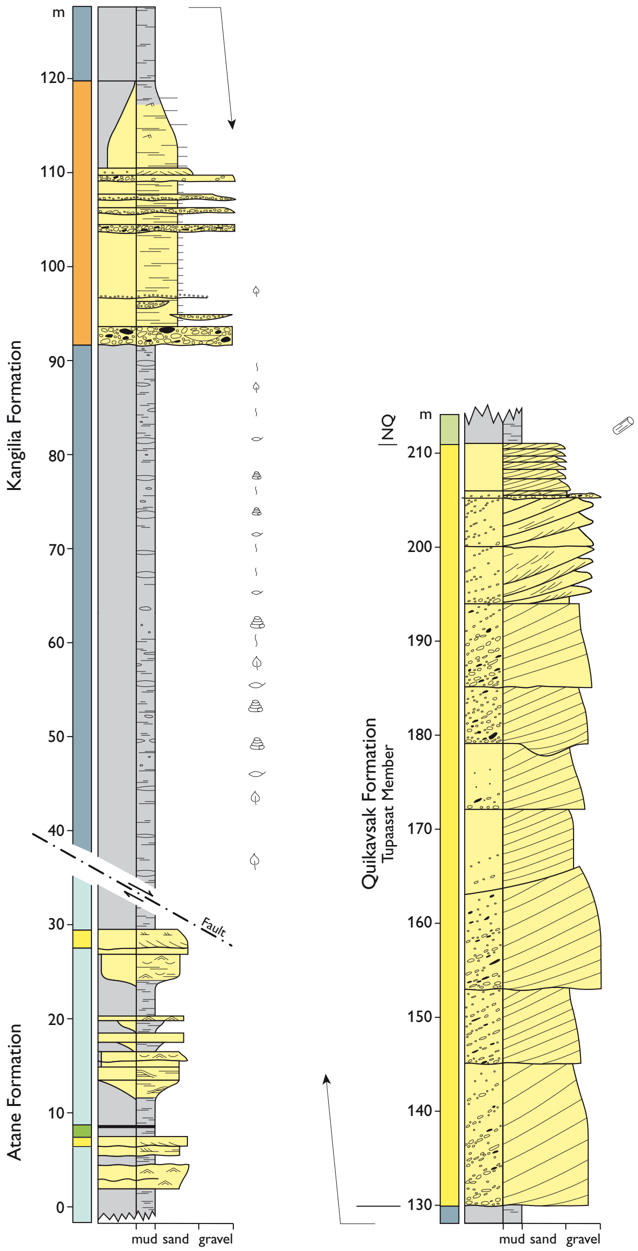


Fig. 101. Generalised sedimentological log from Ivisaannguit on the south coast of Nuussuaq (for location, see Fig. 40). The sandstones and conglomerates of the Kangilia Formation are similar to those seen at Ataa (Fig. 91). At this locality, the Kangilia Formation has a faulted contact with the Atane Formation and is erosionally truncated by the Quikavsak Formation. **NQ**, Nuuk Qiterleq Member. For legend, see Plate 1.

the Quikavsak Formation cuts down into mudstones of the upper Maastrichtian – Lower Paleocene Kangilia Formation (Figs 14, 15, 98, 101).

West of Paatuut, the formation is overlain by marine mudstones of the Eqalulik Formation whereas east of Paatuut it is succeeded by syn-volcanic lacustrine deposits referred to the Atanikerluk Formation.

Geological age. The fauna and flora are not age-diagnostic but a Danian age is indicated by the stratigraphic position between the Kangilia Formation, of Danian age on southern Nuussuaq, and the overlying Eqalulik Formation of Danian to Selandian age (Fig. 16; Piasecki *et al.* 1992; Nøhr-Hansen *et al.* 2002.

Correlation. The Quikavsak Formation deposits can be correlated to the submarine canyon deposits of the Agatdal Formation exposed on central Nuussuaq (Koch 1959; Dam & Sønderholm 1998) and occurring in the subsurface in the GRO#3 well (Fig. 67) and the GANE#1 well (Fig. 119).

Subdivision. The Quikavsak Formation is divided into three members: the Tupaasat, Nuuk Qiterleq and Paatuutkløften Members (Fig. 99).

Tupaasat Member

new member

History. Strata now referred to the Tupaasat Member were first but only briefly described by Steenstrup (1874 p. 79). The member was described in detail by Koch (1959) and referred to as the lower part of the Quikavsak Member (Upper Atanikerdluk Formation). That part of the section at Quikassaap Kuua described by Koch (1959 p. 17, fig. 5) as "cross-bedded quartz sandstone of a considerable thickness" and assigned by him to the Atane Formation, is now referred to the Quikavsak Formation (see Fig. 100).

Name. The member is named after the headland of Tupaasat just west of Ataata Kuua.

Distribution. The member is exposed along the south coast of Nuussuaq as the fill of an incised valley system extending from Nuuk Qiterleq in the west to Saqqaqdalen in the east where it occurs on the western slope of Saqqaqdalen close to the Vaigat strait (Figs 40, 129; Koch 1959; Pulvertaft 1989a, b; A.K. Pedersen *et al.* 2007a). The Tupaasat Member is not present in all outcrops of the Quikavsak Formation. At some localities it was partly or entirely eroded away prior to deposition of the Paatuutkløften Member (see Figs 99B, 109).

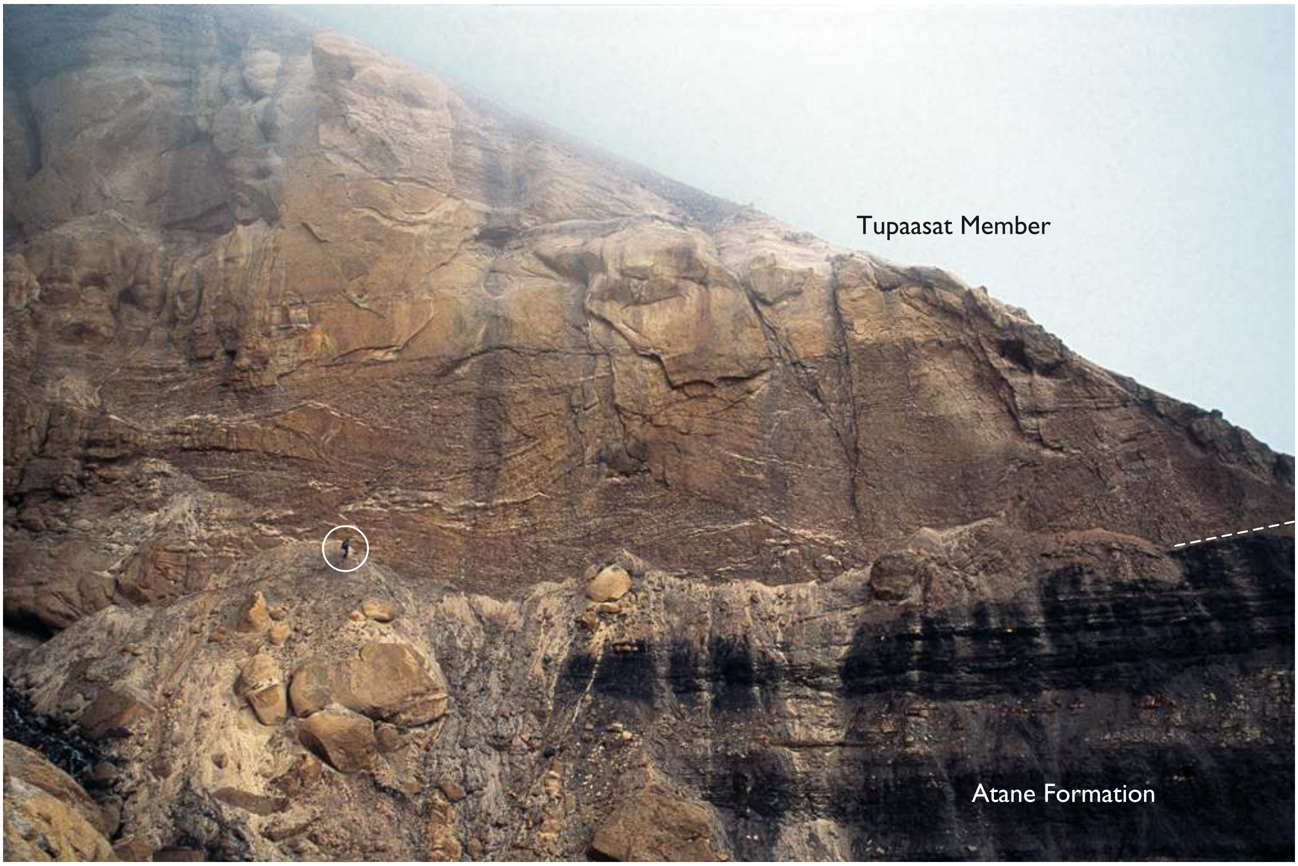


Fig. 102. Giant-scale, cross-bedded conglomerates and sandstones of the Tupaasat Member (Quikavsak Formation). Encircled person for scale. From the coastal slope between Tupaasat and Nuuk Qiterleq (for location, see Fig. 2).

Type section. The thickest deposits and the best exposure of the member occur between Tupaasat and Nuuk Qiterleq, in the coastal slope below the mountain Point 1580 (Figs 6, 98, 99, 102). This exposure is designated as the type section. The type section is located at 70°20.75´N, 53°08.75´W.

Reference sections. There are several well-exposed sections along the south coast of Nuussuaq, e.g. in the coastal cliffs around Ivisaanguit (Dam 2002 fig. 4) and at Quikassaap Kuua (Figs 40, 100).

Thickness. The member is 78 m thick in the type section, at least 80 m at Ivisaannguit, up to 7 m in Paatuutkløften, and *c*. 20 m at Quikassaap Kuua (Figs 40, 100).

Lithology. At the type locality, the lower part of the Tupaasat Member consists of giant-scale trough cross-bedded, parallel-bedded and structureless pebbly to cobbly, very coarse-grained sandstone. In the lower part of the member, each trough set is up to 30 m in thickness (Figs 98, 99, 102, 103), but set thickness decreases upwards to less than 0.5 m at the top concomitant with a fining-upward trend; the sandstones are, however, distinctly different from the cross-bedded medium- to coarse-grained sandstones of the Paatuutkløften Member (Dam 2002). Pebbles are well rounded and consist of quartz (80%), gneiss and granite (10%), metasediments (7%) and chert (3%). Within the pebbly sandstones in the type section area, an up to 10 m thick unit of mudstone rich in detrital mica is intercalated with lenses of sandstone. The mudstone is bounded at the top by an erosional unconformity giving rise to the lenticular shape of the shale. The shale is succeeded by cross-bedded pebbly sandstones.

Around Ivisaannguit, the member has a similar development to that in the type section. In the eastern part of these exposures, the member is only up to 15 m thick. Towards the west, the thickness of the member increases dramatically to at least 80 m where it crosses an Early Paleocene fault scar (Dam 2002 fig. 4).

Fig. 103. Giant-scale, cross-bedded conglomerates and sandstones of the Tupaasat Member. Encircled person for scale. Arrows indicate dip of major foresets. From the coastal slope above Ivisaannguit (for location, see Fig. 40).

In Paatuutkløften and at the spur between the coastal escarpment and Ippigaarsukkløften, the Tupaasat Member consists of a 7 m thin unit of pebbly, coarse- to very coarse-grained sandstones and a pebble to cobble conglomerate (Figs 99B, 104).

On the eastern slope of Quikassaap Kuua, a 20 m thick set of cross-bedded medium- to coarse-grained sandstone is present. It is well consolidated and forms a vertical cliff (Fig. 100). This cross-bedded sandstone unit was included in the Atane Formation by Koch (1959) in spite of the stronger similarity to the lower part of the Quikavsak Member farther west than to the fluvial sandstones of the Atane Formation. This assignment may have been based on the presence of a small unconformity, possibly associated with a fossil podsol profile that separates the sandstones from the overlying heterolithic deposits, which he referred to as the Quikavsak Member but are here assigned to the Nuuk Qiterleq Member of the Quikavsak Formation.

Fossils. Fragments of coal and pieces of coalified wood are common in the member.

Depositional environment. The conglomerates and sandstones of the Tupaasat Member form a characteristic suite of very thick sandstone beds deposited by major bedforms related to catastrophic flows. The flows were confined to incised fluvial valleys formed during major tectonic uplift of the basin (Dam *et al*. 1998a; Dam 2002). From the Tupaasat Member facies alone it is not possible to determine whether deposition took place in a subaerial or a submarine environment. The overlying sediments, how-

Fig. 104. Tupaasat Member conglomerate in Paatuutkløften (for location, see Fig. 99B). Hammer for scale.

ever, have a fluvio-lacustrine origin, which makes a subaerial environment most likely for the Tupaasat Member.

Boundaries. The lower boundary is a major erosional unconformity that follows the base of the incised valley systems. It cuts across faults that bring Lower Paleocene mudstones of the Kangilia Formation against mid-Cretaceous deltaic deposits of the Atane Formation (Figs 98, 99A). The unconformity reflects major tectonic uplift of the basin (Dam 2002).

Where the Nuuk Qiterleq Member is present, the upper boundary is gradational and non-erosional (Figs 97, 98). At other localities, the Tupaasat Member is erosionally truncated by the Paatuutkløften Member (Fig. 99).

Geological age. The Tupaasat Member is referred to the Early Paleocene (Danian), its age being bracketed by data from the Kangilia Formation below and the Nuuk Qiterleq Member above (Dam 2002; Nøhr-Hansen *et al*. 2002).

Nuuk Qiterleq Member

new member

History. Strata now referred to the Nuuk Qiterleq Member are equivalent to the Quikavsak Member as described by Koch (1959) from the type section at Quikassaap Kuua. Moreover, the Nuuk Qiterleq Member includes the middle, very fossiliferous unit of the Quikavsak Member described elsewhere in the area by Koch (1959).

Name. The member is named after the headland Nuuk Qiterleq (Fig. 2).

Distribution. The member is locally exposed along the south coast of Nuussuaq as the fill of an incised valley system extending from Nuuk Qiterleq in the west to Atanikerluk in the east (Fig. 2). It is not recognised in all outcrops of the Quikavsak Formation due to erosion preceding deposition of the succeeding Paatuutkløften Member.

Type section. The member is well exposed between Tupaasat and Nuuk Qiterleq. The type section is the same as that for the Tupaasat Member (Figs 97–99). The type section is located at 70°20.75´N, 53°08.75´W.

Reference sections. Reference sections occur in Paatuutkløften and at Quikassaap Kuua (Figs 99B, 100).

Thickness. In the type section the member is 23 m thick, at Ivisaannguit 3–6 m, at Paatuut up to 42 m and at Quikassaap Kuua up to 50 m. The thickness is mainly dependent on the depth of erosion into the member prior to deposition of the overlying sandstones of the Paatuutkløften Member (Fig. 105).

Lithology. In the type section and in Paatuutkløften, the Nuuk Qiterleq Member is composed of up to 6 m thick coarsening-upward successions, composed of silt- and

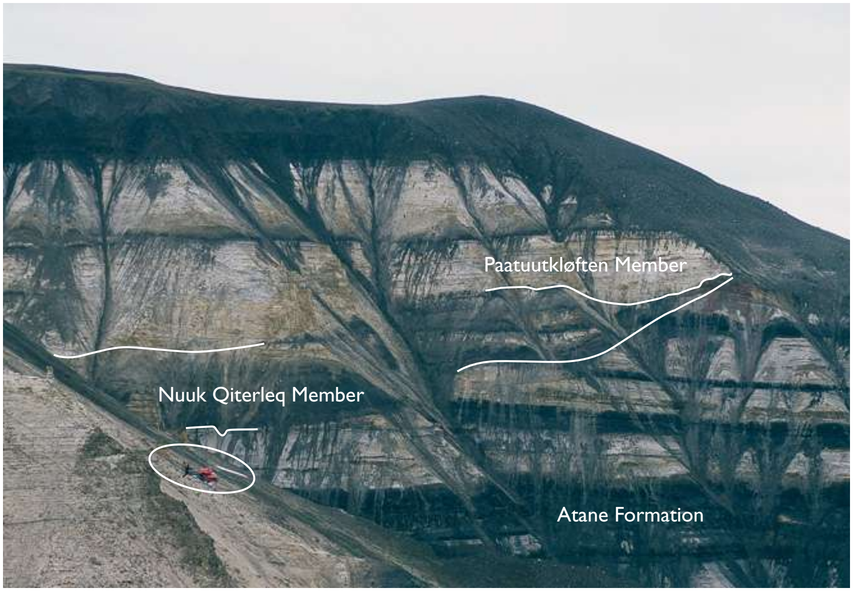


Fig. 105. Nuuk Qiterleq Member erosively overlain by the Paatuutkløften Member in Paatuutkløften (see Fig. 99B). Helicopter (encircled) for scale.

Fig. 106. **A**: Thin coarsening-upward successions in the Nuuk Qiterleq Member composed of silt- and sand-streaked mudstones passing upwards into fine- to medium-grained sandstones. Person for scale. From the type locality near Nuuk Qiterleq (for location, see Fig. 2). Arrows indicate the location of *in situ* coalified tree trunks. Note the upper, sharp, erosional boundary with the Paatuutkløften Member. **B**: *In situ* vertical, coalified tree trunk from the type section of the Nuuk Qiterleq Member. Pencil for scale (arrowed).

sand-streaked mudstones grading upward into fine- to medium-grained sandstones (Fig. 106A). Incipient ripples as well as wave and current ripples and parallel lamination are widespread. *In situ* vertical coalified trees and drifted tree trunks and plant fossils are very common (Fig. 106B). At Ivisaannguit, at Paatuut and at Ippigaarsukkløften, the member is dominated by mudstones with thin sand-streaks. A single, sharply based sandstone bed occurs at Ivisaannguit.

At Quikassaap Kuua, the member consists of interbedded siltstones and graded, occasionally parallel- laminated, very fine-grained to very coarse-grained sandstones (Fig. 107). This interbedded facies alternates with lenticular beds with erosional bases consisting of normally graded, medium- to very coarse-grained trough, cross-bedded sandstones arranged in thinning-upward successions up to *c*. 50 cm thick. The interbedded siltstones and sandstones are rich in plant fossils, clay ironstone concretions, *in situ* vertical coalified tree trunks, drifted coalified tree trunks and finely disintegrated coal fragments.

Fossils. The Nuuk Qiterleq Member is very rich in plant fossils and contains most of the species known from the Quikavsak Formation. The fossil flora from this member and from the lower part of the overlying Naujât Member (Atanikerluk Formation) at Atanikerluk and a few additional localities is known as the 'Upper Atanikerdluk A' flora of Heer (1883a) who recognised 282 species, some of which have been revised by Brown (1939), Seward (1939), Chaney (1951) and Koch (1963). Koch described the Lower Paleocene flora in the Agatdalen area where he recognised 27 species, of which 19 species were recognised by him as also occurring in the Quikavsak Formation.

Depositional environment. Sediments of the Nuuk Qiterleq Member were deposited in various environments within an incised valley system. The stacked coarsening-upward cycles in the type section and in Paatuutkløften were formed by repeated progradation of shoreface or bay-head deltas into a lacustrine environment (Dam 2002).

The deposits at Quikassaap Kuua include lenticular fining-upward successions of sandstones deposited in minor fluvial channels, interbedded with siltstones and graded, very fine-grained to very coarse-grained gravelly sandstones deposited in interchannel areas. The thin graded sandstone sheets were probably deposited during periods of intense overbank flooding.

Boundaries. The lower boundary is placed at the lithological change from pebbly coarse-grained sandstones of the Tupaasat Member to the fine-grained deposits of Nuuk Qiterleq, rich in plant fossils (Fig. 99). At most localities, the lower boundary is non-erosional; at Quikassaap Kuua, however, the Nuuk Qiterleq Member overlies an erosional surface (Koch 1959).

Fig. 107. Interbedded siltstones and sandstones of the Nuuk Qiterleq Member on the western slope of Quikassaap Kuua (for location, see Fig. 40). This section was previously the type section of the Quikavsak Member of Koch (1959).

At most localities, the upper boundary is with the Paatuutkløften Member (Figs 99, 106). At Quikassaap Kuua, the member is overlain by dislocated (landslipped) mudstones of the Atanikerluk Formation (Koch 1959).

Geological age. All the plants are interpreted as Danian in age (Koch 1963).

Paatuutkløften Member

new member

History. Strata now referred to the Paatuutkløften Member were first described and figured as the Quikavsak Member by Koch (1959) along the south coast of Nuussuaq in the Paatuut area (Koch 1959 figs 20–25), the Ataata Kuua area (Koch 1959 figs 26–30) and at the localities between Tupaasat and Nuuk Qiterleq and on central Nuussuaq at Nassaat (Koch 1959 fig. 37). The strata were described in detail by (Dam *et al.* 1998a; Dam & Sønderholm 1998; Dam 2002).

Name. The member is named after the Paatuutkløften ravine (Fig. 40).

Distribution. The Paatuutkløften Member is exposed along the south coast of Nuussuaq as the fill of an incised valley system, exposed from Nuuk Qiterleq in the west to Ippigaarsukkløften in the east and also at Nassaat on central Nuussuaq (Figs 2, 40).

Type section. The eastern slope of Paatuutkløften (Figs 99B, 105, 108). The base of the type section is located at 70°15.27′N, 52°40.65′W.

Reference sections. Reference sections occur on the western slope of Ippigaarsukkløften (Figs 108, 109), at Ivissussat Qaqqaat on the east side of Ataata Kuua (Fig. 110), in the south-west-facing cliffs above the west side of Ataata Kuua (Fig. 14) and between Tupaasat and Nuuk Qiterleq below the mountain Point 1580 (Figs 6, 97, 98, 99; A.K. Pedersen *et al.* 1993).

Thickness. The member is 145 m thick in the type section. Thicknesses in the reference sections are 158 m at Ippigaarsukkløften, more than 110 m at Ivissussat Qaqqaat, 110 m in the coastal cliffs above Ataata Kuua, up to 25 m at the coastal section above Ivisaannguit and 78 m in the section between Tupaasat and Nuuk Qiterleq. The exposures at Nassaat are too poor to estimate the thickness of the member.

Lithology. At Ivissussat Qaqqaat and Ataata Kuua the member is initiated by conglomerates composed of gneiss pebbles and boulders (Fig. 110). This is followed by monotonous successions of light grey, well-sorted, dominantly planar cross-bedded, medium- to very coarse-grained pebbly sandstones that are present at all localities (Fig. 111). These are distinctly different to the succession characterising the Tupaasat Member (Dam 2002). There is a general overall upward decrease in grain size, clast size and set thickness; thin mudstone beds are occasionally present in the uppermost part of the member. Coal clasts, finely disseminated coal fragments and sideritic mudstone clasts are common. Penecontemporaneous deformation structures are widespread in some beds.

