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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.