Along the south coast of Nuussuaq between Nuuk Qiterleq and Ippigaarsukkløften, the sandstones become

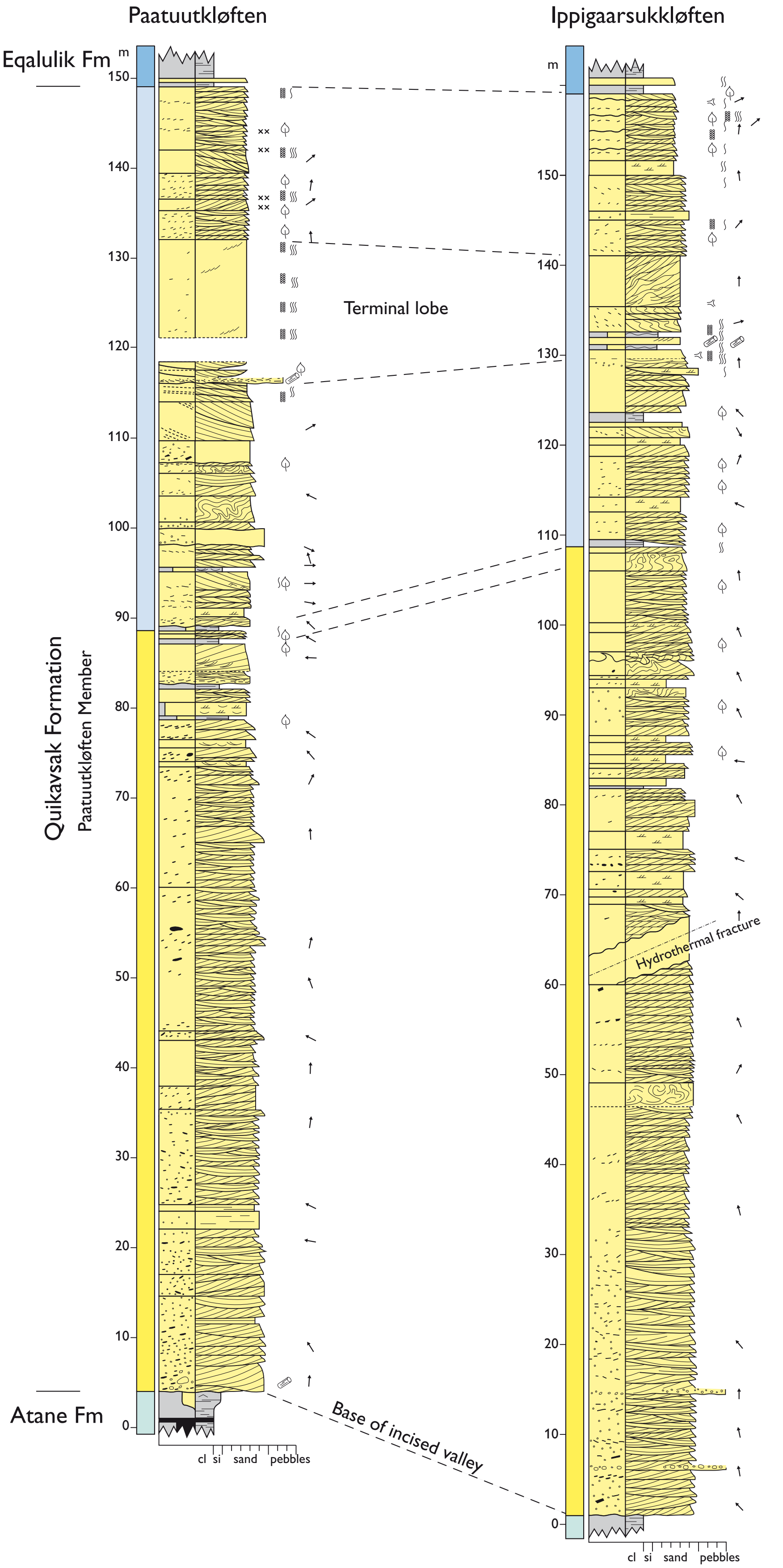


Fig. 108. Type and reference sections of the Paatuutkløften Member at Paatuutkløften and Ippigaarsukkløften, respectively (for location, see Fig. 40; for legend, see Plate 1). The dashed lines indicate correlative surfaces between the two sections.

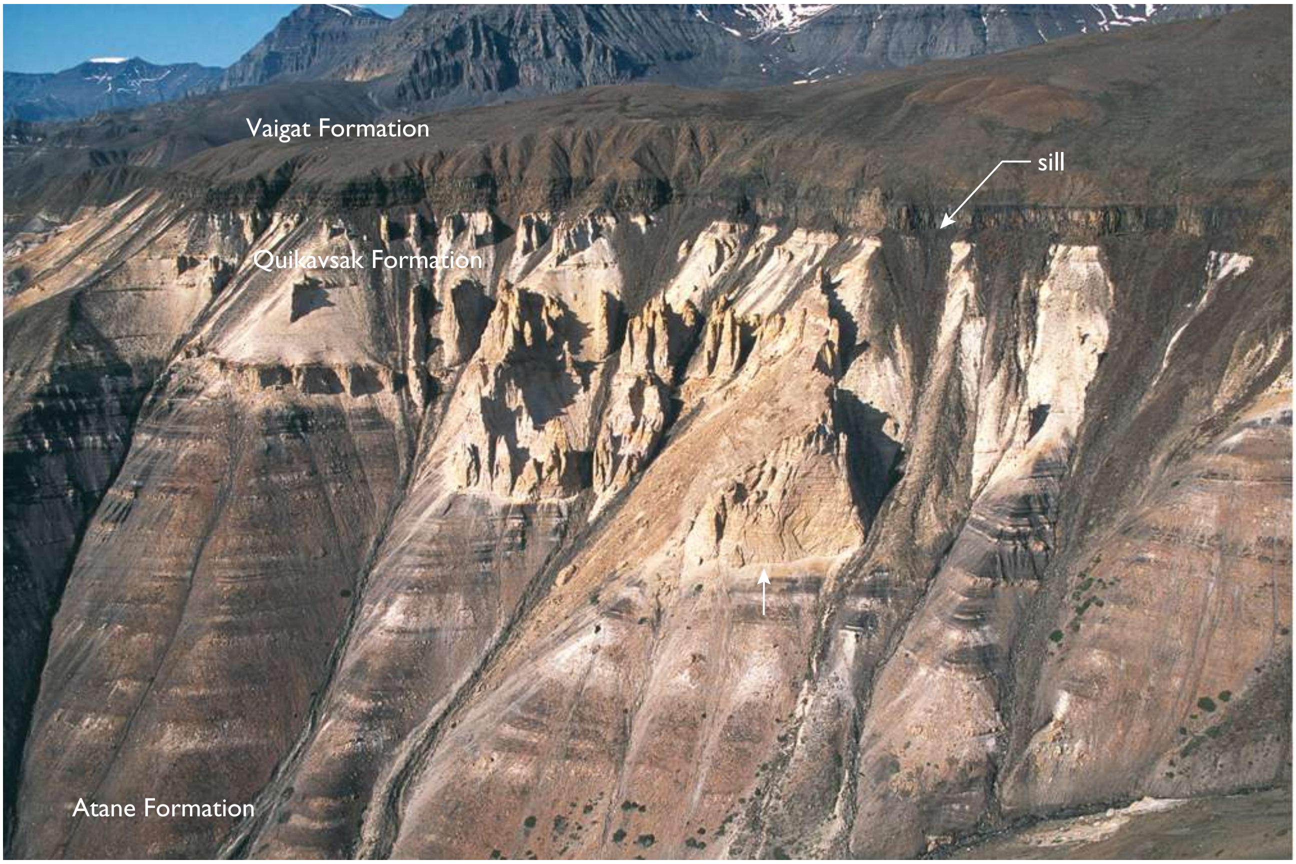


Fig. 109. Paatuutkløften Member as exposed in the Ippigaarsukkløften section (for location, see Fig. 40). The sandstones of the Paatuutkløften Member fill a valley incised into deltaic deposits of the Atane Formation (see Fig. 108). Thickness of valley fill is *c.* 180 m; the white arrow indicates the base of the reference section shown in Fig. 108.

light orange in the upper part of the member and cross-beds show double mud drapes and reactivation surfaces draped by mudstone clasts. Locally the cross-bedding is bidirectional. The sandstones frequently show convolute bedding; coal fragments, sideritic mudstone clasts and concretions are common. Thin mudstone beds with plant debris and heavily bioturbated sandstones occur in the upper part of the succession.

Fossils. Few recognisable plant fossils are present in the mudstones of the member. On the spur between the western slope of the Ippigaarsukkløften ravine and the coastal slope, about 5 m below the basalts, a few Danian marine molluscs have been found (Koch 1959). Danian oysters (*Ostrea* sp.) have been found immediately west of Paatuutkløften and east of Nuuk Killeq (Fig. 2; Koch 1959). These oysters were most probably derived from sandstones in the uppermost part of this member. Trace fossils are common to abundant at most localities in the upper part of the member. They include *Ophiomorpha nodosa*, *Ophiomorpha* isp., *Diplocraterion parallelum* and *Thalassinoides* isp. (Fig. 108).

Depositional environment. The sediments of the Paatuutkløften Member were deposited in an incised valley system formed after an episode of renewed Early Paleocene faulting. The valley system seems to follow the system generated prior to the deposition of the Tupaasat Member, resulting in considerable or in some cases complete erosion of the earlier deposits within the incised valleys. Deposition of the lower part of the member took place in a fluvial environment during a period of rapidly rising sea level, high river discharge and high sedimentation rates (Koch 1959; Dam & Sønderholm 1998; Dam 2002). The upper part of the member is characterised by a change in colour, by sedimentary structures typical of tidal activity and by intense bioturbation, indicating a change to a tidal estuarine environment during infilling of the valleys (Dam & Sønderholm 1998).

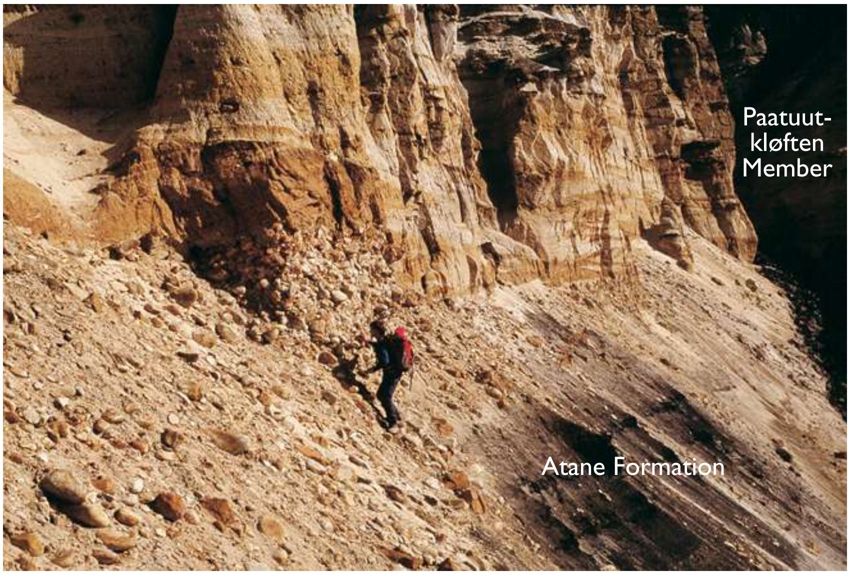


Fig. 110. Basal gneiss-clast conglomerate of the Paatuutkløften Member at Ivissussat Qaqqaat (east slope of Ataata Kuua; for location, see Fig. 40). Person for scale.

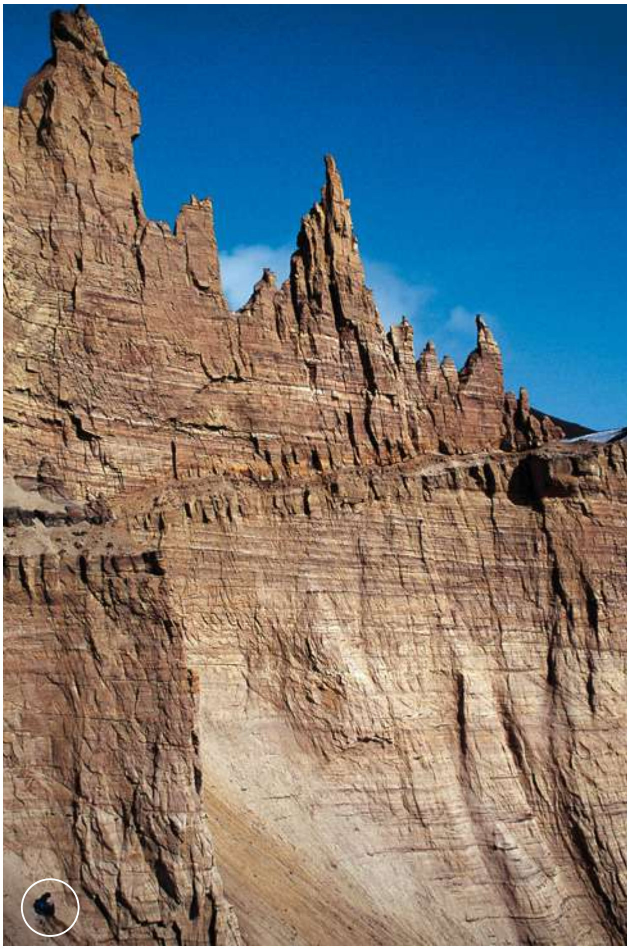


Fig. 111. Uniformly cross-bedded fluvial sandstones of the Paatuutkløften Member at Ippigaarsukkløften (for location, see Fig. 40). The apparent discontinuity in the middle of a section is due to hydrothermal alteration (see Fig. 108). Encircled person for scale.

Boundaries. An erosional unconformity separates the sandstones of the Paatuutkløften Member from the underlying incised valley deposits of the Nuuk Qiterleq or Tupaasat Members (Figs 97, 99, 105). In some cases, the Paatuutkløften Member is incised directly into the Kangilia or Atane Formations suggesting either that the previous deposits within the valley system were completely eroded away or that new valleys were eroded locally (Figs 14, 99, 109, 110). The sandstones of the Paatuutkløften Member are abruptly overlain by mudstones of the Eqalulik Formation (Figs 108, 112).

Geological age. The age of the Paatuutkløften Member is bracketed by the Danian age of the underlying Kangilia Formation and the latest Danian to Selandian age of the overlying Eqalulik Formation (see p. 137), suggesting that the age of Paatuutkløften Member is late NP3–NP4 (Nøhr-Hansen *et al.* 2002).

Correlation. The Paatuutkløften Member has been correlated with marine deposits of the Agatdal Formation on central Nuussuaq (Koch 1959; Dam & Sønderholm 1998), and with the Agatdal Formation in the GANE#1 and GRO#3 wells (Nøhr-Hansen *et al.* 2002).

Fig. 112. The sharp boundary between estuarine sandstones of the Paatuutkløften Member and the mudstones of the Eqalulik Formation above. Hammer (left) for scale. From Ippigaarsukkløften (for location, see Fig. 40).

Agatdal Formation

revised formation

History. The Agatdal Formation was established by Rosenkrantz (in: Koch 1959 pp. 75–78) to encompass Upper Danian marine mudstones, sandstones and conglomerates found in the Agatdalen area on central Nuussuaq; these sediments were further described by H.J. Hansen (1970), Rosenkrantz (1970) and Henderson *et al*. (1976). In some papers, the formation is referred to as the Agatdalen Formation.

The Agatdalen area was the key study area for the Nûgssuaq Expeditions led by A. Rosenkrantz because of the rich fossil content of the sediments (see 'Previous work'). Focus was on the fossil assemblages, and the various outcrops (sections) were only shown schematically and described provisionally. The component lithological units of the section were assigned to individual members resulting in a complex lithostratigraphic terminology. Four members were recognised within the small area of outcrop: the Turritellakløft, Andreas, Sonja and Abraham Members. Schematic sections from the localities in the Agatdalen area are shown in Rosenkrantz (1970 figs 4, 5). The outcrops in the Agatdalen area are discontinuous, and because many of the sandstone and conglomerate units are channellised – and lateral facies changes are therefore pronounced – the members are difficult to correlate and map in detail (Figs 113, 114). A possible correlation between the outcrops of the Agatdal Formation is shown in Plate 3. Furthermore, the members cannot be recognised outside the type area and therefore the three lower members are no longer treated as formal units. They are, however, treated as informal members below in order to facilitate correlation between the new data presented here and the older literature and fossil records (see Plate 3).

The Agatdal Formation as defined here is entirely prevolcanic. Thus, the Abraham Member, which is synvolcanic, is now included in the new Eqalulik Formation (see below). Rosenkrantz (1970) referred other synvolcanic marine sediments found on Nuussuaq to the tuffaceous *Thyasira* and *Propeamussium* Members (abandoned here) of the Kangilia Formation. In Agatdalen, the Turritellakløft Member, from which tuffs are not reported, overlies the *Propeamussium* Member (Rosenkrantz 1970 fig. 5). The correlation between the pre- and synvolcanic members of the Kangilia and Agatdal Formations of Rosenkrantz is not well explained.

Strata assigned to the Agatdal Formation (Sonja Member) at Nassaat north-east of Agatdalen (Fig. 2) by Rosenkrantz (1970 fig. 4c, d) are here assigned to the Quikavsak Formation, following Koch (1959). The tuffaceous deposits of the Abraham Member are coeval with the volcanic Asuk Member of the Vaigat Formation and are therefore now included in the Eqalulik Formation (see p. 137). A sandstone unit underlying the pillow breccias at Kangilia on the north coast of Nuussuaq was tentatively assigned to the Agatdal Formation by H.J. Hansen (1970), Rosenkrantz (1970) and Dam & Sønderholm (1998); this unit is regarded here as forming part of the Eqalulik Formation.

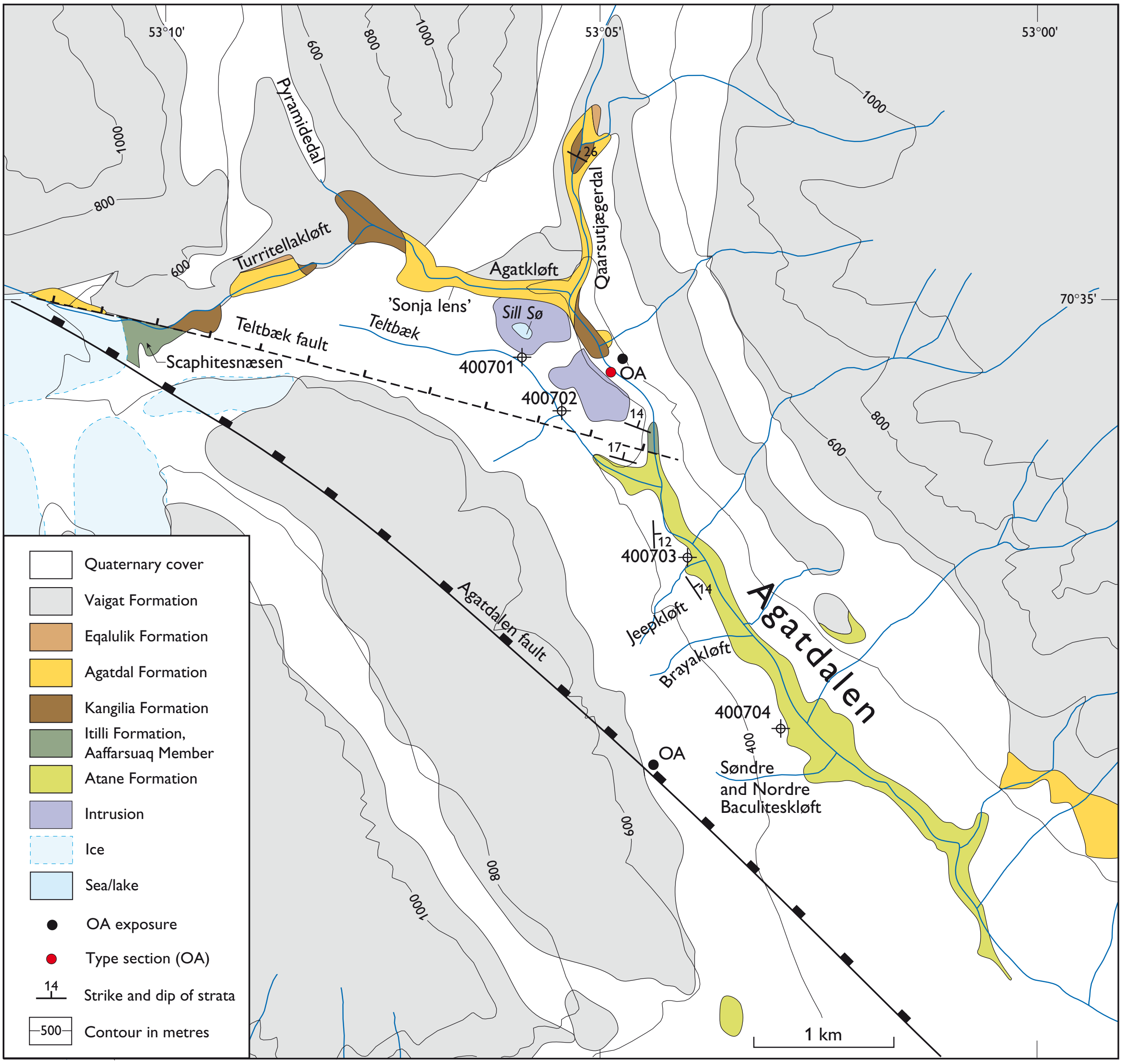


Fig. 113. Geological map of the Agatdalen area. The positions of the four shallow wells drilled by GGU in 1992 (GGU 400701–400704) are shown. Exposures of Oyster–Ammonite Conglomerate Bed (**OA**) shown with dots. From Dam *et al.* (2000) based on Rosenkrantz *et al.* (1974). Turritellakløft is also named Turritelladal on some maps. For location, see Fig. 2.

Subsurface strata, here assigned to the Agatdal Formation, were first cored in the GANE#1 well drilled by grønArctic Energy Inc. at Eqalulik on western Nuussuaq in 1995 (Fig. 65). A thick succession of marine Paleocene sandstones and conglomerates was drilled in 1996 by the GRO#3 exploration well south-east of the Kuussuaq river delta (Figs 9, 65, 67). This succession was referred to the Quikavsak Formation by Christiansen *et al.* (1999), but is here referred to the Agatdal Formation.

Name. The formation is named after the Agatdalen valley on central Nuussuaq.

Distribution. Outcrops of the Agatdal Formation are only known from the Agatdalen area (Fig. 113; Dam *et al.* 2000). From subsurface data (GRO#3, GANE#1 and GANE#1A wells), the formation is known also to be present on western Nuussuaq, west of the Kuugannguaq–Qunnilik Fault.

Fig. 114. Type locality of the Agatdal Formation in Turritellakløft (Rosenkrantz 1970; for location, see Fig. 113). The section is approximately 80 m high. In the present paper, the Agatdal Formation is not subdivided, but the formally abandoned 'Turritellakløft Member' and 'Andreas Member' are shown to provide a link to Rosenkrantz (1970). The Agatdal Formation is overlain by a thin development of the Abraham Member which is part of the Eqalulik Formation. For measured section, see Plate 3 (section 1).

The Turritellakløft Member and the Abraham Member of Rosenkrantz (1970) were described from the western end of the Turritellakløft gorge and Qaarsutjægerdal (Figs 113–115, Plate 3; H.J. Hansen 1970), whereas the Andreas Member was only recognised in Turritellakløft (Figs 113, 114, Plate 3). The Sonja Member of Rosenkrantz (1970) is only known from a section in Agatkløft, 2 km east of Turritellakløft (Figs 116, 117, Plate 3).

On Svartenhuk Halvø, on the east slope of Firefjeld, a thin (30 m) Paleocene conglomeratic unit is present between the Itilli Formation and the hyaloclastic rocks of the Vaigat Formation (Fig. 73; J.G. Larsen & Pulvertaft 2000). This unit may be correlated with either the Agatdal Formation or the Quikavsak Formation.

Type section. The type section of the Agatdal Formation is at the so-called 'Store Profil' (or 'Big Section') in Turritellakløft in the north-western end of Agatdalen (Fig. 114, Plate 3, section 1; Rosenkrantz 1970 fig. 5; Henderson *et al.* 1976 fig. 312). The type section is located at 70°35.01´N, 53°08.02´W.

Reference sections. Reference sections occur on the southern slopes of Agatkløft and on the eastern slope of Qaarsutjægerdal (Figs 115, 116, 117, Plate 3).

In the subsurface, a complete section through the formation was encountered in the GRO#3 well from 718 m to 423 m (Fig. 67). No cores were taken but a complete suite of well logs is available (Kristensen & Dam 1997). The upper part of the Agatdal Formation was drilled and fully cored in the GANE#1A well from 706.7 m to 601.5 m (Fig. 119).

Thickness. The formation varies considerably in thickness from 65 m in the type section to 18 m in Qaarsutjægerdal (Plate 3). In the GRO#3 well, the formation is approximately 250 m thick (excluding igneous intrusions; Fig. 67).

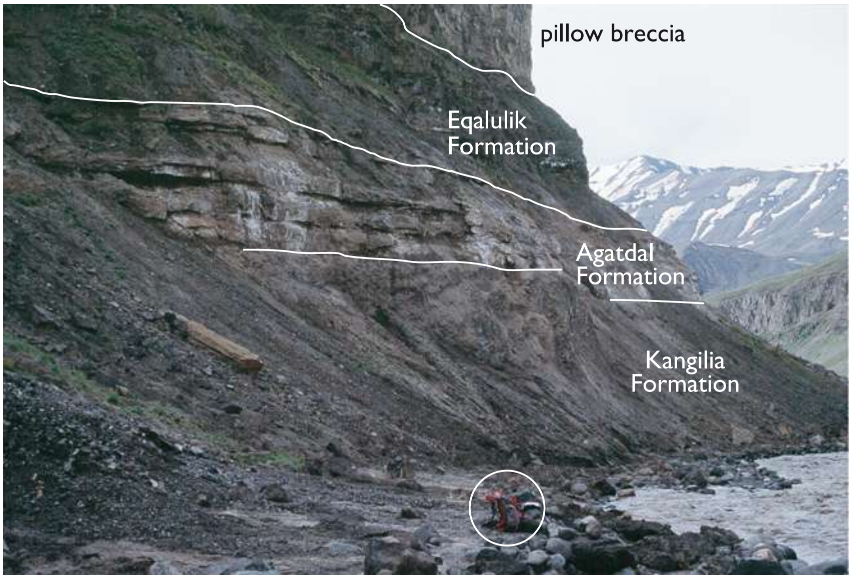


Fig. 115. Thin development of the Agatdal Formation in Qaarsutjægerdal (for location, see Fig. 113). Sandstone beds of the Agatdal Formation overlie mudstones of the Kangilia Formation with marked angular unconformity. The Agatdal Formation is overlain by the Abraham Member of the Eqalulik Formation. The exposed section below the pillow breccias is 21 m thick. For measured section, see Plate 3 (section 4).

Lithology. In the Agatdalen area, the Agatdal Formation comprises mudstones with several thick, lenticular conglomeratic and sandstone units (Figs 114–117, Plate 3) that Rosenkrantz (1970) had already recognised to be partly laterally equivalent.

The Agatdal Formation, as exposed in the junction between Agatkløft and Qaarsutjægerdal, is characterised by a major, fining-upward succession composed of a basal conglomerate unit grading upwards into alternating arkosic sandstones, conglomerates and mudstones with marine fossils and plant remains (Plate 3). The basal conglomerate unit can be followed laterally for about 1 km, but disappears rapidly towards the south-east along the Agatdalen river (Figs 113, 116, 117, Plate 3). The conglomerates also seem to wedge out towards the north-west in Agatkløft. The clasts are pebble to boulder grade and are composed of gneiss. The conglomerates form amalgamated beds up to 7 m thick, or alternate with clast-rich, coarse-grained sandstones. The sandstone beds of the overlying succession usually show normal grading and both parallel- and cross-lamination. Sandstone streaks are common in the mudstones interbedded with the sandstone beds.

In the Turritellakløft section, the Kangilia Formation is unconformably overlain by dark grey to black, sand-streaked mudstones with sandstone lenses and sheets which form the base of the Agatdal Formation (Fig. 114, Plate 3; Rosenkrantz 1970). The lower part of the formation here consists of thinly interbedded mudstones, siltstones and sandstones. The mudstones show graded, parallel lamination. The sandstone beds are parallel- and cross-laminated. Trace fossils are common (J.M. Hansen 1980b).

Upwards, the sandstone beds become thicker and occur as sheets and lenses with erosional bases. The beds are parallel laminated or show normal grading from coarse-grained to fine-grained sand. Locally the sandstones are highly fossiliferous (predominantly *Turritella* sp.). Intraformational mudstone and sandstone clasts are common. Loose slabs show a preferred orientation of *Turritella* shells; this parallel orientation indicates that the shells were current-worked and may serve as palaeocurrent indicators.

In the upper part of the Turritellakløft section is a channellised unit of well-sorted, very coarse-grained, tabular to wedge-shaped, cross-bedded sandstone (Fig. 114). The top of the Agatdal Formation is a 1.5 m thick gravelly, very coarse-grained sandstone bed. Body and trace fossils are very rare in these sandstones.

In Qaarsutjægerdal, a matrix-supported conglomerate bed occurs at the base of the formation (Fig. 115, Plate 3). It is succeeded by well-sorted, fine- to medium-grained sandstones, with few mudstone interbeds. Locally the sandstones show parallel- and low-angle cross-lamination. Bioturbation is intense at the top of the section where *Ophiomorpha* isp. and *Planolites* isp. are common. The sediments are highly fossiliferous; *Turritella* sp. is particularly numerous and the shells show a preferred parallel orientation.

In the GANE#1 well, the Agatdal Formation consists of a thick, fining-upward succession composed of a lower sandstone unit grading upwards into a heterolithic unit.

Fig. 116. Basal conglomerate unit of the Agatdal Formation south of the junction between Agatdalen and Agatkløft (for location, see Fig. 113). Note how the conglomerate pinches out towards the left (south). Section is approximately 13 m high. For measured section, see Plate 3 (section 3).

The cored succession in the GANE#1 and GANE#1A wells consists of amalgamated, thickly bedded, coarse- to very coarse-grained sandstones with normally graded beds in places alternating with thinly interbedded sandstones and mudstones (Fig. 119). The upper heterolithic part of the formation consists of mudstones, thinly interbedded sandstones and mudstones, amalgamated sandstones grading upwards into thinly interbedded sandstones and mudstones and muddy sandstones. Probable scape burrows are observed locally (Dam 1996b).

Fossils. The Agatdal Formation is the most fossiliferous of the marine units in West Greenland, with more than 500 described macrofossil species (see also 'Previous work' above).

Marine fossils in the mudstones (the former Turritellakløft Member) include gastropods, bivalves, scleractinian corals, fish, ostracods, coccoliths and foraminifera (Bendix-Almgreen 1969; Rosenkrantz 1970; Szczechura 1971; J.M. Hansen 1976; Kollmann & Peel 1983; Petersen & Vedelsby 2000). Dinocysts are rare (J.M. Hansen 1980b).

The sandstones of the former Andreas Member are very poor in fossils in the Turritellakløft section, whereas certain levels in Qaarsutjægerdal are very fossiliferous. *Turritella* sp. is particularly common, but other gastropods together with bivalves, scleractinian corals and spines of echinoids have also been found in the member (Rosenkrantz 1970; Floris 1972; Kollmann & Peel 1983; Petersen & Vedelsby 2000). Wood and fragments of leaves and fruits have been collected in this member in Qaarsutjægerdal (Koch 1963, 1972a, b).

The sandstones and conglomerates of the former Sonja Member are generally poor in marine fossils but locally contain a very rich marine fauna, known mainly from the 'Sonja lens'. The lens was originally 7 m long and 0.7 m thick but was completely excavated by Rosenkrantz and his co-workers. The fauna from this bed is dominated by bivalves and gastropods, but also includes scleractinian corals, octocorals, asteroids, crinoids, echinoids, serpulids, brachiopods, bryozoans, scaphopods, crustaceans, fish, foraminifera, coccoliths and palynomorphs (Bendix-Almgreen 1969; H.J. Hansen 1970; Rosenkrantz 1970; Szczechura 1971; Floris 1972; Perch-Nielsen 1973; Henderson *et al.* 1976; J.M. Hansen 1980b; Kollmann & Peel 1983; Collins & Wienberg Rasmussen 1992; Petersen & Vedelsby 2000). Moreover, the Agatdal Formation contains a well-preserved macroflora (Koch 1963). On western Nuussuaq, however, no determinable macrofossils have been found in the Agatdal Formation.

Dinocysts are common in samples from the GRO#3 and GANE#1 wells (Nøhr-Hansen 1997b, c; Nøhr-Hansen *et al.* 2002). The trace fossils *Ophiomorpha* isp. and *Planolites* isp. are locally common (see above).

Depositional environment. In the Agatdalen area, the macrofossils are indicative of a relatively shallow-water, marine depositional environment, such as a lower shoreface or inner shelf environment (Petersen & Vedelsby 2000). In contrast, the sedimentary facies are interpreted to reflect deposition in a deep-water slope environment.

Fig. 117. Exposure of the Agatdal Formation in Agatkløft (for location, see Fig. 113; for measured section, see Plate 3 (section 2)). The section is approximately 50 m high and, together with the basal conglomerate unit shown in Fig. 116, was referred to the 'Sonja Member' by Rosenkrantz (1970). The completely excavated Sonja Lens was part of this section. According to H.J. Hansen (1970) the succession is capped by 6 m of concretionary mudstone (covered by scree during the authors' visit in 1992) underlying volcanic pillow breccias and a sill.

The mudstone-dominated units were deposited from dilute turbidity currents in an unconfined slope setting where the sandstone interbeds possibly represent splay deposits from nearby submarine channels. The thick lenticular, conglomeratic sandstones were deposited by high- and low-density turbidite currents in submarine slope channels. The fossils found in these units must therefore have been transported, but probably only over short distances, as they are not worn or fragmented.

The presence of basement boulders in the conglomerate close to the base of the formation implies fluvial transport from areas east of the Ikorfat fault system (A.K. Pedersen *et al.* 1996 fig. 6). The conglomerates were thus probably deposited in a submarine canyon in front of a major delta at the mouth of the coeval incised fluvial valley system represented by the Quikavsak Formation.

Palynological and geochemical investigations of the GRO#3 and GANE#1 wells also indicate a marine depositional environment (Bojesen-Koefoed *et al.* 1997; Nøhr-Hansen 1997c) and the sediments record deposition dominated by high-density turbidity currents. The thickness of the formation in the GRO#3 and GANE#1 wells and the overall geological setting suggests that deposition took place in a major submarine canyon system on a fault-controlled slope (Dam 1996b; Kristensen & Dam 1997). The small, fining-upward cycles in the upper, heterolithic part of the canyon fill were deposited in small turbidite channels.

Boundaries. Where the lower boundary is exposed in the Agatdalen area the Agatdal Formation rests unconformably on the Kangilia Formation (Figs 113, 115, Plate 3). The Agatdal Formation is overlain by the Eqalulik Formation (Figs 113–115, 119, Plate 3) or locally by volcaniclastic breccias of the Vaigat Formation.

In the GRO#3 well the lower boundary is probably an erosional unconformity separating coarse- to very coarse-grained sandstones of the Agatdal Formation from heterolithic deposits of the Kangilia Formation below (Fig. 67). The upper boundary is placed at the base of the reworked volcaniclastic sediments or tuffs of the Eqalulik Formation (Fig. 67).

Age. Most fossil groups indicate a Paleocene (Late Danian) age for the formation (Fig. 16; Bendix-Almgreen 1969; H.J. Hansen 1970; Rosenkrantz 1970; Szczechura 1971; Kollmann & Peel 1983; Collins & Wienberg Rasmussen 1992). The coccolith assemblage indicates a *Chiasmolithus danicus* zone age (NP 3 Zone; Perch-Nielsen 1973). The co-occurrence of the foraminifera *Globoconusa daubjergensis* and *Globigerina compressa* indicates a P1c plankton zone age for the Agatdal Formation (H.J. Hansen 1970; Berggren *et al*. 1995; Olsson *et al*. 1999) which corresponds to a late NP3 – early NP4 age. In the GRO#3 well, dinocysts and nannofossils indicate an age not younger than nannoplankton zone NP4 (Late Danian or Early Selandian; Nøhr-Hansen 1997c; Nøhr-Hansen *et al*. 2002).

Correlation. The age of the Agatdal Formation suggests that it is coeval with the major incised valley systems of the Quikavsak Formation on southern Nuussuaq and with most of the upper part of the Kangilia Formation on the north coast of Nuussuaq (Figs 11, 15, 16; Nøhr-Hansen et al. 2002). The basal unconformity described between the Agatdal and Kangilia Formations in the Agatdalen area may be due to either condensation or nondeposition of nannoplankton zones NP1 and NP2 in the type section of the Kangilia Formation.

Eqalulik Formation

new formation

History. Deposits now assigned to the Eqalulik Formation embrace the marine synvolcanic strata below the basalts of the West Greenland Basalt Group (Hald & Pedersen 1975) that contain volcaniclastic sandstones and tuffs. On the north coast of Nuussuaq and on central Nuussuaq, these strata have previously been assigned to the *Thyasira* and *Propeamussium* Members of the Kangilia Formation (Rosenkrantz 1970) and the Abraham Member of the Agatdal Formation (Rosenkrantz 1970). However, the *Thyasira* and *Propeamussium* Members are considered inappropriate as they were established solely on the basis of the faunal content. The use of these two members as defined by Rosenkrantz (1970) is now abandoned and the strata included in the new Eqalulik Formation.

On the south coast of Nuussuaq, a thin unit of marine black shale including bioturbated sandstone beds below the volcaniclastic breccias of the Vaigat Formation was referred to the Asuup Inatartaa Member of the Quikavsak Formation by Dam (2002) but is here included in the Eqalulik Formation. Strata previously mapped as unnamed Paleocene (Tertiary) on the north coast of Nuussuaq east of the Ikorfat fault, in the region around the Tunorsuaq valley, and in the Itilli and Aaffarsuaq valleys are now assigned to the Eqalulik Formation.

Name. After Eqalulik, a lake close to the location of the GANE#1 drill site on western Nuussuaq (Fig. 65).

Distribution. The formation is widely distributed below the hyaloclastites of the Anaanaa and Naujánguit Members of the Vaigat Formation (West Greenland Basalt Group) and, although it is generally poorly exposed, it has been recognised at many localities on Nuussuaq (Piasecki *et al*. 1992), locally on the north coast of Disko, and locally on Svartenhuk Halvø (Fig. 73; J.G. Larsen & Pulvertaft 2000). On the north coast of Nuussuaq, the formation has been recognised both east and west of the Ikorfat fault. It is present in the Tunorsuaq valley and has been locally observed in the Itilli and Aaffarsuaq valleys (Floris 1972). West of Ataa on the south coast of Nuussuaq, the formation forms a thin unit dominated by marine mudstones below the hyaloclastites of the Vaigat Formation. East of Ataa, it is sandwiched between the sandstones of the Quikavsak Formation and overlying non-marine mudstones referred to the Naujât Member of the Atanikerluk Formation (see also Koch 1959 pp. 78–79).

Type section. The outcrop section at Kangilia where the Eqalulik Formation conformably overlies the Kangilia Formation is very poorly exposed (Figs 74, 87, 118). A complete, well-preserved section through the formation was cored from 598 m to 496.5 m in the GANE#1 well (Figs 65, 119) and this is therefore chosen as the type section (Fig. 119). The cores are stored at GEUS in Copenhagen. The GANE#1 well is located at 70°28.25´N, 54°00.40´W.

Reference section. Reference sections occur on central Nuussuaq in Agatdalen (Plate 3) and Aaffarsuaq (Fig 83), and on the south coast of Nuussuaq at Ippigaarsukkløften (Fig. 120).

In the GANK#1 well, a reference section was cored from 333 m to 114.9 m (Fig. 121), and the formation was also cored in the sidetrack well GANK#1A from 332.9 m to 218.6 m. The cores are stored at GEUS.

Fig. 118. Exposure of the Eqalulik Formation overlying the Kangilia Formation at Kangilia. The photo shows the lower *c*. 20 m of the formation; for location, see Fig. 74.

Thickness. On the north coast of Nuussuaq, the formation ranges from 100 to 160 m thick, in Agatdalen it is approximately 12 m thick (H.J. Hansen 1970), and in Aaffarsuaq it is less than 20 m in thickness. In the GANE#1A well, the formation is 102 m thick and it is 218 m thick in the GANK#1 well. The very variable thickness of the formation is the result of varying proportions of tuffaceous material (the presence of which defines the formation) and intensive loading and deformation of the mudstones by prograding thick lobes of submarine basaltic breccia beds.

Lithology. The formation comprises mudstones, tuff beds and volcaniclastic sandstones; the latter lithologies are essential to the definition of the formation (Fig. 122). Internal structures in the mudstones cannot be recognised due to poor exposure. The thicker sandstone units consist of amalgamated graded beds composed of fine- to very coarse-grained, volcaniclastic sandstones with scattered pebble-sized volcanic and mudstone clasts. Parallel lamination, current cross-lamination and dish structures have locally been observed within the graded beds. In some areas volcanic material may constitute up to 25% of the section (A.K. Pedersen 1978) and fossils are common (Rosenkrantz 1970; Floris 1972). The tuff beds are up to 7 m thick at Kangilia, and tuff beds up to several metres thick are also seen in Danienkløft (Tunorsuaq) and in Koralkløft (Ilugissoq; Figs 2, 74). Most of these tuff beds contain scleractinian corals; these are without preferred orientation, but only slightly worn (Floris 1972).

In the GANE#1 well the formation consists of mudstones, interbedded quartz-rich, siliciclastic and volcaniclastic sandstones and mudstones, muddy sandstones and chaotic beds (Dam 1996b). Volcanic clasts and rounded basement pebbles and angular mudstone rip-up clasts are common, and concretions and plant debris are locally present (Fig. 119). Several thinning- and fining-upward successions have been recognised in the core. These are sharply based and consist of amalgamated normally graded, very coarse- to coarse-grained sandstone beds passing upwards into thinly interbedded sandstones and mudstones. Occasionally the sandstone beds are internally stratified, showing parallel-lamination or cross-lamination, dish structures and soft sediment folds. Sandstones are occasionally burrowed and escape burrows

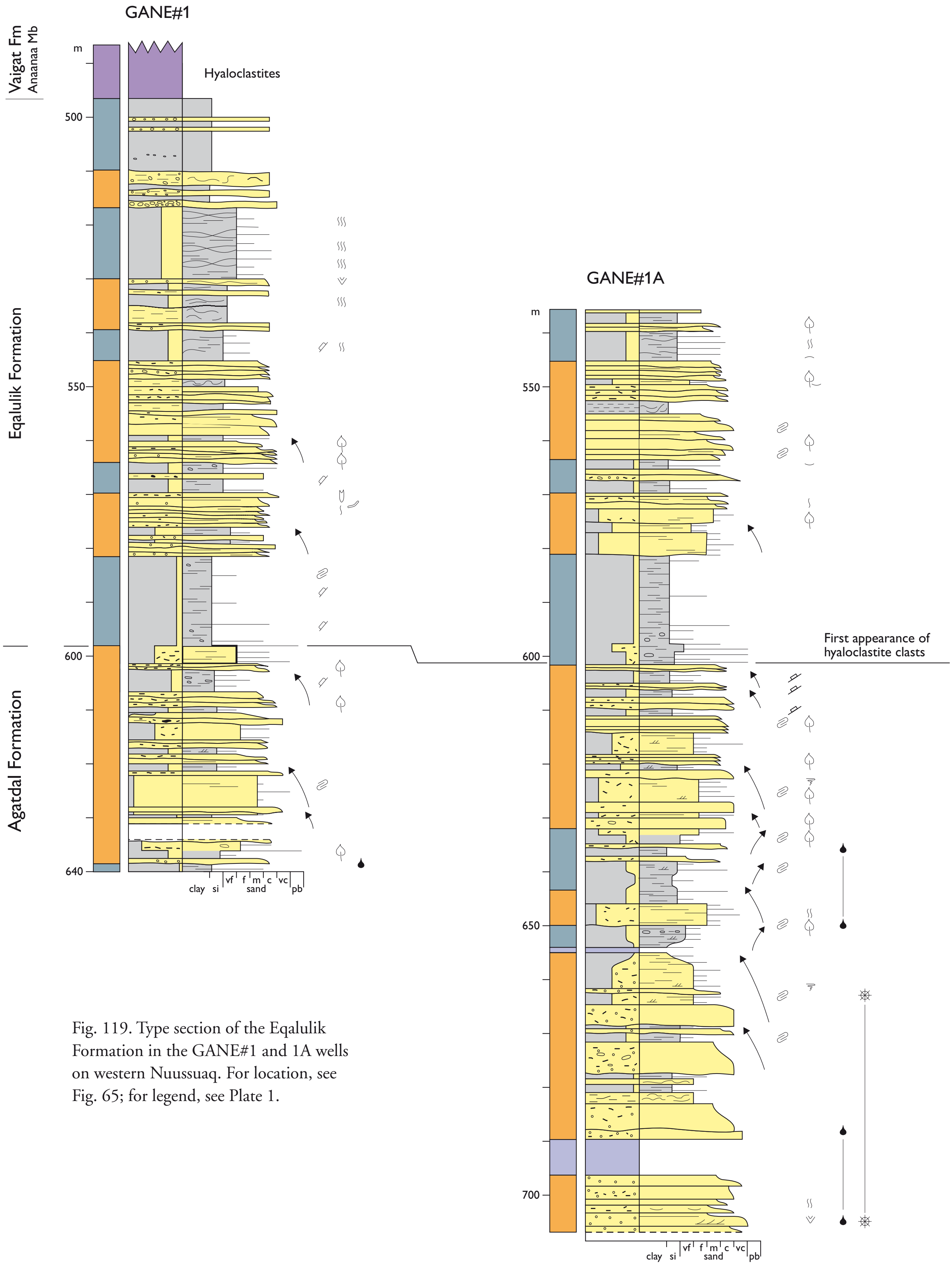


Fig. 119. Type section of the Eqalulik Formation in the GANE#1 and 1A wells on western Nuussuaq. For location, see Fig. 65; for legend, see Plate 1.

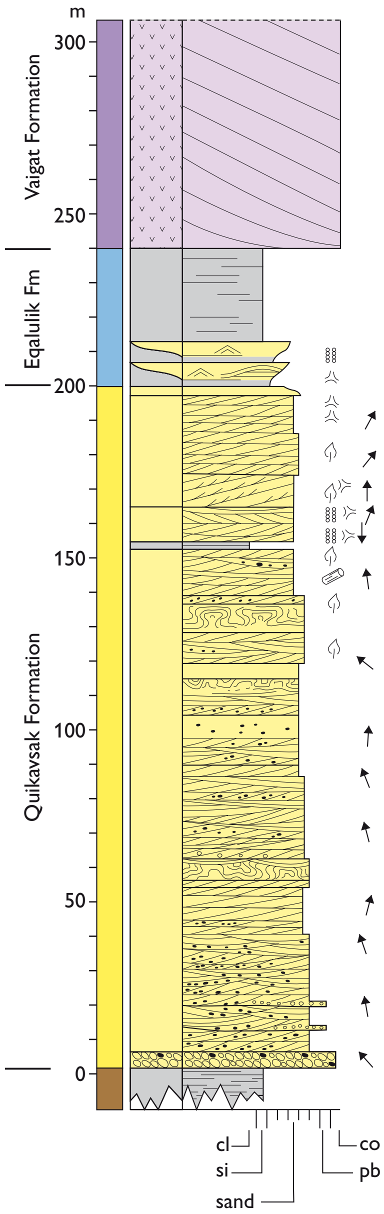


Fig. 120. Reference section of the Eqalulik Formation overlying the Paatuutkløften Member (Quikavsak Formation) at Ippigaarsukkløften on southern Nuussuaq (for location, see Fig. 40). The upper part of the Eqalulik Formation comprises fine-grained, tuffaceous mudstones deposited at water depths up to 700 m, as demonstrated by the height of the foresets in the overlying and laterally equivalent hyaloclastite breccias. Modified from Dam & Nøhr-Hansen (2001). For legend, see Plate 1.

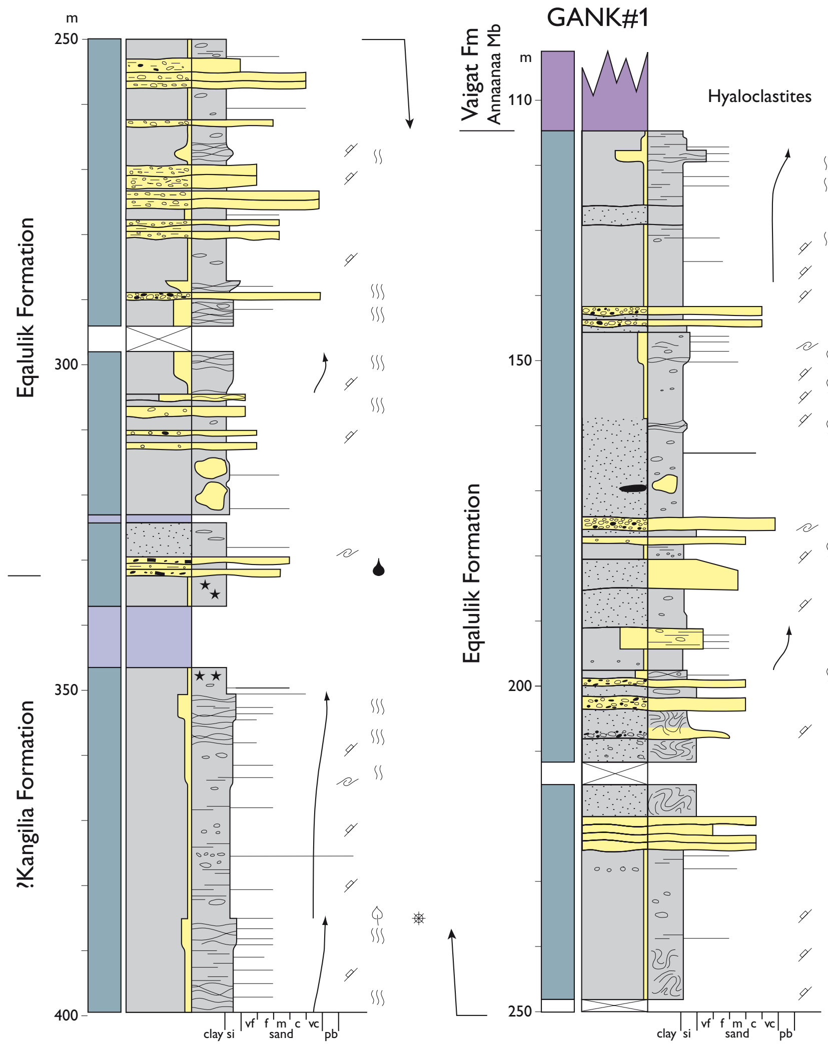
are present in a few beds. Mudstone laminae show normal grading. The chaotic beds in the GANE#1 well consist of homogenised mudstones with evenly scattered sand grains, granules, volcanic clasts and concretions. The beds are interbedded with structureless muddy sandstones and slumped mudstones showing contorted bedding (Fig. 119; Dam 1996b).

Fossils. The formation has yielded a very rich fauna, particularly in the Kangilia section where the concretions in the mudstones include gastropods, bivalves, corals, echinoderms and nautiloids, and also foraminifera, crinoids and serpulids. The bivalve *Thyasira (Conchocele)* aff. *T. conradi* (Rosenkrantz) and the pectinid *Propeamussium ignoratum* Ravn are especially common in the concretions together with a large thick-shelled *Echinocorys, Hercoglossa groenlandica* (Rosenkrantz) and stems of *Isselicrinus groenlandicus* Wienberg Rasmussen (Rosenkrantz 1970; Henderson *et al.* 1976; Kollmann & Peel 1983; Petersen & Vedelsby 2000). A fish fauna is also represented in the concretions (Bendix-Almgreen 1969) and scleractinian corals and coccoliths have been reported from the volcaniclastic sandstones (Floris 1972; Jürgensen & Mikkelsen 1974). Some corals are attached to tuff clasts, indicating that this was their original substrate. Their random orientation suggests, however, that they are redeposited, but as they are only slightly worn, transport distances must have been short (Floris 1972). A sparse nannoplankton and dinocyst flora is present at most localities (Piasecki *et al.* 1992; Nøhr-Hansen *et al.* 2002), including the mudstones at the base of the volcanic breccias of the Vaigat Formation along the south coast of Nuussuaq. The trace fossils *Planolites* isp. and *Helminthopsis horizontalis* have been recognised in the GANE#1 and GANK#1 cores (Dam 1996b, c).

Depositional environment. The macrofossils and the dinocysts indicate a marine depositional environment. Based on the height of the overlying foresets in the hyaloclastite breccias, the water depth can be estimated to have been up to 700 m (A.K. Pedersen *et al.* 1993). The sandstones are interpreted as the deposits of waning stage high- to low-density turbidity currents. However, tuff layers deposited from suspension have also been recorded (A.K. Pedersen *et al.* 1989). Volcanism started from eruption centres in the north-western and western part of the region erupting directly into a deep marine environment covering large parts of Nuussuaq and northern Disko. The fossiliferous volcaniclastic sandstones and tuffs represent the distal bottomsets of major hyaloclastite beds of the Vaigat Formation (A.K. Pedersen 1985), the result of sediment gravity flows that transported volcanic detritus and fossils into deeper water.

Boundaries. The lower boundary is placed at the base of the first volcaniclastic sandstones or tuffs. This bound-

Fig. 121. Well reference section of the Eqalulik Formation in the GANK#1 well. For location, see Fig. 65; for legend, see Plate 1.



ary is, however, difficult to place in the field since outcrops are generally very poor in these mudstone-dominated successions. Along the north coast of Nuussuaq and in the Tunorsuaq valley, a conspicuous change in the colour of bottom sediment in small streams draining the local lithologies has been observed to occur at a distinctive level high in the sections. In the lower part of the sections, the stream-bed sediments are ochreous whereas this colouring is not present at higher levels; this change may reflect the sulphide content in the mudstones of the two formations and thus aid localisation of the formation boundary. If so, the mudstones of the Kangilia Formation were deposited in a poorly oxygenated, deep-water environment in contrast to the Eqalulik Formation where more oxygenated conditions could have resulted from intermittent disturbance of bottom waters by progradation of volcanic breccias.

The upper boundary is generally placed at the base of the West Greenland Basalt Group, at the base of the major hyaloclastic foreset beds of the Vaigat Formation or at sills situated along the base of the Vaigat Formation (Hald & Pedersen 1975; A.K. Pedersen *et al.* 1993). On southern Nuussuaq, however, between Ataa and Ippigaarsukkløften (Fig. 40), the marine conditions prevailing during deposition of the Eqalulik Formation were succeeded by lacustrine environments, and consequently the Eqalulik Formation is overlain by non-marine shales of the Atanikerluk Formation (A.K. Pedersen *et al.* 1996; G.K. Pedersen *et al.* 1998).

Geological age. The Eqalulik Formation is visibly diachronous, reflecting the progressive eastward progradation of the hyaloclastite fans which are very well exposed along the slopes overlooking the south coast of Nuussuaq

Fig. 122. Fossiliferous, volcaniclastic sandstones of the Eqalulik Formation at Danienrygge. Pencil (encircled) and person for scale.

(A.K. Pedersen *et al.* 1993). However, the biostratigraphic resolution is in most cases not good enough to resolve this diachronism. The macrofauna at the type locality and on central Nuussuaq indicates an Early Danian age (Rosenkrantz 1970; Floris 1972; Henderson *et al.* 1976). The coccolith assemblage has been related to the NP3 nannoplankton zone by Jürgensen & Mikkelsen (1974); however, new dinocyst and nannoplankton data indicate an NP4 – possibly base NP5 zone age (latest Danian – early Selandian; Nøhr-Hansen *et al.* 2002). ^{40}Ar/^{39}Ar age determinations of the volcanic rocks of the Anaanaa Member (Vaigat Formation) overlying the Eqalulik Formation yield an age of 60.7 ± 1.0 (recalculated from Storey *et al.* 1998).

Correlation. On the basis of dinocyst markers, the strata in the type section can be correlated with the volcanic hyaloclastites of the Anaanaa and Naujánguit Members of the Vaigat Formation in the north-western part of the basin (Nøhr-Hansen *et al.* 2002). The tuffs of the Abraham Member (see below) have a unique composition with graphite and native iron that allows them to be correlated with the volcanic Asuk Member (A.K. Pedersen *et al.* 1989).

Subdivision. The volcaniclastic sediments in Agatdalen and Qilakitsoq will continue to be assigned to a separate member, the Abraham Member, because of their unique geochemical composition which permits correlation of the sediments with the volcanic Asuk Member of the Vaigat Formation.

Abraham Member

revised member

History. The Abraham Member was established by Rosenkrantz (in: Koch 1959 pp. 75–78) as the uppermost member of the Agatdal Formation, but is now included in the Eqalulik Formation on the basis of the characteristic content of volcaniclastic material.

Name. After Abraham Løvstrøm from Niaqornat, who for 30 years was a member of Rosenkrantz's expeditions to Nuussuaq (Fig. 7).

Distribution. The Abraham Member is known from two localities in the northernmost part of the Agatdalen valley (Fig. 113) and from the Qilakitsoq area in the Aaffarsuaq valley (Fig. 82).

Type section. The type section of the Abraham Member is in Turritellakløft at the northern end of Agatdalen (Fig. 113, 114, Plate 3, section 1). The type section is located at 70°35.01´N, 53°08.02´W.

Reference section. A reference section occurs in 'Ravine 4' east of Qilakitsoq (Figs 82, 83).

Thickness. The thickness of the Abraham Member is approximately 12 m in the type section, 10 m in Qaersutjægerdal in Agatdalen and 10–20 m at Qilakitsoq.

Lithology. The Abraham Member consists of black and grey sandy mudstones intercalated with fossiliferous reworked volcaniclastic sandstones and basement pebble conglomerates (Figs 114, 115, Plate 3). Volcanic material may constitute up to 25% of the section (A.K.

Pedersen 1978). The beds are usually structureless, but cross-bedding has been recognised locally. Volcaniclastic sandstones also occur as thin streaks in the mudstones and may include spherules of volcanic glass or tuff with a distinct chemical composition known only from the Asuk Member erupted from the Ilugissoq graphite andesite volcano (A.K. Pedersen 1985; A.K. Pedersen & Larsen 2006). In the lower part of the member, the mudstones are very dark, fossiliferous and rich in concretions. At one horizon, *in situ* corals are present in small bioherms, 10–20 cm high and less than 1 m wide (Plate 3, section 4). This horizon can be followed for more than a kilometre on the eastern bank of Qaersutjægerdal. The content of volcaniclastic sandstones increases upwards in the section.

Fossils. A sparse but diverse marine fauna and flora has been recorded from the Abraham Member, comprising scleractinian corals, echinoids, bivalves, gastropods, crustaceans, fish remains and palynomorphs (Bendix-Almgreen 1969; Rosenkrantz 1970; Floris 1972; Kollmann & Peel 1983; Piasecki *et al*. 1992; Petersen & Vedelsby 2000).

Depositional environment. The macrofossil content in the lower part of the member indicates a marine depositional environment. However, an increase up-section in terrestrially derived palynomorphs indicates that the environment became increasingly brackish with time.

Sedimentary structures in the volcaniclastic sandstones indicate deposition from turbidity currents. The corals suggest a shallow water (50?–80 m) marine environment in a warm temperate climate (Floris 1972), but where the corals were redeposited the water depth may well have exceeded 80 m.

Boundaries. A sharp lithological boundary occurs between the sandstones of the Agatdal Formation and the interbedded mudstones and volcaniclastic sandstones of the Abraham Member (Figs 114, 115). At Qilakitsoq and in the northern part of Agatdalen, the Abraham Member is succeeded by hyaloclastites of the Naujánguit Member, whereas in the eastern part of Agatdalen the Abraham Member is succeeded by hyaloclastites of the Tunoqqu Member (A.K. Pedersen 1978; Piasecki *et al*. 1992; A.K. Pedersen, personal communication 1999).

Geological age. As for the Eqalulik Formation, i.e. latest Danian to early Selandian.

Correlation. The geochemical correlation of the Abraham Member with the hyaloclastites of the Asuk Member of the Vaigat Formation (A.K. Pedersen 1978, 1985; A.K. Pedersen & Larsen 2006) ties these isolated outcrops to the mapped volcanic succession on the south coast of Nuussuaq (A.K. Pedersen *et al*. 1993).

Atanikerluk Formation

new formation

History. The Atanikerluk Formation comprises the synvolcanic non-marine sediments in the Nuussuaq Basin; in the eastern part of the basin, it includes almost all the sediments overlying the Atane Formation (Fig. 16). It is divided into five members (Fig. 123), which are correlated to members in the volcanic Vaigat and Maligât Formations (Fig. 131). The intra- and post-volcanic sediments of the Nuussuaq Basin are not included in the Nuussuaq Group and are therefore not discussed here.

<table>
<tr><th colspan="2">Koch 1959</th><th colspan="3">This paper</th></tr>
<tr><th colspan="2">Nuussuaq</th><th>Nuussuaq</th><th colspan="2">Disko</th></tr>
<tr><td rowspan="5">Upper Atanikerdluk Formation</td><td>Point 976 Member</td><td rowspan="2">Assoq Member</td><td rowspan="2">Assoq Member</td><td rowspan="4">Atanikerluk Formation</td></tr>
<tr><td>Aussivik Member</td></tr>
<tr><td>Umiussat Member</td><td>Umiussat Member</td><td>Umiussat Member</td></tr>
<tr><td>Naujât Member</td><td>Naujât Member</td><td>Pingu Member
Akunneq Member
Naujât Mb</td></tr>
<tr><td>Quikavsak Member</td><td>Quikavsak Formation</td><td colspan="2">Not present</td></tr>
</table>

Fig. 123. Lithostratigraphical subdivisions of the synvolcanic, non-marine deposits of the Nuussuaq Basin.

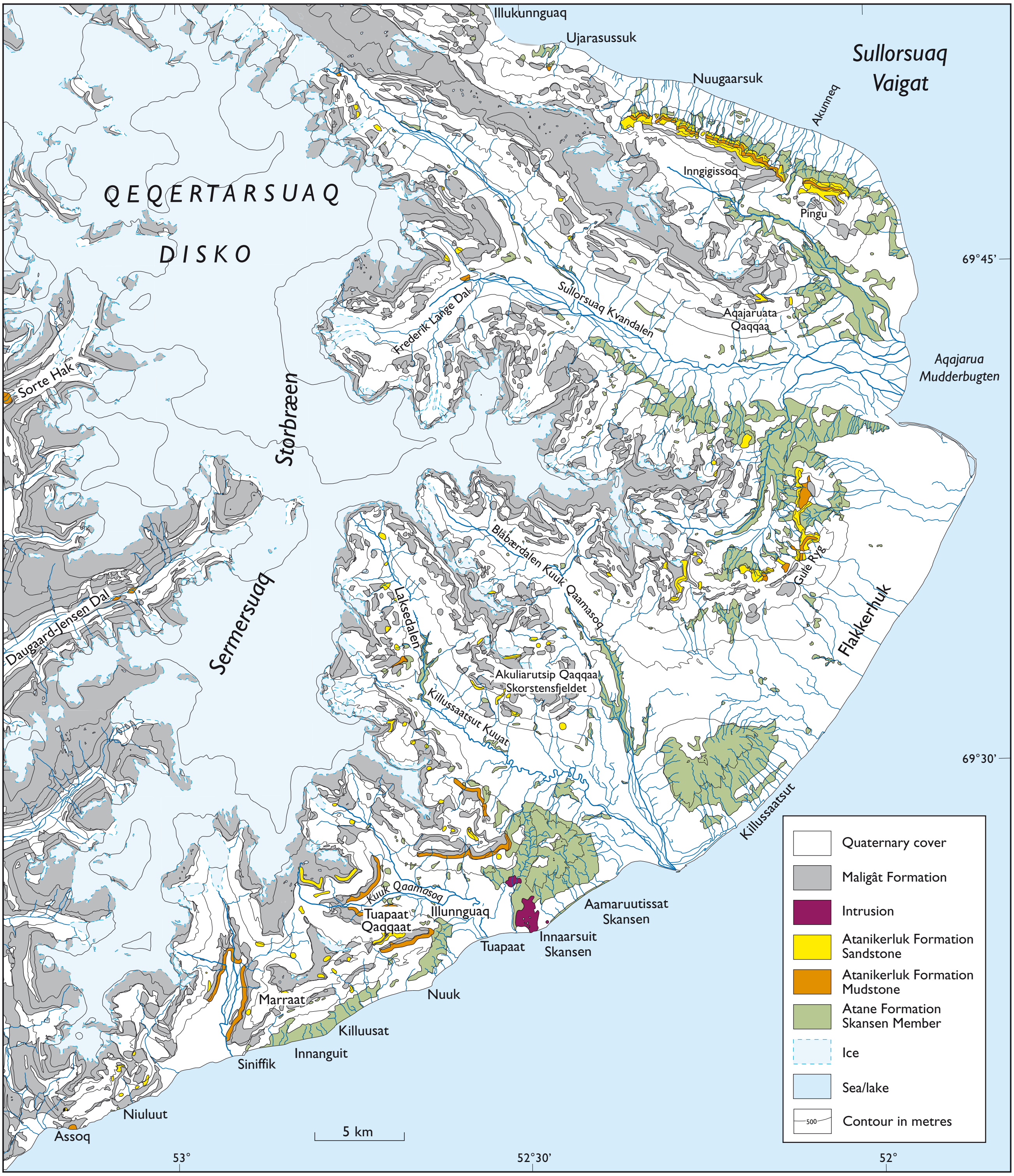


Fig. 124. Geological map showing the distribution of the Atane and Atanikerluk Formations on eastern Disko, simplified from A.K. Pedersen *et al.* (2001). Note that the outcrops of the Atanikerluk Formation are discontinuous. Contour interval is 200 m. For location, see Fig. 2.

In detail, however, the boundary between the Atanikerluk Formation and the volcanic formations can be complex, hyaloclastite breccias and invasive lavas interdigitating with the sedimentary succession. These sediments, interstratified locally with the lowermost volcanic layers, are intimately associated with the uppermost Nuussuaq Group strata and are thus referred to the Atanikerluk Formation where demonstrably related to an interdigitating volcanic–sediment facies front (Figs 17, 131).

Two new formations, the Quikavsak Formation and the Atanikerluk Formation, replace the 'Upper Atanikerdluk Formation' of Nordenskiöld (1871), Troelsen (1956) and Koch (1959). The term 'Upper Atanikerdluk Formation' dates back to Nordenskiöld (1871), who used this name for the beds (Öfre Atanekerdluklagren) containing the upper flora in the Atanikerluk area. The plant fossils occur in concretions that are dark grey on fresh surfaces but weather to a dark red colour (Nordenskiöld 1871 pp. 1051–52). Koch (1959) reported that these concretions contain the Upper Atanikerdluk A flora of Heer (1883a, b) and that they occur in his Quikavsak Member, i.e. the Quikavsak Formation of the present paper. The name Atanikerluk Formation is proposed because it does not imply the existence of a 'Lower Atanikerdluk Formation'. Although a Lower Atanikerdluk Flora was mentioned by Heer (1868), this originated from the Atane Formation as recognised as early as 1871 by Nordenskiöld.

Koch (1959) subdivided the Upper Atanikerdluk Formation into five members on Nuussuaq (Fig. 123) but attempted no subdivision of the formation on Disko. His Quikavsak Member is here established as the Quikavsak Formation. Two of Koch's members on Nuussuaq are retained (the Naujât and Umiussat Members), whereas the Aussivik and Point 976 Members are abandoned and the sediments are referred to the new Assoq Member. The reason for this is that the Aussivik and Point 976 Members are only found in a very small area of south-eastern Nuussuaq (A.K. Pedersen *et al.* 2007b). On Disko, a subdivision into five members is proposed (the Naujât, Akunneq, Pingu, Umiussat, and Assoq Members; Fig. 123). The subdivision of the Atanikerluk Formation into five members reflects the dramatic palaeogeographic changes that accompanied the intense volcanic activity.

Name. The formation is named after the Atanikerluk peninsula formed by a sill on the south coast of Nuussuaq (Fig. 40). The name was formerly spelled Atanekerdluk or Atanikerdluk.

Distribution. The Atanikerluk Formation is known on south-east Nuussuaq (Saqqaqdalen, Atanikerluk, Kingittoq, Paatuut, and Ataata Kuua), on central Nuussuaq (Nassaat and locally in Aaffarsuaq), on eastern Disko (Assoq, Tuapaat Qaqqaat, Gule Ryg, Pingu, Nuugaarsuk, Frederik Lange Dal) and central Disko (Daugaard Jensen Dal and Sorte Hak; Figs 2, 40, 124). In the Atanikerluk area, the formation was mapped in great detail by Koch & Pedersen (1960). Paleocene siliciclastic sediments are also present on Svartenhuk Halvø, where they are overlain by the volcanic Vaigat and Svartenhuk Formations (J.G. Larsen, personal communication 2008). These sediments remain unstudied in detail and the distribution of marine pre-volcanic, marine synvolcanic and non-marine synvolcanic deposits is not known at present. In the future, Paleocene non-marine, synvolcanic sediments on Svartenhuk Halvø may be established as one or more members within the Atanikerluk Formation.

Type section. The section in the south-facing slope between Atanikerluk and Tartunaq on south-east Nuussuaq is retained as the type section (Figs 125, 126) for the Atanikerluk Formation. This was described in detail by Koch (1959), who defined type sections for several members of the formation in this area. The type section is located at 70° 03.63′N, 52°13.53′W.

Reference sections. Reference sections of the Atanikerluk Formation are found at Kingittoq, at Pingu and in the Tuapaat area (Figs 7, 132, 140). The stratigraphic succession in north-east Disko has been compiled from the (mainly sedimentary) sections on both sides of Akunneq and the volcanic succession at Aqajaruata Qaqqaa, south of Akunneq (A.K. Pedersen *et al.* 2005) (Figs 124, 131).

Thickness. The Atanikerluk Formation is up to 500 m thick in a composite section, but individual outcrops reach thicknesses of *c.* 400 m (Pingu), *c.* 300 m (Kingittoq, Atanikerluk) and 200–250 m (Saqqaqdalen) (Figs 126, 128). At Tuapaat Qaqqaat, the thickness is difficult to measure due to landslides and interbedding of sediments and invasive lava flows (Fig. 140). Invasive lava flows are discussed below under 'Lithology'.

Lithology. The Atanikerluk Formation comprises mudstones, heterolithic sandstones, and fine-grained, loosely cemented sandstones. Mudstones are dominant in the Naujât and Pingu Members (Fig. 127) and in the lower part of the Assoq Member, whereas very friable sandstones characterise the Akunneq and Umiussat Members and the upper part of the Assoq Member. On a regional

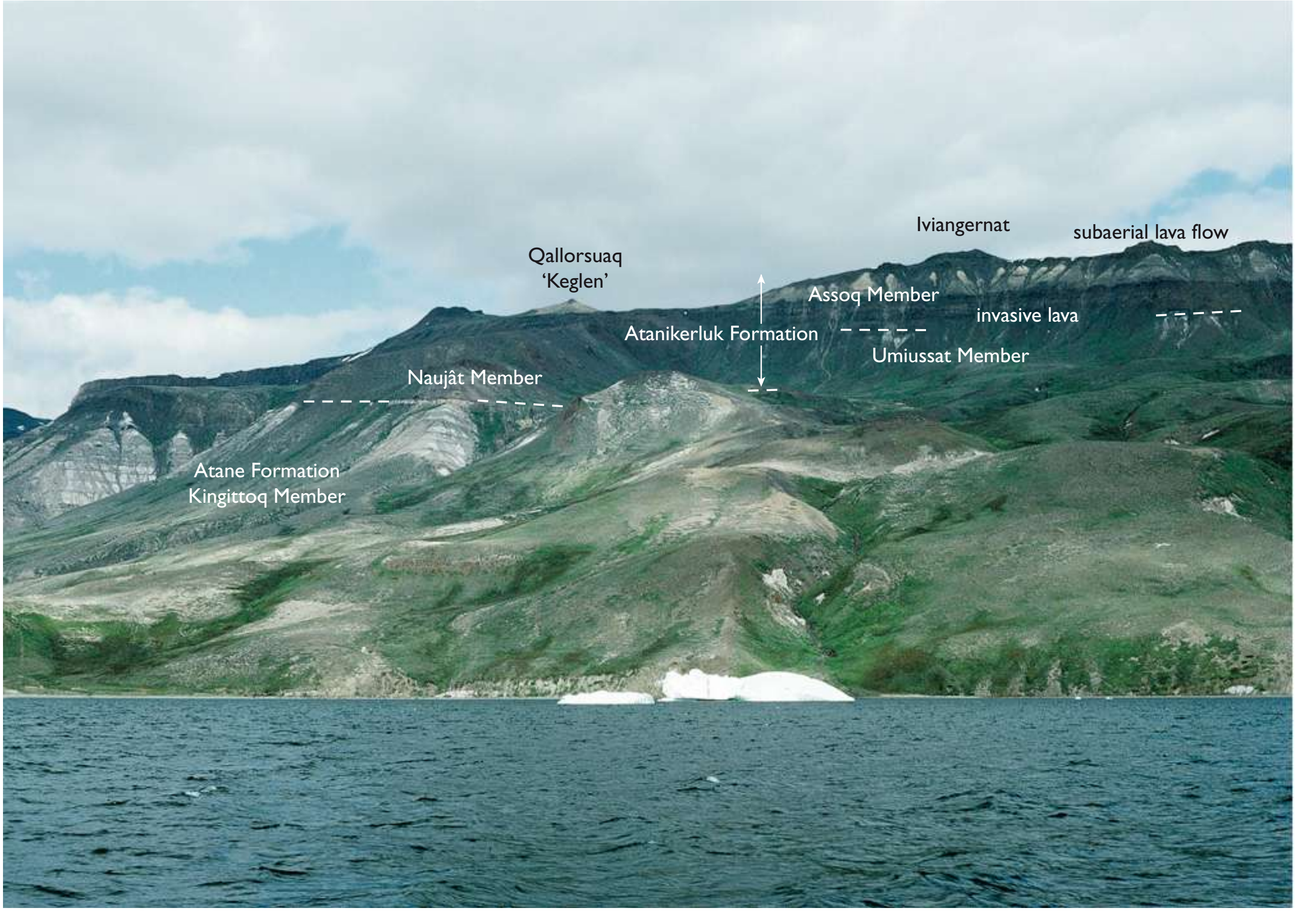


Fig. 125. The coastal slope above Atanikerluk where Koch (1959) described the strata of the Atanikerluk Formation (for location, see Fig. 40). The peak at Iviangernat is 1031 m a.s.l. The Albian to Cenomanian Kingittoq Member of the Atane Formation is up to 500 m thick and is overlain by the Paleocene Atanikerluk Formation (see Figs 16, 17).

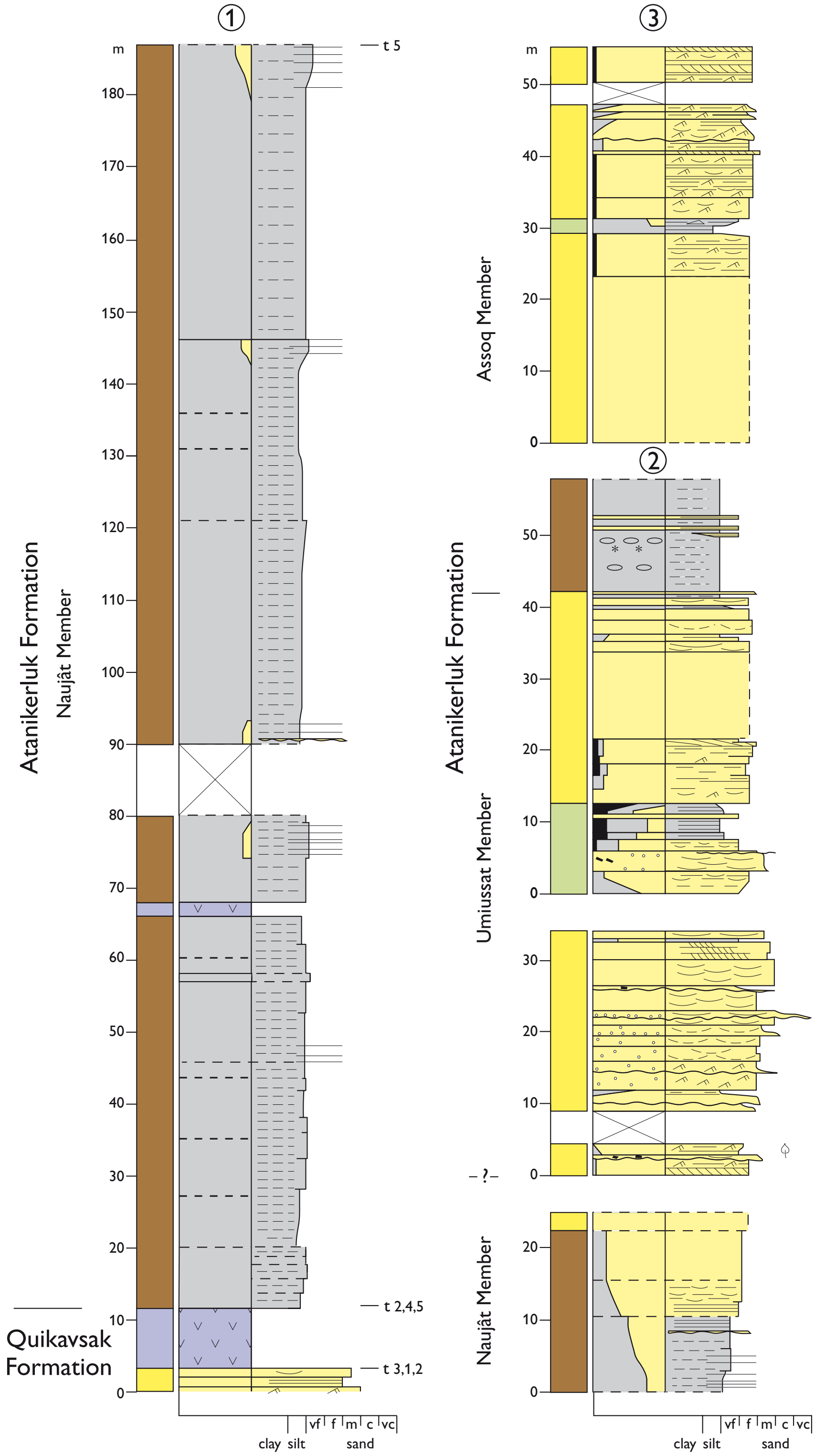
scale, the formation comprises two coarsening-upward successions that may include thinner, coarsening-upward successions on a local scale (Figs 16, 131).

The mudstones are grey to dark grey, with abundant silt-sized particles and with kaolinite and quartz as the dominant minerals. In addition, gibbsite in subordinate amounts has been detected consistently in samples from the Pingu Member and commonly in the Assoq Member. Locally, rows of small, yellowish brown siderite concretions occur in the mudstones (G.K. Pedersen 1989; G.K. Pedersen *et al.* 1998). Reworked Cretaceous palynomorphs are found in the lowest part of the Atanikerluk Formation at Akunneq (Hjortkjær 1991), suggesting that the formation also contains redeposited silt and clay. Interbedded with the mudstones are thin layers of tuff. The particles are in the coarse sand fraction and have a brownish colour that weathers to pale buff or white. The strong alteration precludes a determination of the original chemical composition of the volcanic glass.

The sandstones are weakly cemented, and in several outcrops the lithology may be better described as sand. Colours range from pale grey to deep yellow, and fine coal debris is common. The sand or sandstones are generally fine- to medium-grained; coarser grain sizes occur but are volumetrically insignificant. Chert pebbles derived from Ordovician sediments occur in the coarser facies, as also seen locally in the Atane Formation. The sediments of the Atanikerluk Formation could therefore include material reworked from Cretaceous Atane Formation sand or sandstones. This is supported by the occurrences of few Paleocene palynomorphs together with more numerous Cretaceous spores and pollen in the lower part of the Akunneq Member at Pingu (Fig. 132, 285–355 m).

The siliciclastic sediments are interbedded with volcanic rocks such as hyaloclastite breccias, invasive or subaqueous lava flows and tuffs. Hyaloclastite breccias comprise particles ranging from boulder-sized pillow fragments to sand-sized grains of glass; these rocks formed

Fig. 126. Composite type section of the Atanikerluk Formation from the Atanikerluk area between Naajaat and Umiusat, south-eastern Nuussuaq (for location, see Fig. 40). **1**: Section through the Naujât Member from Saqqaqdalen at the type locality defined by Koch (1959) (Fig. 129). **2**: Sections through the Umiussat Member from discontinuous outcrops in the Umiusat area (Figs 136, 137). **3**: Section through the upper part of the Naujât Member and the upper part of the Assoq Member, formerly the Point 976 Member of Koch (1959) from discontinuous outcrops below Keglen (Fig. 125). For legend, see Plate 1.



when lava flowed into water. The breccias are often foreset-bedded and the height of the foresets provides an indication of water depth (Jones & Nelson 1970; A.K. Pedersen *et al.* 1996; G.K. Pedersen *et al.* 1998). Invasive or subaqueous lava flows formed from large volumes of lava that reached the lake floor and continued into (invaded) the unconsolidated sediment without forming breccias (Schmincke 1967; Duffield *et al.* 1986; L.M. Larsen & Pedersen 1990; Tucker & Scott 2009). Invasive or subaqueous lava flows can be traced laterally into sub-

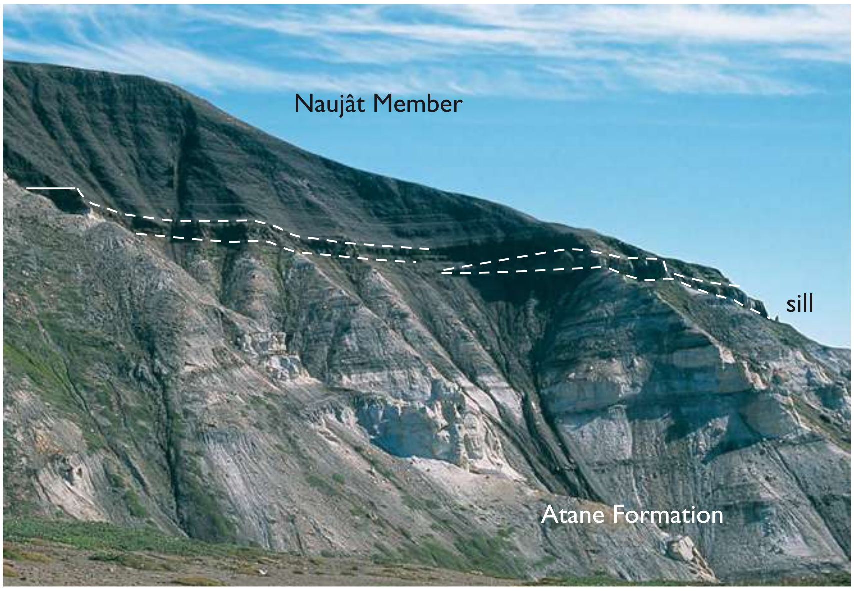


Fig. 127. Reference locality of the Naujât Member (Atanikerluk Formation) at Kingittoq where lacustrine mudstones overlie the Atane Formation (see also G.K. Pedersen *et al.* 1998 fig. 7). For location, see Fig. 2.

aerial lava flows and are thus different from sills, and are only slightly younger than the sediments they invade. Many of the invasive lava flows have retained their chemical composition and may thus be correlated to the volcanic lithostratigraphy. Layers of tuff are composed of sand-sized particles, and typically are less than 3 cm thick. The volcanic glass is strongly altered, and it is rarely possible to determine the original chemical composition of the glass.

Fossils. The Atanikerluk Formation contains a rich macroflora (Koch 1959, 1963, 1964), which Koch referred to the Paleocene Macclintockia Zone characterised by *Metasequoia occidentalis, Cercidiphyllum arcticum, Macclintockia Kanei, Macclintockia Lyalli and Dicotylophyllum bellum* (Koch 1959, 1963). Koch identified the Upper Atanikerdluk A flora and the Upper Atanikerdluk B flora of Heer (1883a, b) in the basal part of the formation (lowermost Naujât Member). The Upper Atanikerdluk A flora is also present in the Nuuk Qiterleq Member of the Quikavsak Formation. The difference between the two floras reflects changes in depositional environments, but the floras are essentially coeval (Koch 1963). The diagnostic species of the Macclintockia Zone occur in the Naujât Member but have also been found in the Abraham Member of the Eqalulik Formation (Koch 1963 p. 112).

The palynomorphs (mainly spores and pollen) of the Atanikerluk Formation have been described by Croxton (1978a, b), Hjortkjær (1991), L.M. Larsen *et al.* (1992), Piasecki *et al.* (1992), Lanstorp (1999) and D.J. McIntyre, personal communication 2009. Marine dinocysts and rare bivalves have been reported locally from the Assoq Member.

Depositional environment. The mudstones are interpreted as lacustrine deposits on the basis of the high C/S ratios, the absence of pyrite, the presence of terrestrial fossils (macrofossil plants, spores and pollen) and the general absence of marine dinocysts (Hjortkjær 1991; Piasecki *et al.* 1992; G.K. Pedersen *et al.* 1998). The sandstones are interpreted as dominantly fluvial and lacustrine in origin on the basis of the current-generated sedimentary structures, the lack of marine trace fossils, and their stratigraphic position relative to the lacustrine mudstones. Periodic marine inundations are indicated by the presence of marine fossils in the mudstones of the Assoq Member (Piasecki *et al.* 1992).

Boundaries. Over large areas, the Atanikerluk Formation rests on an unconformity that defines the upper boundary of the Atane Formation and which reflects a hiatus of varying duration. In more restricted areas, the Atanikerluk Formation conformably overlies the Quikavsak and Eqalulik Formations, or the volcanic Vaigat Formation (Fig. 16). On south-eastern Nuussuaq, the Atanikerluk Formation overlies either the Atane or the Quikavsak Formation. Strata of the Atane Formation dip towards the north-east, whereas the strata of the Atanikerluk Formation are sub-horizontal (Fig. 129). Where the Quikavsak Formation is present, its upper boundary is also horizontal, indicating that the angular unconformity between the Atane and Atanikerluk Formations formed prior to the Danian. At other outcrops, the lacustrine mudstones of the Naujât Member drape erosional relief at the top of the Atane Formation (Figs 127, 130; Pulvertaft 1989a; A.K. Pedersen *et al.* 2007a). The lower boundary of the Atanikerluk Formation on Nuussuaq is

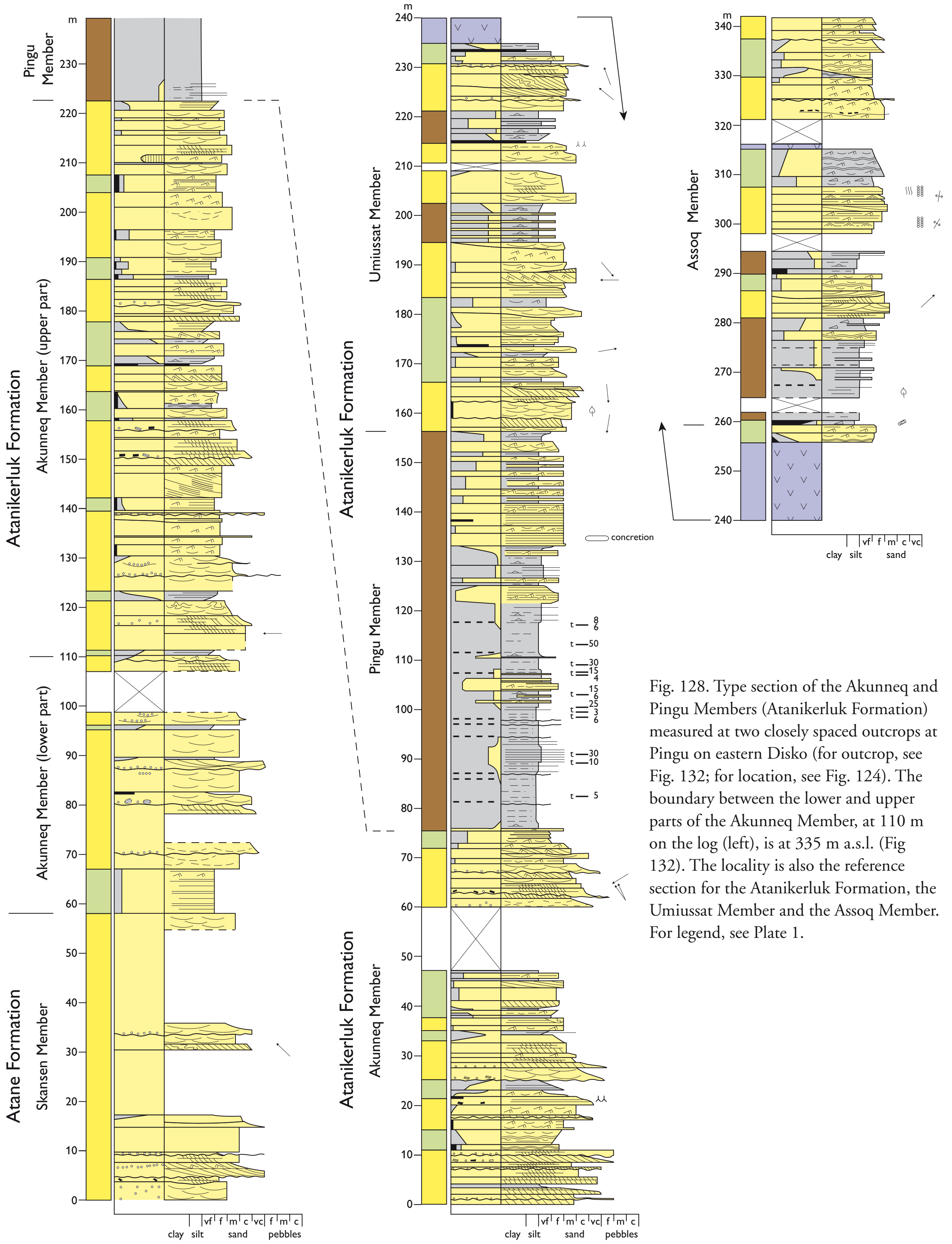


Fig. 128. Type section of the Akunneq and Pingu Members (Atanikerluk Formation) measured at two closely spaced outcrops at Pingu on eastern Disko (for outcrop, see Fig. 132; for location, see Fig. 124). The boundary between the lower and upper parts of the Akunneq Member, at 110 m on the log (left), is at 335 m a.s.l. (Fig 132). The locality is also the reference section for the Atanikerluk Formation, the Umiussat Member and the Assoq Member. For legend, see Plate 1.

interpreted as a lacustrine flooding surface which can be mapped westwards into the volcanic terrain where it separates subaerial lavas of the Naujánguit Member from overlying hyaloclastite breccias at or just above the base of the Ordlingassoq Member (A.K. Pedersen 1985; A.K. Pedersen *et al.* 1993; G.K. Pedersen *et al.* 1998) (Fig. 131). On eastern Disko, the lowest member of the Atanikerluk Formation is the dominantly fluvial Akunneq Member, and the base of this member constitutes the lower boundary of the formation; this is well exposed in the coastal section from Pingu to Nuugaarsuk (Figs 132, 133). The upper boundary of the Atanikerluk Formation is either a recent erosion surface or the boundary with volcanic or volcaniclastic deposits of the Vaigat or Maligât Formations (Figs 16, 131).

Geological age. The Atanikerluk Formation is dated by dinocysts, pollen or plant macrofossils, and is constrained by magnetostratigraphic and radiometric dating of the correlative volcanic units. A maximum age for the Atanikerluk Formation is obtained from the NP4 – possibly early NP5 marine dinocysts in the underlying Eqalulik Formation (Nøhr-Hansen *et al.* 2002). Samples from the volcanic Ordlingassoq and Rinks Dal Members give radiometric ages of 60.7–61.1 ± 0.5–1.0 Ma, recalculated from Storey *et al.* (1998). This indicates an early to mid-Paleocene (possibly Selandian) age for the Atanikerluk Formation according to the timescale of Gradstein *et al.* (2004) and Ogg *et al.* (2008).

Correlation. The two regional, coarsening-upward successions recognised in the Atanikerluk Formation correlate with the volcanic Ordlingassoq and Rinks Dal Members of the Vaigat and Maligât Formations respectively (Fig. 131). Correlation of individual members of the Atanikerluk Formation to strata of the Vaigat Formation on Disko presents some difficulties due to lack of exposures along the north coast of the island. The Atanikerluk Formation is younger than the Eqalulik Formation despite the similarity in macroplant fossils between the Abraham and the Naujât Members.

Subdivision. The Atanikerluk Formation is subdivided into five members: the Naujât, Akunneq, Pingu, Umiussat and Assoq Members (Fig. 123).

Naujât Member

revised member

History. The Naujât Member was established by Koch (1959). Its distribution is expanded here, but otherwise the definition of the member is retained.

Name. The member is named from a small cove (modern spelling Naajaat) on the south coast of Nuussuaq, just west of Saqqaqdalen (Fig. 40; Koch 1955).

Distribution. The distribution of the Naujât Member along the south-east coast of Nuussuaq was mapped by Koch (1959 plates 5–7). He recognised the Naujât Member in almost continuous outcrops and scree-covered slopes on the western side of Saqqaqdalen and along

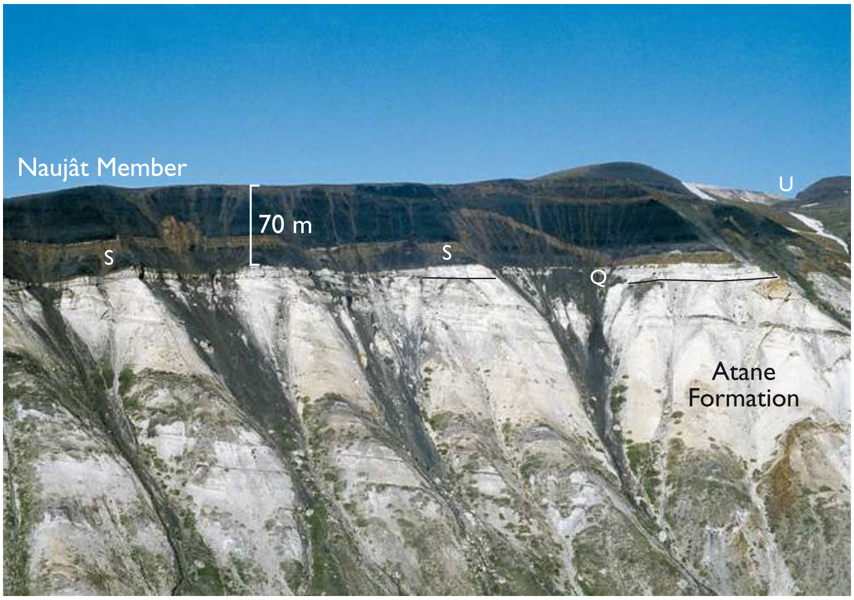


Fig. 129. Type locality of the Naujât Member (Atanikerluk Formation) along the western slope of Saqqaqdalen near Naajaat (for location, see Fig. 40). An angular unconformity is seen between the Atane Formation and the Quikavsak Formation (**Q**). The latter is conformably overlain by lacustrine mudstones of the Naujât Member, which is cut by a sill (**S**). The outcrop of pale yellow sandstones in the distance belongs to the Umiussat Member (**U**).

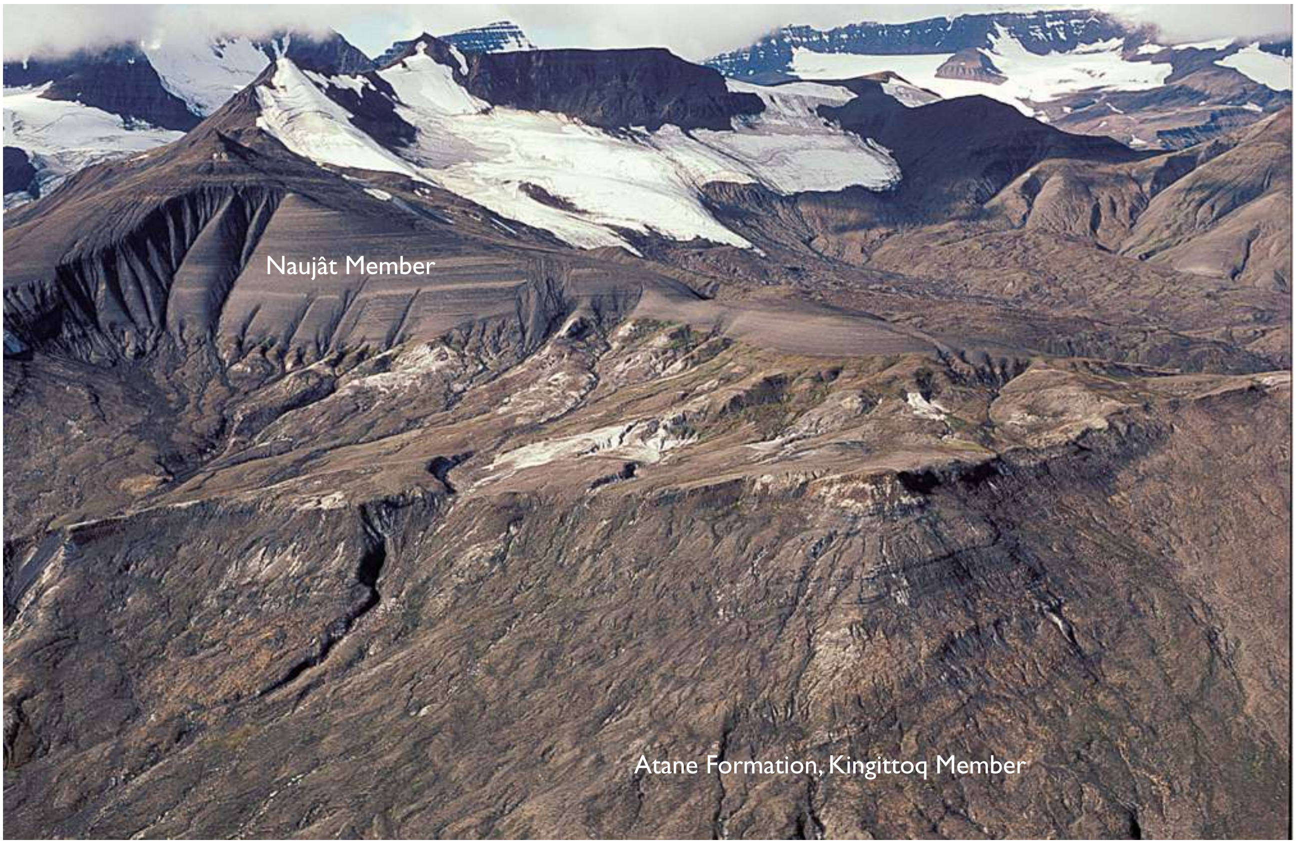


Fig. 130. Outcrop of the Naujât Member overlying the Atane Formation at Eqip Inaarsuata Qaqqaa, at the northern end of the Saqqaqdalen valley (located as EIQ in Fig. 2). The lacustrine mudstones drape erosional relief on the top of the Atane Formation. The Naujât Member is *c.* 200 m thick.

the coast from Naajaat to Kingittoq (Fig. 40). The member was traced in scree and landslides in the Paatuut area, and, at Ataata Kuua, in a thin succession between the mudstones of the Eqalulik Formation and the hyaloclastite breccias of the Ordlingassoq Member below Point 1010 m (Figs 15, 16; A.K. Pedersen *et al.* 1993, 2007b). In Saqqaqdalen, the Naujât Member continues northwards for about 25 km along the upper western slopes of the valley (A.K. Pedersen *et al.* 2007a).

On Disko, the Naujât Member is known from scattered outcrops along the north coast at Qorlortorsuaq and towards Nuugaarsuk (G.K. Pedersen *et al.* 1998 fig. 12). The delineation of the member on Disko is also discussed under the distribution of the Pingu Member.

Type section. The type section was described in the southwestern end of Saqqaqdalen, above Naajaat, by Koch (1959; Figs 124, 129). The type section is located at 70°04.10′N, 52°10.78′W.

Reference section. A reference section is proposed at Kingittoq (Fig. 127). A sedimentological log is shown in G.K. Pedersen *et al.* (1998 fig. 10).

Thickness. The Naujât Member is thickest on Nuussuaq, up to 230 m at Kingittoq (Koch 1959) and in Saqqaqdalen (G.K. Pedersen *et al.* 1998). On Disko, the member is thin; up to 10 m are preserved at Qorlortorsuaq on the north coast between Qullissat and Asuk (A.K. Pedersen 1985).

Lithology. The Naujât Member comprises dark grey to black mudstones with thin, discontinuous layers of sandstones and thin tuff beds. The tuffs are strongly altered and the original chemical composition cannot be determined, but examination of thin sections suggests that the tuffs correlate with the Vaigat Formation. Mineralogically, the mudstones are dominated by kaolinite and quartz with minor feldspar, illite and smectite. Gibbsite has only been identified in 15% of the samples, mostly from the upper part of the member. Pyrite has not been detected.

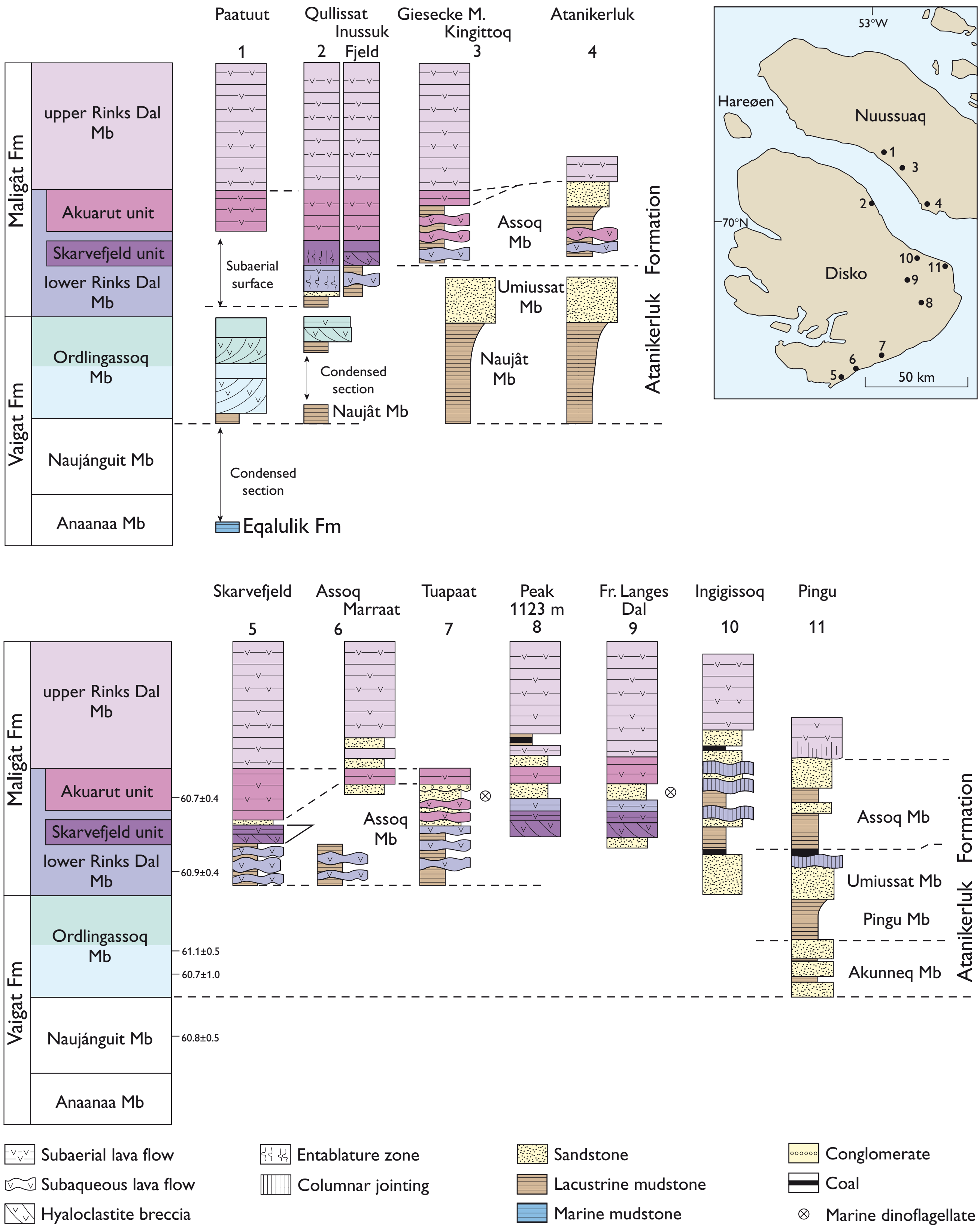


Fig. 131. Simplified stratigraphic sections showing the relationships between the volcanic rocks (colour coded) of the Vaigat and Maligât Formations (West Greenland Basalt Group) and the Atanikerluk Formation. The upper boundary of the Assoq Member is indicated (dashed line). The invasive, subaqueous lavas are all assigned to the Maligât Formation. The radiometric ages are recalculated from Storey *et al.* (1998).

The TOC [Total Organic Carbon] content is high (up to 11%) and C/S ratios are high (G.K. Pedersen *et al.* 1998). Perregaard & Schiener (1979) noted that the organic matter is immature, consisting of exinite (*c.* 50%), vitrinite (*c.* 35%) and inertinite (*c.* 15%), and that it is chemically dominated by saturated and aromatic hydrocarbons. A study of palynofacies indicates a predominance of brown and black lignite (Hjortkjær 1991).

Fossils. The Naujât Member has yielded well-preserved macroplant fossils, the Upper Atanikerdluk flora A and B of Heer (1883a, b; Koch 1959, 1963). Leaves from deciduous trees are an important constituent in the flora which includes: *Cladophlebis groenlandica, Metasequoia occidentalis, Cercidiphyllum arcticum, Dicotylophyllum bellum, Dicotylophyllum Steenstrupianum, Macclintokia Kanei, Macclintockia Lyalli* and *Credneria spectabilis* (Koch 1963).

The assemblage of spores and pollen in the Naujât Member was studied by Hjortkjær (1991). The flora is dominated by palynomorphs of terrestrial origin, whereas remains of lacustrine plants and algae are rare. Pollen of *Taxodium* spp. are abundant. The stratigraphically important mid-Paleocene species *Momipites actinus* and *Caryapollenites wodehouseia* are present in this member.

Depositional environment. The Naujât Member is interpreted as a succession of lacustrine mudstones (Koch 1959; Schiener & Leythaeuser, 1978; G.K. Pedersen *et al.* 1998). The lake formed through damming by the volcanic rocks of the Ordlingassoq Member, and it was filled simultaneously by hyaloclastite breccias from the west and siliciclastic mud from the east and south-east (G.K. Pedersen *et al.* 1998). The abundance of kaolinite among the clay minerals suggests that these have the same provenance as the mudstones of the Cretaceous Atane Formation, probably areas of deeply weathered crystalline rocks east of the basin boundary fault.

Boundaries. The lower boundary of the Naujât Member corresponds to the lower boundary of the Atanikerluk Formation in the area where the Naujât Member occurs (Figs 126, 129, 130). Mapping of the lower boundary is difficult in the Paatuut and Ataata Kuua areas where the member overlies marine mudstones of the Eqalulik Formation. In this area, the Naujât Member is also interbedded with the toesets of hyaloclastite breccias of the Ordlingassoq Member (Fig. 17, locality 5). The upper boundary of the Naujât Member is everywhere towards either the Umiussat Member or the Ordlingassoq Member of the Vaigat Formation (Fig. 136).

Geological age. Within the resolution of the dating methods, the age of the Naujât Member lies within the age range of the Atanikerluk Formation (i.e. early to mid-Paleocene, see p. 146).

Correlation. The Naujât Member is coeval with the volcanic breccias of the Ordlingassoq Member; both members overlie the same lacustrine flooding surface (A.K. Pedersen *et al.* 1993; G.K. Pedersen *et al.* 1998). The lacustrine Naujât Member on Nuussuaq correlates with the fluvial Akunneq Member on north-eastern Disko. The palynomorph assemblages of the Naujât, Akunneq and Pingu Members are similar, and the upper part of the Naujât Member correlates with the Pingu Member (Figs 123, 131).

Akunneq Member

new member

History. The sediments now referred to the Akunneq Member were formerly referred to the Upper Atanikerdluk Formation (Koch 1964; Croxton 1978a section C2).

Name. The member is named after the Akunneq valley between the Pingu and Inngigissoq mountains on the north-east coast of Disko.

Distribution. The Akunneq Member is known from the north-east coast of Disko (Pingu to Nuugaarsuk) and southwards to Gule Ryg (Fig. 124).

Type section. The section at Pingu on the eastern side of Akunneq is chosen as the type section (Figs 128, 132). The type section is located at 69°47.53´N, 52°05.43´W.

Reference section. The section on the western side of Akunneq is chosen as the reference section.

Thickness. The Akunneq Member is *c.*165 m thick at Pingu but only *c.*145 m at Nuugaarsuk. Thus the member decreases in thickness towards the west (Fig. 133).

Lithology. The Akunneq Member is dominated by very friable sandstone. It comprises a coarse-grained lower part and a finer-grained upper part, separated by a mudstone horizon at 335 m a.s.l. in the Pingu–Akunneq sec-

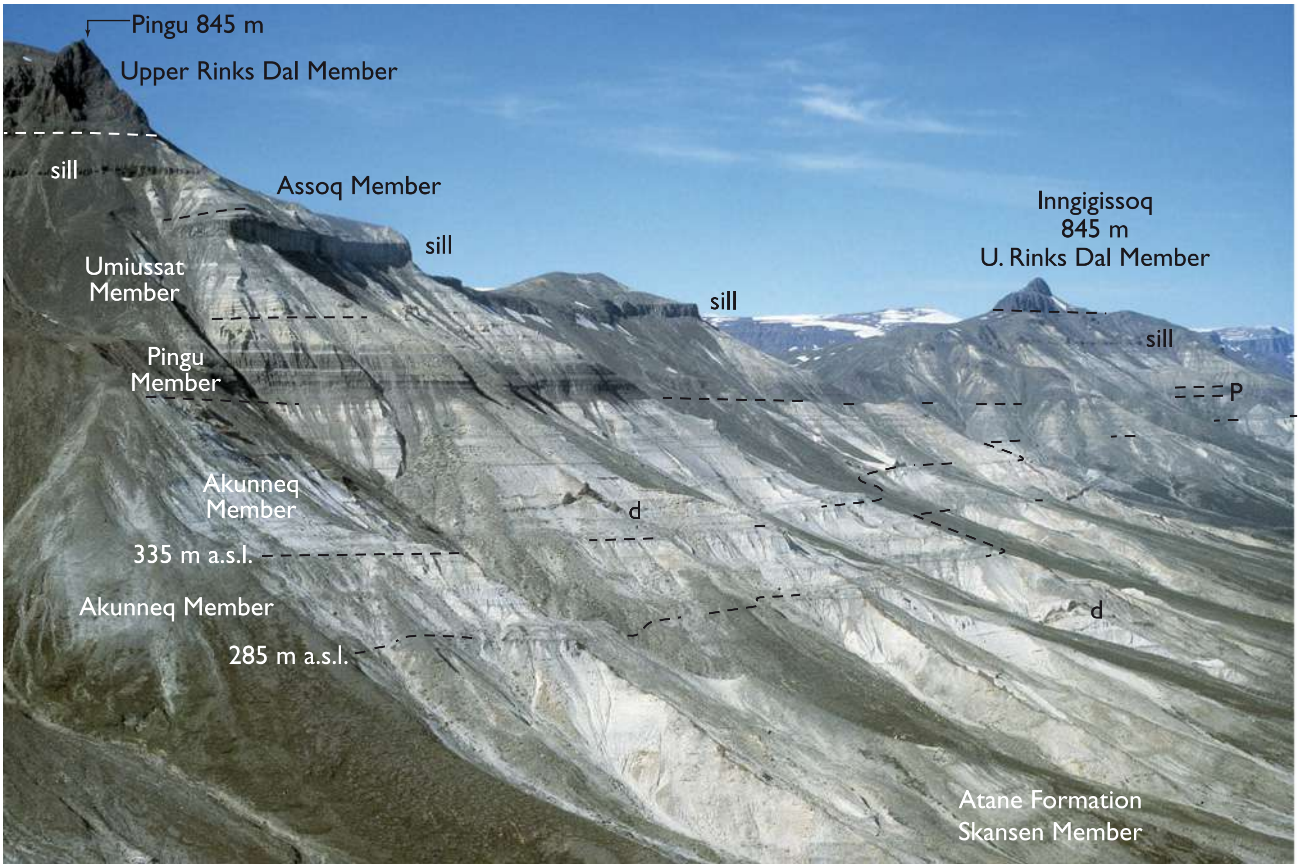


Fig. 132. Outcrop of Atanikerluk Formation in the area between Pingu and Inngigissoq on eastern Disko cut by several dykes (**d**) and sills (for location, see Fig. 124). The boundary between the Atane Formation (Skansen Member) and the Atanikerluk Formation is set at 285 m a.s.l. The boundary at 335 m a.s.l. separates the lower and upper parts of the Akunneq Member (for section, see Fig. 128). **P**, Pingu Member.

tion (Figs 132, 133). The lower part consists of large-scale cross-beddded, coarse-grained sandstones that differ little from the fluvial sandstones of the Atane Formation (Figs 128, 134). The upper part is dominated by fine-grained white sands interbedded with thinner horizons of mudstone, carbonaceous mudstone or thin coal seams. Bedding planes in the sandstone are often draped by coaly plant debris. Photogrammetric work shows that the *c.* 5 m thick mudstones are laterally continuous over a distance of 10 km, and that the proportion of fine-grained facies increases in a westerly direction from Pingu to Nuugaarsuk. Locally, the upper sandstones include 2–3 m thick beds with low-angle, composite cross-bedding. Bedform migration directions suggest westerly palaeocurrents.

Fossils. Thin mudstone horizons in the Akunneq Member contain Paleocene spores and pollen as well as reworked species of Cretaceous (Cenomanian) age (Croxton 1978a, b; Hjortkjær 1991, D.J. McIntyre, personal communication 2009). The upper part of the Akunneq Member is dominated by Paleocene species identical to those occurring in the Naujât and Pingu Members (Hjortkjær 1991; B.F. Hjortkjær, personal communication 1999). The lower part of the Akunneq Member is dominated by reworked Cenomanian species, and unquestionable Paleocene species are scarce (B.F. Hjortkjær, personal communication 1999; D.J. McIntyre, personal communication 2009).

Depositional environment. The Akunneq Member is interpreted as a succession of sandy fluvial deposits interbedded with thin lacustrine mudstones. The sandstones in the lower part of the Akunneq Member are interpreted as deposited in braided channels. The change in grain-size and the ubiquitous coaly plant debris indicate lower energy, and the occasional occurrence of sandy point bar deposits suggests deposition in meandering fluvial channels. The thin but laterally widespread mudstones are interpreted as reflecting short-lived phases of lake formation, and the coal beds represent peat formation. Towards the west, in a downstream direction, the Akunneq

Fig. 133. Correlation of the members within the Atanikerluk Formation on north-east Disko. Note the general thinning of units westwards from Pingu to Nuugaarsuk. Altitudes above sea level are indicated. For location, see Fig. 124; for legend, see Plate 1.

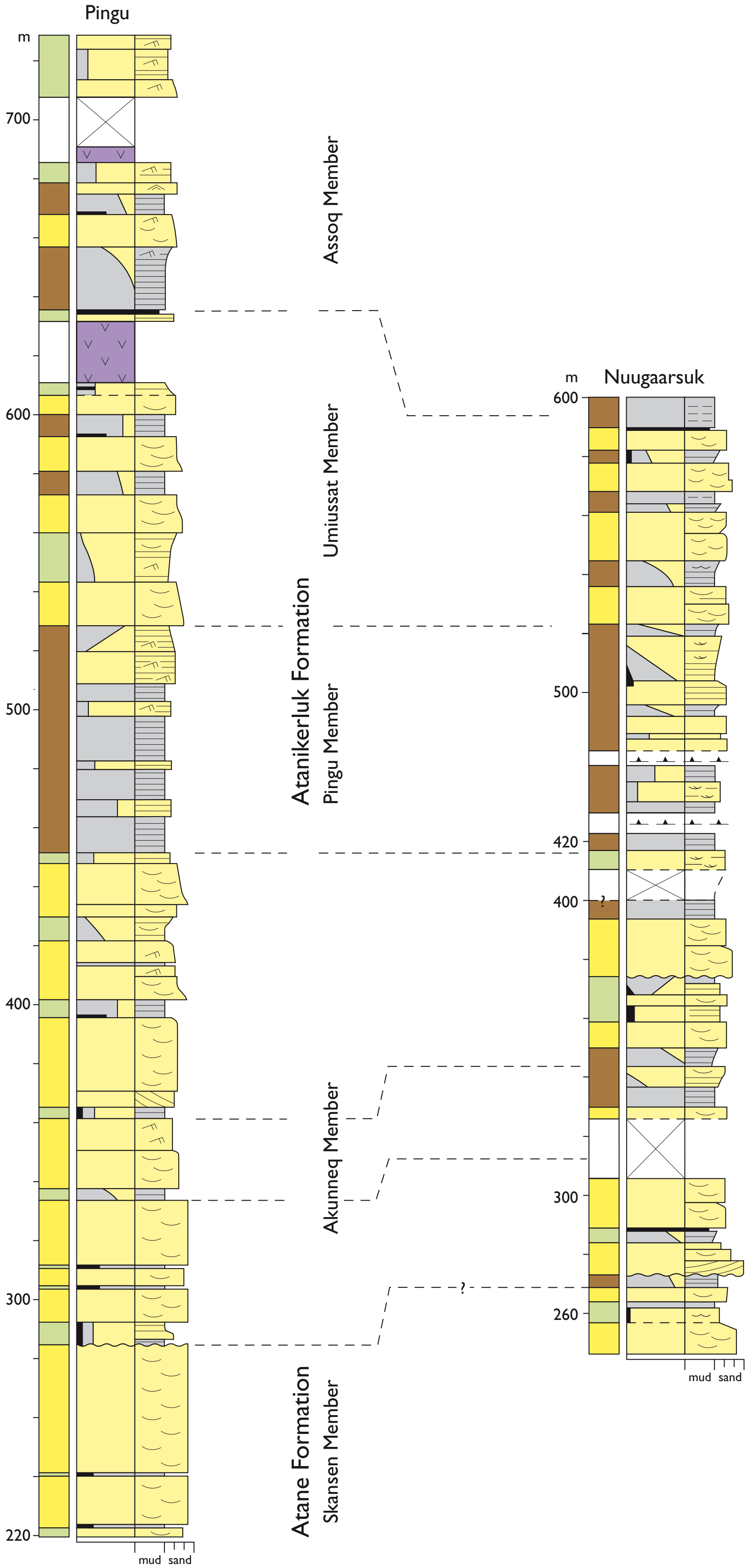


Fig. 134. The illustrated, coarse-grained, fluvial sandstone unit, *c.* 30 m thick, showing large-scale cross-bedding is characteristic of the lower part of the Akunneq Member on the western side of Akunneq. The sandstone is abruptly overlain by grey muddy sandstones, also referred to the Akunneq Member. For location, see Fig. 124.

Member becomes thinner with an increasing amount of mudstone, which suggests that it was deposited on a floodplain adjacent to the 'Naujât lake'.

Boundaries. The lower boundary of the Akunneq Member corresponds to the lower boundary of the Atanikerluk Formation in the area of distribution of the Akunneq Member (Fig. 132). The geological map of the Pingu area shows that both the Atane and the Atanikerluk Formations are subhorizontal in north-east Disko (A.K. Pedersen *et al.* 2001). The boundary between the fluvial Skansen Member and the fluvial Akunneq Member may be difficult to identify in outcrops. In the Pingu area, the lower boundary of the Akunneq Member is placed at the base of a *c.* 3 m thick unit of bluish grey, laterally continuous mudstones, which forms a terrace with a steep front. The upper boundary of the Akunneq Member is placed at the base of the mudstones of the Pingu Member (Figs 132, 133, 135).

Geological age. Reworked Cretaceous spores and pollen dominate the lower part of the Akunneq Member, but the few Paleocene forms show that the age of the Akunneq Member lies within the age range of the Atanikerluk Formation (i.e. early to mid-Paleocene, see above).

Correlation. The Akunneq Member is interpreted to correlate with the lower or middle part of the Naujât Member. Abundant landslides on the north coast of Disko obscure the relationships between the Akunneq Member and the Ordlingassoq Member of the Vaigat Formation (A.K. Pedersen *et al.* 2005).

Pingu Member

new member

History. Sediments referred to the Pingu Member were earlier described by Croxton (1978a section C2). Their sedimentary facies and depositional environment were discussed by G.K. Pedersen (1987, 1989). The deposits were tentatively referred to the Naujât Member by G.K. Pedersen (1987). The difference in mineralogy, the lack of positive evidence that the Pingu and Naujât Members are continuous, and the prominence of this mudstone unit on north-east Disko are the reasons for erecting the Pingu Member.

Name. The member is named from the mountain of Pingu on north-east Disko (Figs 124, 132).

Distribution. The Pingu Member is only known from outcrops on Disko. It is continuously exposed in the coastal section from Pingu to Nuugaarsuk and can be traced south-west of Pingu to Gule Ryg (Fig. 124).

Type section. The section on the north side of Pingu (east of Akunneq) is chosen as the type section of the Pingu Member (Figs 128, 135). The type section is located at 69°47.13′N, 52°02.12′W.

Reference section. The section between Akunneq and Nuugaarsuk is chosen as the reference section of the Pingu Member (Figs 124, 133).

Fig. 135. Type locality of the Pingu Member on the north side of Pingu (for location, see Fig. 124). Note the sharp lower boundary with the Akunneq Member and the transitional upper boundary with the Umiussat Member.

Thickness. The Pingu Member is 85 m thick at Pingu, probably thinning towards Nuugaarsuk, although the thickness is difficult to measure at the latter locality due to landslides (Fig. 133). The member is more than 30 m thick at Gule Ryg.

Lithology. The Pingu Member consists of dark grey mudstones interbedded with thin layers of tuff and fine-grained sandstone beds that increase in frequency upwards. The member thus constitutes an overall coarsening-upward succession (Fig. 128; G.K. Pedersen 1989).

Mineralogically, the mudstones consist of kaolinite and quartz with a little illite and feldspar; neither calcite nor pyrite has been detected. Gibbsite is found in 96% of the samples where it makes up 5–10% of the sediment. Siderite occurs in small concretions that weather bright yellow. The mudstones are rich in organic matter (up to 8%), most of which is terrestrial (G.K. Pedersen 1989). A palynofacies study demonstrated the predominance of brown and black wood (Hjortkjær 1991). The sandstones are fine-grained, well-sorted and form thin beds showing parallel lamination or current ripple cross-lamination.

Fossils. The assemblage of spores and pollen in the Pingu Member was studied by Hjortkjær (1991), who found that it corresponds to that of the Naujât Member. The flora is dominated by palynomorphs of terrestrial origin, whereas remains of lacustrine plants and algae are rare. Pollen of *Taxodium* spp. are abundant. The stratigraphically important mid-Paleocene species *Momipites actinus* and *Caryapollenites wodehouseia* occur together with a few specimens of the mid- to late Paleocene *Insulapollenites rugulatus* (Hjortkjær 1991). Neither Croxton (1978a, b) nor Hjortkjær (1991) observed marine dinocysts in samples from the Pingu Member.

Depositional environment. The Pingu Member represents a predominantly low energy depositional environment characterised by settling of mud from suspension and occasional deposition of sand from low energy sediment gravity flows. The lack of marine fossils coupled with the absence of both pyrite and its weathering product jarosite indicates a lacustrine depositional environment. The increasing number of sand layers up-section are interpreted to record gradual progradation of the shoreline and consequent filling of the lake (G.K. Pedersen 1989). The supply of gibbsite to the lacustrine mud suggests input from a new provenance area. The expanding areas of subaerial basalt flows may have weathered to lateritic soils that could have supplied gibbsite during deposition in the 'Pingu lake'. This new provenance area is also reflected in the mineralogy of the top of the lacustrine Naujât Member.

Boundaries. The Pingu Member has a sharp lower and a gradational upper boundary (Figs 128, 132, 135). The lower boundary separates the lacustrine mudstones of the Pingu Member from the underlying sandy fluvial Akunneq Member; this abrupt boundary is overlain either directly by mudstones or by a thin succession of mudstones interbedded with sandstone layers and it is interpreted as an erosional surface formed during lacustrine drowning (Figs 128, 135). The upper boundary is defined by the base of the Umiussat Member (Figs 128, 132, 133, 134, 135).

Geological age. The age of the Pingu Member is the same that of the Atanikerluk Formation (i.e. early to mid-Paleocene, see p. 146).

Correlation. The deposits assigned here to the Pingu Member have been correlated with the Naujât Member (Henderson *et al.* 1981 fig. 4). The assemblages of spores and pollen in the two members are similar (Hjortkjær 1991), but the mineralogy differs, especially with respect to the distribution of gibbsite. We interpret the Pingu Member on Disko as correlating with the upper part of the Naujât Member on Nuussuaq.

A correlation between the Pingu Member and the volcanic Ordlingassoq Member cannot be proven because the north coast of Disko is ravaged by landslides and rock glaciers between Nuugaarsuk and Qullissat (A.K. Pedersen *et al.* 2005). Between Pingu and Nuugaarsuk, the oldest magmatic rocks have a composition corresponding to the Maligât Formation (Fig. 131).

Umiussat Member

revised member

History. The Umiussat Member was established by Koch (1959) on south-east Nuussuaq where it overlies the Naujât Member. In the present paper the definition of the Umiussat Member is retained, but its geographical distribution is expanded.

Name. The member is named from the Umiusat ridge on south-eastern Nuussuaq (Fig. 40).

Distribution. The Umiussat Member is known on south-east Nuussuaq in the area between Naajaat and Kingittoq, and in Saqqaqdalen. It covers a smaller area than the Naujât Member. The Umiussat Member is also present on eastern Disko between Nuugaarsuk and Pingu, and at Gule Ryg (Figs 40, 124).

Type section. The type section of the Umiussat Member of Koch (1959) at Umiusat is retained (Figs 126, 136). The type section is located at 70°09.00´N, 52°26.57´W.

Reference section. The section on the north side of Pingu, east of Akunneq, is suggested as a reference section for the Umiussat Member (Figs 128, 132).

Thickness. The Umiussat Member is 70–100 m thick. It is rarely well exposed, hence lateral variations in thickness are not documented. The member is *c.* 80 m thick at Pingu (Fig. 128) and *c.* 100 m thick in the Atanikerluk area (Koch 1959).

Lithology. The Umiussat Member is dominated by fine- to medium-grained sands or sandstones which range in colour from white or pale grey on Disko to yellow on Nuussuaq. Comminuted plant debris is abundant and outlines bedding planes and sedimentary structures such as cross-lamination and cross-bedding. The sands or sandstones are interbedded with 1–5 m thick mudstones,

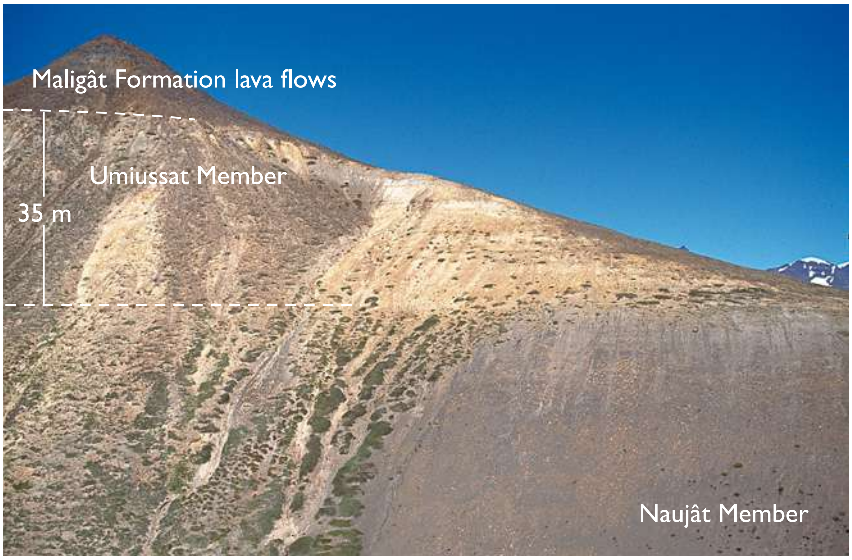
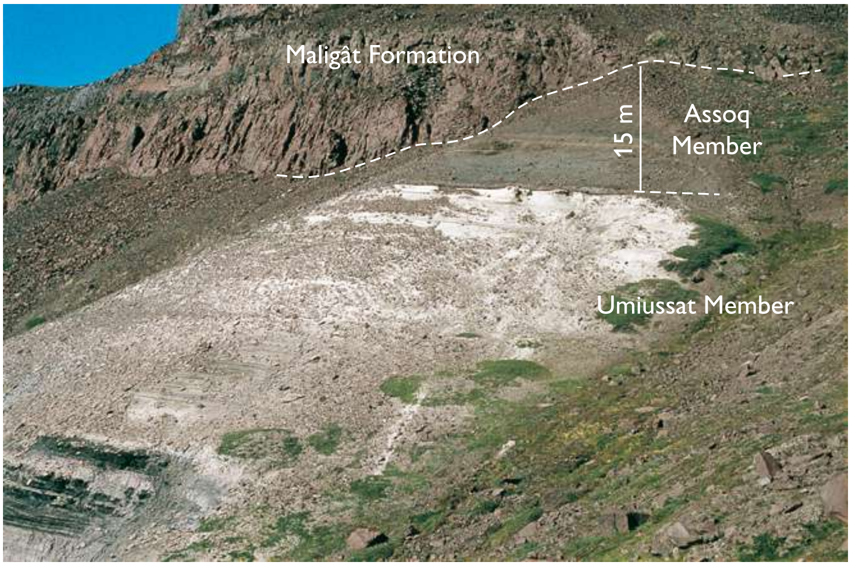


Fig. 136. Type locality of the Umiussat Member (Atanikerluk Formation) at Umiusat, south-eastern Nuussuaq (for location, see Fig. 40). At the top of the Naujât Member, an increase in the number of thin sandstone beds results in a transitional boundary between the two members.

Fig. 137. Lower, sharp boundary of the Assoq Member with the Umiussat Member at Umiusat. See section 2 in the composite sedimentological log in Fig. 126.



some of which include thin coal beds (Figs 126, 128, 137). A 120 cm thick coal bed forms the top of the Umiussat Member on north-east Disko (Fig. 131).

Fossils. No fossils have been reported from the Umiussat Member.

Depositional environment. The sediments of the Umiussat Member are interpreted to have been deposited in predominantly braided fluvial channels and on floodplains.

Boundaries. The lower boundary with the Naujât Member is transitional and is rarely well exposed (Fig. 136; Koch 1959). The lower boundary with the Pingu Member is placed at an erosional surface separating the heterolithic sandy mudstones at the top of the Pingu Member from the overlying fluvial sandstones of the Umiussat Member (Figs 128, 135). The upper boundary of the Umiussat Member is placed at the drowning surface which forms the lower boundary of the Assoq Member (Figs 133, 137).

Geological age. The age of the member lies within the age range of the Atanikerluk Formation (i.e. early to mid-Paleocene, see p. 146).

Correlation. The Umiussat Member is interpreted as coeval with the uppermost subaerial lava flows of the Ordlingassoq Member, and deposition of the Umiussat Member probably continued during the break in volcanic activity between the Vaigat and the Maligât Formations (Fig. 131).

Assoq Member

new member

History. The sediments referred to the Assoq Member include those overlying the Umiussat Member on Disko as well as those referred to the Aussivik Member and the Point 976 Member of Koch (1959) (Fig. 123). The Aussivik and Point 976 Members are abandoned because they are poorly exposed and only cover small areas on south-eastern Nuussuaq.

Name. The member is named from the coastal mountain slope at Assoq on southern Disko (Fig. 124).

Distribution. The geological map sheets 1:100 000 Uiffaq and 1:100 000 Pingu show that the Assoq Member covers most of Disko, east of the Disko Gneiss Ridge (A.K. Pedersen *et al.* 2000, 2001). The area in which the Assoq Member is distributed is strongly affected by landslides and reliable outcrops are discontinuous (Fig. 124). On Nuussuaq, the Assoq Member is present at Kingittoq, between Umiusat and Saqqaqdalen, in the Atanikerluk area and probably also on central Nuussuaq, east of the Ikorfat fault (Fig. 40; A.K. Pedersen *et al.* 1993, 2002, 2007b).

Type section. The type section is at Assoq within a huge landslipped block (Fig. 138). This locality has the best exposures of the fissile mudstones, but neither the lower nor the upper boundary of the Assoq Member is confi-

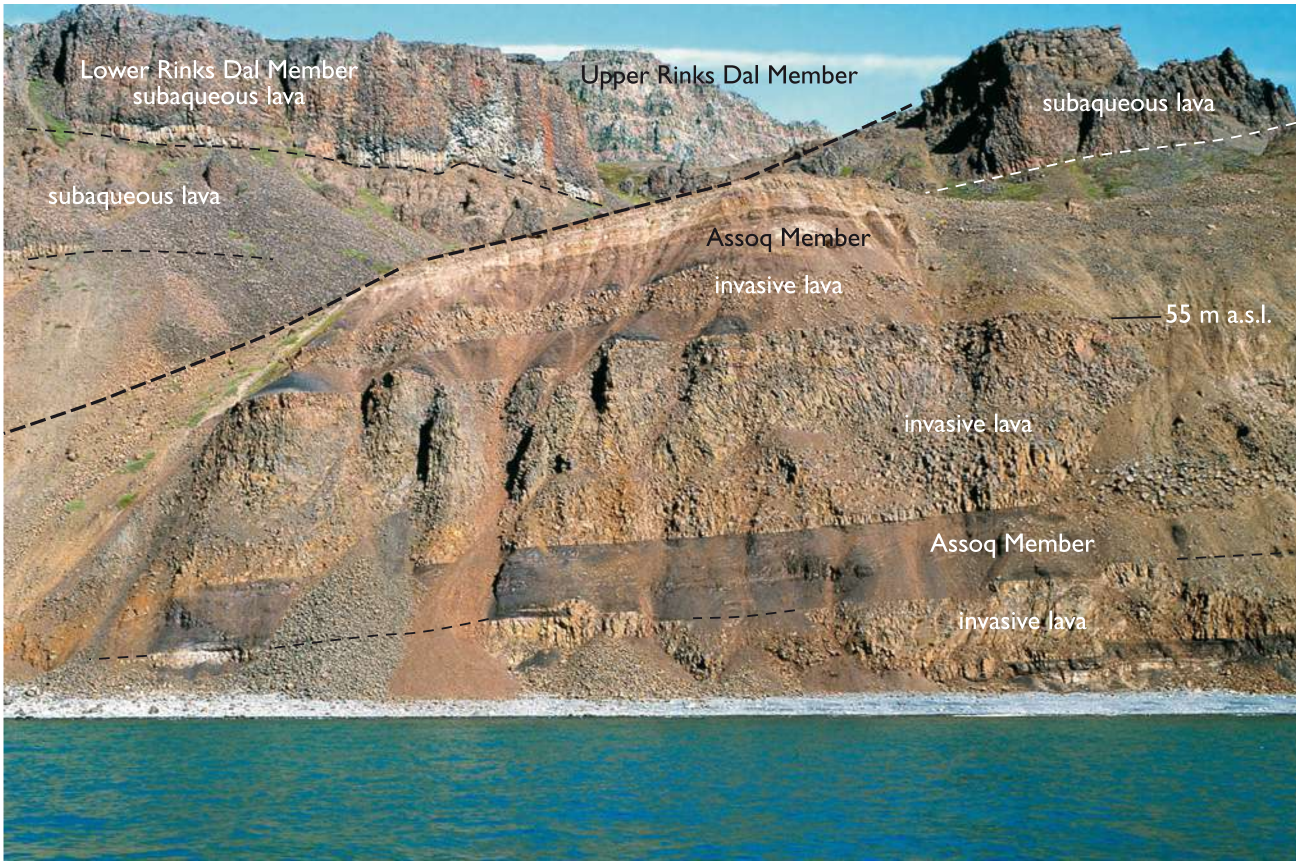


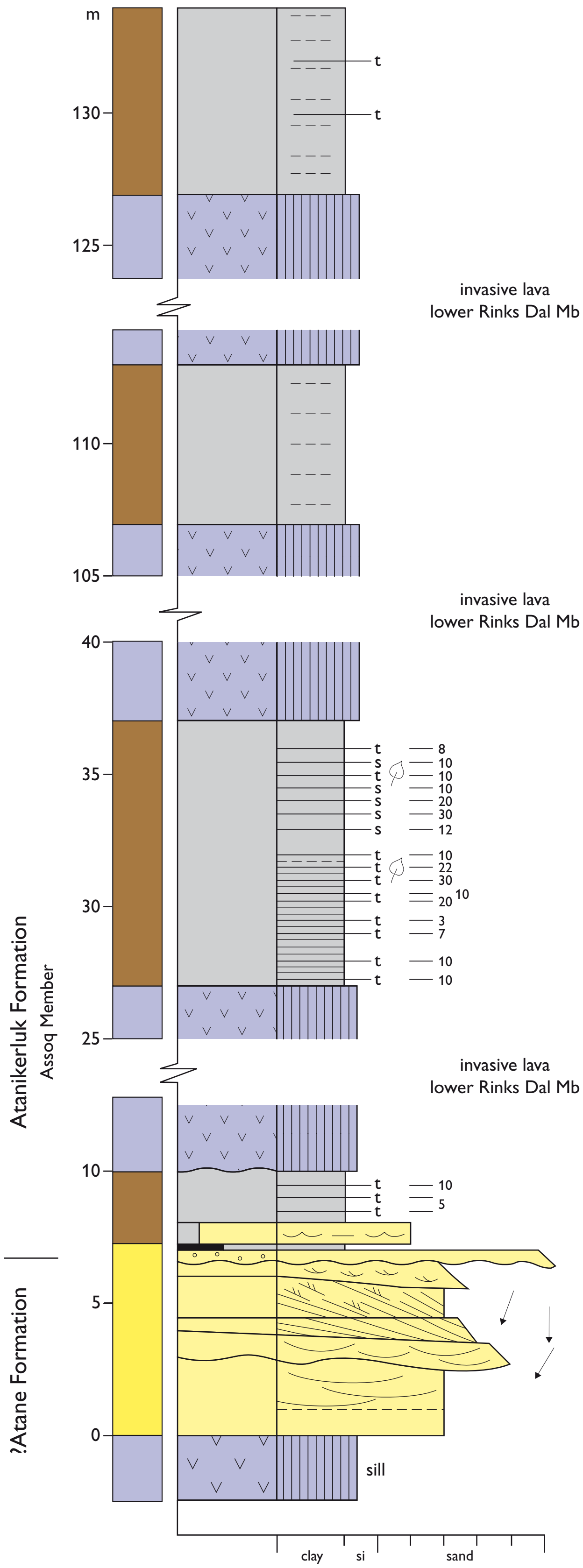
Fig. 138. Type locality of the Assoq Member at Assoq on the south coast of Disko (for location, see Fig. 124). The brownish black mudstones of the Assoq Member are interbedded with invasive lava flows and overlain by subaqueous lava flows of the lower Rinks Dal Member of the Maligât Formation (see Fig. 131). Sediments and interbedded volcanic rocks are part of a huge landslide, two blocks of which are separated by the dash–dot line. The Assoq Member is also found at higher altitudes away from the coast (A.K. Pedersen *et al.* 2003). For log, see Fig. 139.

dently identified (Fig. 139). The type section is located at 69°19.23´N, 53°09.10´W.

Reference sections. Reference sections are exposed on southern Disko east of Assoq (Fig. 139), on northern Disko at Pingu (Figs 124, 128), and on southern Nuussuaq at Qallorsuaq (Keglen). The sediments here were formerly referred to the Aussivik and Point 976 Members of Koch (1959) (Figs 40, 125).

Thickness. The Assoq Member is up to *c*. 200 m thick, but the thickness is difficult to measure in areas where the sediments are interbedded with volcanic or intrusive rocks and are subject to landslides.

Lithology. The Assoq Member constitutes a major, coarsening-upward succession with a lower part dominated by brownish black fissile mudstones, and an upper part that is dominated by sands but also includes a single, 3 m thick, coal seam (Figs 126, 128, 138, 140). The mudstones have TOC contents of up to 7%. The dominant clay mineral is kaolinite, but gibbsite is also present in most samples. Thin beds are cemented by siderite. Numerous thin tuff layers are interbedded with the mudstones. They are typically a few millimetres to a few centimetres thick, deposited by settling through the water column. Examination of thin sections shows that the tuff is strongly altered diagenetically. The mudstones are interbedded with hyaloclastite breccias and subaqueous lava flows which formed where lava flows of the lower Rinks Dal Member entered the 'Assoq lake' (L.M. Larsen *et al.* 2006). Based on their chemical composition, the invasive lava flows are correlated with various units within the volcanic lower Rinks Dal Member (Figs 131, 139, 140).



The upper part of the Assoq Member is dominated by sands, often with comminuted plant debris. In the scree-covered slopes at Tuapaat Qaqqaat and Qallorsuaq (Keglen), the sands are yellow and fine-grained, but rarely well exposed. At Pingu and Gule Ryg, the sedimentary structures suggest deposition from traction currents in a low-energy environment (Fig. 128). A thick coal bed has been observed at the top of the Assoq Member (Fig. 141) which probably correlates to coal beds interbedded with volcanic rocks at several localities west of Gule Ryg, eastern Disko (L.M. Larsen & Pedersen 1990; A.K. Pedersen *et al.* 2001) (Fig. 131). These sediments are considered part of the Atanikerluk Formation as they can be traced from continuous sedimentary successions into the basal part of the subaerial lava flow succession. The chemistry of these volcanic rocks corresponds to the lower part of the upper Rinks Dal Member.

Fossils. Plant macrofossils are unevenly distributed in the Assoq Member, but they are generally scarce. From the Atanikerluk area, Koch (1959) reported a leaf of *Cercidiphyllum arcticum* from the lower part (his Aussivik Member) and pieces of fossil wood of *Taxodioxylon* type from his Point 976 member. Bedding planes covered by plant remains were observed west of Kingittoq by the present authors. The freshwater bivalve *Unio* sp. occurs in the upper, sandy part of the Assoq Member (Koch 1959). Fish scales and bones are preserved in a concretion from Akuliarusinnguaq (*c*. 4 km north of Gieseckes Monument; Fig. 2).

The spores and pollen in the Assoq Member were described by Hjortkjær (1991) and differ little from those in the older members of the Atanikerluk Formation. Piasecki *et al.* (1992) reported finds of marine dinocysts in a few samples from the Assoq Member in southern and eastern Disko. In the inner part of Kvandalen (Fig. 124), the mudstones are found to contain rare bivalves (protobranchs?) and rare dinocysts (Piasecki *et al.* 1992). A few marine dinocysts were found at Tuapaat Qaqqaat at the top of the Assoq Member just below the basalt conglomerate (Fig. 140).

Fig. 139. Type section of the Assoq Member at Assoq on the south coast of Disko (for location, see Fig. 124). The lacustrine mudstones contain numerous millimetre-thick tuff beds. For legend, see Plate 1.

Depositional environment. At Skarvefjeld (Fig. 2), the lower, shaly part of the Assoq Member is interbedded with hyaloclastite breccias that are traced laterally into the lower Rinks Dal Member (Heinesen 1987; L.M. Larsen & Pedersen 1990). Water depths of 80–100 m are calculated from the height of the foresets of the hyaloclastite breccias. Similar interbedding of Assoq Member mudstones and hyaloclastite breccias is also known from Sorte Hak on central Disko, slightly east of the Disko Gneiss Ridge (Fig. 124). The Assoq Member is interpreted as lacustrine in origin, deposited within the 'Assoq lake'. At present it is not possible to demonstrate whether this was one huge lake or several smaller lakes. Scarce marine dinocysts indicate that the Assoq lake was subject to marine inundations. The dinocysts were found in samples from eastern and south-eastern Disko, but were not recorded from Nuussuaq. This distribution, coupled with a south-eastward tilting of an originally nearly horizontal magmatic boundary (L.M. Larsen & Pedersen 1992) suggests that the marine inundations were from the south. The upward transition from mudstones to sandstones reflects shallowing and gradual fill of the lake. During a break in clastic sediment input, peat accumulated in a large swamp in eastern Disko, and resulted in a thick coal bed (Fig. 141).

Boundaries. The lower boundary of the Assoq Member is placed at the base of the mudstone succession, and is interpreted as a lacustrine drowning surface (Figs 128, 137). On north-east Disko, the lower boundary overlies a coal bed. The upper boundary is placed where the sediments are overlain by subaerial lava flows of the Rinks Dal Member. Note that locally thin tongues of sediment within the lower Rinks Dal Member are assigned to the Assoq Member; such sediment wedges are bounded abruptly beneath and above by volcanic strata. At Tuapaat Qaqqaat, the uppermost bed in the Assoq Member is a conglomerate with clasts of basaltic rocks derived from lava flows of the Akuarut unit of the Rinks Dal Member (Fig. 140; L.M. Larsen & Pedersen 1990, 2009).

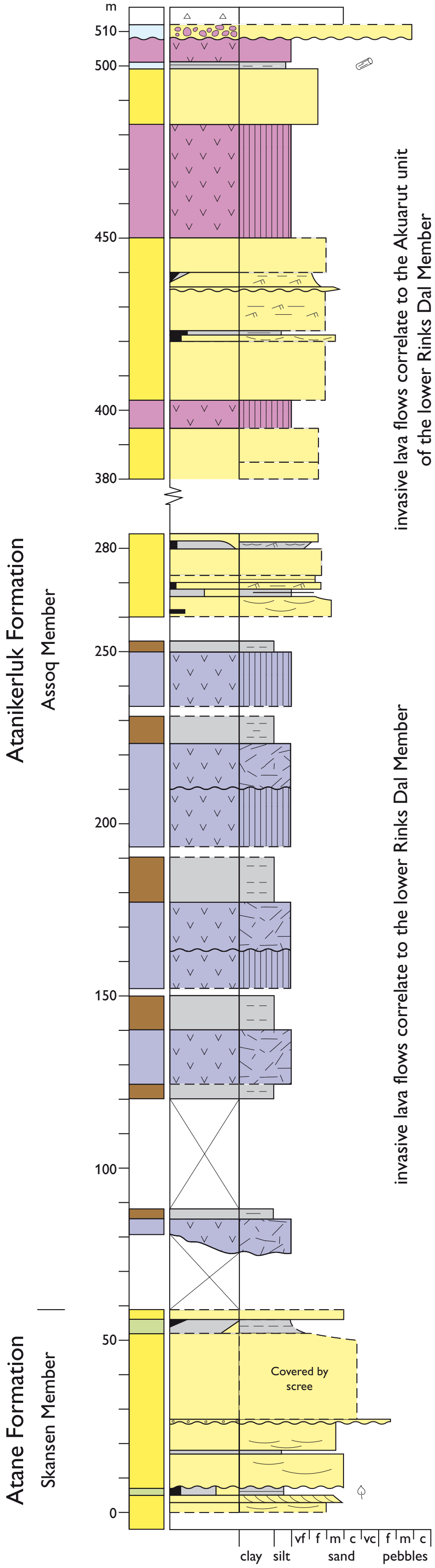


Fig. 140. Composite reference section of the Assoq Member at Tuapaat Qaqqaat, south-eastern Disko (for location, see Fig. 124). Note the occurrence of marine dinocysts at the top of the lacustrine section, indicating a brief marine inundation. Colour coding of volcanic rocks follows Fig. 131. For legend, see Plate 1.

Fig. 141. Upper part of the Assoq Member including a 5.1 m thick coal bed. South side of Blåbærdalen, eastern Disko (for location, see Fig. 124). Correlative coal beds are seen at several widely spaced outcrops indicating the development of large swamps. The sediments are overlain by subaerial lava flows of the volcanic Rinks Dal Member (see Fig. 131).

Geological age. The age of the Assoq Member lies within the age range of the Atanikerluk Formation (i.e. early to mid-Paleocene, see p. 146).

Correlation. On southern Disko, the lower, shaly, part of the Assoq Member is interbedded with subaqueous lava flows and hyaloclastite breccias, which continue westwards into the Skarvefjeld unit (formerly Pahoehoe unit) of the lower Rinks Dal Member (Fig. 131; Heinesen 1987; L.M. Larsen & Pedersen 1990, 2009; A.K. Pedersen *et al*. 2003; L.M. Larsen *et al*. 2006). On north-eastern Disko (Akunneq and Pingu), the earliest volcanic rocks are thick invasive lava flows with columnar jointing, which invaded the uppermost part of the Umiussat Member and the Assoq Member. The composition of these volcanic rocks tie them to the uppermost lower Rinks Dal Member and the Akuarut unit (formerly FeTi unit) (Fig. 131; A.K. Pedersen *et al*. 2005; L.M. Larsen *et al*. 2006; L.M. Larsen & Pedersen 2009).

On Nuussuaq, lava flows of the Akuarut unit invaded mudstones of the Assoq Member and increased markedly in thickness due to ponding of the lavas in the 'Assoq lake'. Throughout eastern Disko and southern Nuussuaq the Assoq Member is thus interbedded with invasive flows of the Rinks Dal Member, and the various volcanic facies (breccias, invasive lavas or ponded subaerial lava flows) are thought to reflect different extrusion rates. In most of its area of distribution, the Assoq Member is overlain by subaerial lava flows of the upper Rinks Dal Member (Fig. 131). It is concluded that the Assoq Member generally correlates with the Rinks Dal Member. On easternmost central Nuussuaq, however, an outcrop of mudstones interbedded with invasive lava flows of the younger Niaqussat Member is also referred to the Assoq Member (A.K. Pedersen *et al*. 2002).

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Appendix: Place names and localities

The place names and localities mentioned in the text are shown on one or more maps. Figure 2 contains many names and indicates the position of more detailed maps where the remaining names are shown. *Names in italics* are names with old spelling. They are located under their modern spelling or indicated on the historical maps (Figs 3, 4). The old forms of the names are typically mentioned under the heading 'History'.

Place name		
A		
Aaffarsuaq	central Nuussuaq	Figs 2, 82
Aamaruutissat (also Skansen)	southern Disko	Fig. 124
Aasiaat	southern Disko Bugt	Figs 2, 10
Agatdalen	central Nuussuaq	Fig. 113
Agatkløft	central Nuussuaq	Fig. 113
Akuliarusinnguaq (Ak)	southern Nuussuaq	Fig. 2
Akunneq	northern Disko	Fig. 124
Alianaatsunnguaq	southern Nuussuaq	Fig. 2
Alianaitsúnguaq (now Alianaatsunnguaq)	southern Nuussuaq	Figs 2, 4
Anariatorfik	western Nuussuaq	Fig. 65
Angiarsuit	northern Nuussuaq	Fig. 22
Angiissat (part of Grønne Ejland)	southern Disko Bugt	Fig. 2
Angnertuneq (now Annertuneq)		
Annertuneq	northern Nuussuaq	Fig. 74
Aqajaruata Qaqqaa	eastern Disko	Fig. 124
Auvfarssuaq (now Aaffarsuaq)		
Assoq	southern Disko	Figs 2, 124
Asuk	northern Disko	Fig. 2
Ata (now Ataa)	southern Nuussuaq	Fig. 4
Atâ (now Ataa)		
Ataa	southern Nuussuaq	Fig. 40
Ataata Kuua	southern Nuussuaq	Figs 6, 40
Atane (now Ataa)	southern Nuussuaq	Fig. 3
Atanekerdluk (now Atanikerluk)	southern Nuussuaq	Fig. 3
Atanikerdluk (now Atanikerluk)	southern Nuussuaq	Fig. 4
Atanikerluk	southern Nuussuaq	Fig. 40
Atâta kûa (now Ataata Kuua)		
B		
Baffin Bay		Fig. 1
Blåbærdalen	southern Disko	Fig. 124
D		
Danienrygge (DR)	northern Nuussuaq	Fig. 74
Daugaard Jensen Dal	central Disko	Fig. 124
Davis Strait		Fig. 1
Disko		Figs 2, 10, 124
Disko Bugt		Figs 2, 10
Disko Gneiss Ridge (DGR)	western Disko	Fig. 10
E		
Ekkorfat (now Ikorfat)	northern Nuussuaq	Fig. 3
Ekorgfat (now Ikorfat)	northern Nuussuaq	Fig. 4
Eqalulik	western Nuussuaq	Fig. 65
Eqip Inaarsuata Qaqqaa (EIQ)	eastern Nuussuaq	Fig. 2
F		
Firefjeld	Svartenhuk Halvø	Fig. 73
FP93-3-1	northern Disko	Fig. 2
FP94-11-02	northern Nuussuaq	Fig. 74
FP94-11-04	northern Nuussuaq	Fig. 74
FP94-11-05	northern Nuussuaq	Fig. 74
FP94-9-01	western Nuussuaq	Fig. 65
Frederik Lange Dal	eastern Disko	Fig. 124
G		
GANE#1	western Nuussuaq	Fig. 65
GANK#1	western Nuussuaq	Fig. 65
GANT#1	northern Nuussuaq	Fig. 74
GANW#1	western Nuussuaq	Fig. 65
GGU 247701	southern Nuussuaq	Fig. 40
GGU 247801	southern Nuussuaq	Fig. 40
GGU 247901	southern Nuussuaq	Fig. 40
GGU 400701	central Nuussuaq	Fig. 113
GGU 400702	central Nuussuaq	Fig. 113
GGU 400703	central Nuussuaq	Fig. 113
GGU 400704	central Nuussuaq	Fig. 113
GGU 400705	northern Nuussuaq	Fig. 74
GGU 400706	northern Nuussuaq	Fig. 74
GGU 400707	northern Nuussuaq	Fig. 74
GGU 400708	Svartenhuk Halvø	Fig. 73
GGU 400709	Svartenhuk Halvø	Fig. 73
GGU 400710	Svartenhuk Halvø	Fig. 73
GGU 400711	Svartenhuk Halvø	Fig. 73
GGU 400712	Svartenhuk Halvø	Fig. 73
Giesecke Monument	southern Nuussuaq	Figs 6, 40

Place name		
GRO#3	western Nuussuaq	Fig. 65
Grønne Ejland	southern Disko Bugt	Figs 2, 10
Gule Ryg	eastern Disko	Fig. 124

I

Igdlokungoak		
(now Illokunnguaq)	northern Disko	Fig. 3
Igdlokunguak		
(now Illokunnguaq)	northern Disko	Fig. 4
Igdlunguaq		
(now Illunnguaq)		
Ikorfat	northern Nuussuaq	Figs 2, 22
Ikorfat fault zone (Ik)	northern Nuussuaq	Fig. 10
Illukunnguaq	northern Disko	Fig. 124
Illunnguaq	southern Disko	Fig. 124
Ilugissoq	central Nuussuaq	Fig. 2
Ilulissat	eastern Disko Bugt	Figs 2, 10
Innanguit	southern Disko	Fig. 124
Inngigissoq	northern Disko	Fig. 124
Innaarsuit (also Skansen)	southern Disko	Fig. 124
Ippigaarsukkløften	southern Nuussuaq	Fig. 40
Itilli	western Nuussuaq	Figs 2, 65
Itivnera	central Nuussuaq	Fig. 82
Itsaku	Svartenhuk Halvø	Fig. 73
Ivissussat	southern Nuussuaq	Fig. 40
Ivissussat Qaqqaat	southern Nuussuaq	Figs 6, 40
Ivisaannguit	southern Nuussuaq	Figs 6, 40
Ivnanguit (now Innanguit)	southern Disko	Fig. 4
J.P.J. Ravn Kløft	northern Nuussuaq	Fig. 22

K

Kaersuarsuk (now Qaarsut)		
Kaersut (now Qaarsut)	northern Nuussuaq	Fig. 4
Kangersooq	central Nuussuaq	Fig. 82
Kangersôq		
(now Kangersooq)		
Kangilia	northern Nuussuaq	Fig. 74
Kardlok		
(now Qallunguaq)	southern Nuussuaq	Fig. 4
Kardlunguaq		
(now Qallunguaq)		
Karsoq (now Qaarsut)		
Killuusat	southern Disko	Fig. 124
Kingigtok		
(now Kingittoq)	southern Nuussuaq	Fig. 4
Kingigtoq (now Kingittoq)		
Kingittoq	southern Nuussuaq	Fig. 40
Kitdlusat (now Killusat)	southern Disko	Fig. 4
Kome (now Kuuk)	northern Nuussuaq	Fig. 3
Kook (now Kuuk)	northern Nuussuaq	Fig. 4
Kook angnertunek		
(now Annertuneq)	northern Nuussuaq	Fig. 4
Kudliset (now Qullissat)	northern Disko	Fig. 3
Kûk (now Kuuk)	northern Nuussuaq	Fig. 21
Kûk quamassoq		
(now Kuuk Qaamasoq)		
Kussinerujuk	northern Disko	Fig. 2
Kugannguaq valley	northern Disko	Fig. 2
Kuugannguaq–Qunnilik Fault		
(KQ)	western Nuussuaq	Fig. 10
Kuuk	northern Nuussuaq	Fig. 21
Kuuk Qaamasoq	southern Disko	Fig. 124
Kuussuaq	central Nuussuaq	Fig. 65
Kvandalen	eastern Disko	Fig. 124

L

Labrador Sea		Fig. 1
Laksedalen	eastern Disko	Fig. 124

M

Majorallattarfik	northern Nuussuaq	Fig. 21
Maligaat	north-west of Disko	Fig. 2
Marraat	southern Disko	Fig. 124
Marraat-1	western Nuussuaq	Fig. 65
Marrait (now Marraat)		
Marrak (now Marraat)	southern Disko	Fig. 4
Melville Bay		Fig. 1

N

Naajaat	southern Nuussuaq	Fig. 40
Naassat	central Nuussuaq	Fig. 2
Nalluarissat	central Nuussuaq	Fig. 82
Naujat (now Naajaat)	southern Nuussuaq	Fig. 4
Naujât (now Naajaat)		
Niakornak		
(now Niaqornat)	northern Nuussuaq	Fig. 3
Niakornat		
(now Niaqornat)	northern Nuussuaq	Fig. 4
Niaqornat	northern Nuussuaq	Fig. 74
Noursoak Halfö		
(now Nuussuaq)		Fig. 3
Nûgârssuk		
(now Nuugaarsuk)		
Nûgssuaq		
(now Nuussuaq)		
Nugsuak		
(now Nuussuaq)		
Nugsuaks-Halvö		
(now Nuussuaq)		Fig. 4
Nuugaarsuk	northern Disko	Fig. 124
Nuuk Killeq	southern Nuussuaq	Fig. 2
Nuuk Qiterleq	southern Nuussuaq	Fig. 2
Nuussuaq		Figs 2, 10
Nuussuaq Basin		Fig. 1

O

Omenak (now Uummannaq)		Fig. 3

Place name		
P		
Paatuut	southern Nuussuaq	Figs 2, 40
Paatuutkløften	southern Nuussuaq	Fig. 40
Patoot (now Paatuut)	southern Nuussuaq	Fig. 4
Pâtût (now Paatuut)		
Pautût (now Paatuut)		
Peak 1010 m	southern Nuussuaq	Figs 6, 40
Pingo (now Pingu)		
Pingu	eastern Disko	Figs 2, 124
Pingunnguup Kuua	western Nuussuaq	Fig. 65
Q		
Qaarsut	northern Nuussuaq	Figs 2, 22
Qaarsutjægerdal	central Nuussuaq	Fig. 113
Qagdlúnguaq (now Qallunnguaq)		
Qallorsuaq (Keglen)	southern Nuussuaq	Fig. 40
Qallunnguaq	southern Nuussuaq	Fig. 40
Qardlok (now Qallunnguaq)		
Qeqertarsuaq (island)		Figs 2, 10, 73
Qeqertarsuaq (town)	southern Disko	Figs 2, 10
Qilakitsoq	central Nuussuaq	Fig. 82
Qorlortorsuaq	northern Disko	Fig. 2
Quikassaap Kuua	southern Nuussuaq	Fig. 40
Quikavsaup kûa (Quikassaap Kuua)		
Qutdligssat (now Qullissat)		
Qullissat	northern Disko	Fig. 2
R		
Ritenbenks Kulbrud (now Qullissat)	northern Disko	Figs 3, 4
S		
Sakkak (now Saqqaq)	southern Nuussuaq	Fig. 3
Sarkak (now Saqqaq)	southern Nuussuaq	Fig. 4
Saqqaq	southern Nuussuaq	Fig. 2
Saqqaqdalen	southern Nuussuaq	Figs 2, 40
Sarfâgfik	northern Nuussuaq	Fig. 21
Sarqaq (now Saqqaq)		
Scaphitesnæsen	central Nuussuaq	Fig. 113
Serfat	northern Nuussuaq	Fig. 74
Sill Sø	central Nuussuaq	Fig. 113
Sinigfik (now Siniffik)	southern Disko	Fig. 4
Sinnifik (now Siniffik)	southern Disko	Fig. 3
Skandsen (now Skansen)		
Skansen	southern Disko	Figs 2, 124
Skarvefjeld	southern Disko	Fig. 2
Slibestensfjeldet	northern Nuussuaq	Fig. 22
Sorte Hak	central Disko	Figs 2, 124
Stordal	central Disko	Fig. 2
Svartenhuk Halvø		Figs 2, 10, 73

Place name		
T		
Talerua	northern Nuussuaq	Fig. 22
Tartunaq	southern Nuussuaq	Fig. 40
Teltbæk fault	central Nuussuaq	Fig. 113
Tuapassuit	northern Nuussuaq	Fig. 21
Tuapaat	southern Disko	Fig. 124
Tuapaat Qaqqaat	southern Disko	Fig. 124
Tunoqqu	central Nuussuaq	Fig. 82
Tunorqo (now Tunoqqu)		
Tunorsuaq	northern Nuussuaq	Fig. 74
Tupaasat	southern Nuussuaq	Figs 2, 6
Turritellakløft	central Nuussuaq	Fig. 113
U		
Ujaragsugsuk (now Ujarassussuk)	northern Disko	Fig. 4
Ujarattoorsuaq	northern Nuussuaq	Fig. 22
Ujarasusuk (now Ujarassussuk)	northern Disko	Fig. 3
Ujarasussuk	northern Disko	Fig. 124
Ukalersalik	western Nuussuaq	Fig. 65
Umanak (now Uummannaq)		Fig. 4
Umiivik-1	Svartenhuk Halvø	Fig. 73
Umiiviup Kangerlua	Svartenhuk Halvø	Fig. 73
Umiussat (now Umiusat)		
Umiusat	southern Nuussuaq	Fig. 40
Upernivik Næs		Fig. 33
Upernivik Ø		Figs 2, 10
Uppalluk, Giesecke Monument	southern Nuussuaq	Figs 6, 40
Uummannaq		Figs 2, 10
Uummannaq Fjord		Fig. 10
V		
Vaigat		Figs 2, 10
Vesterfjeld	northern Nuussuaq	Fig. 22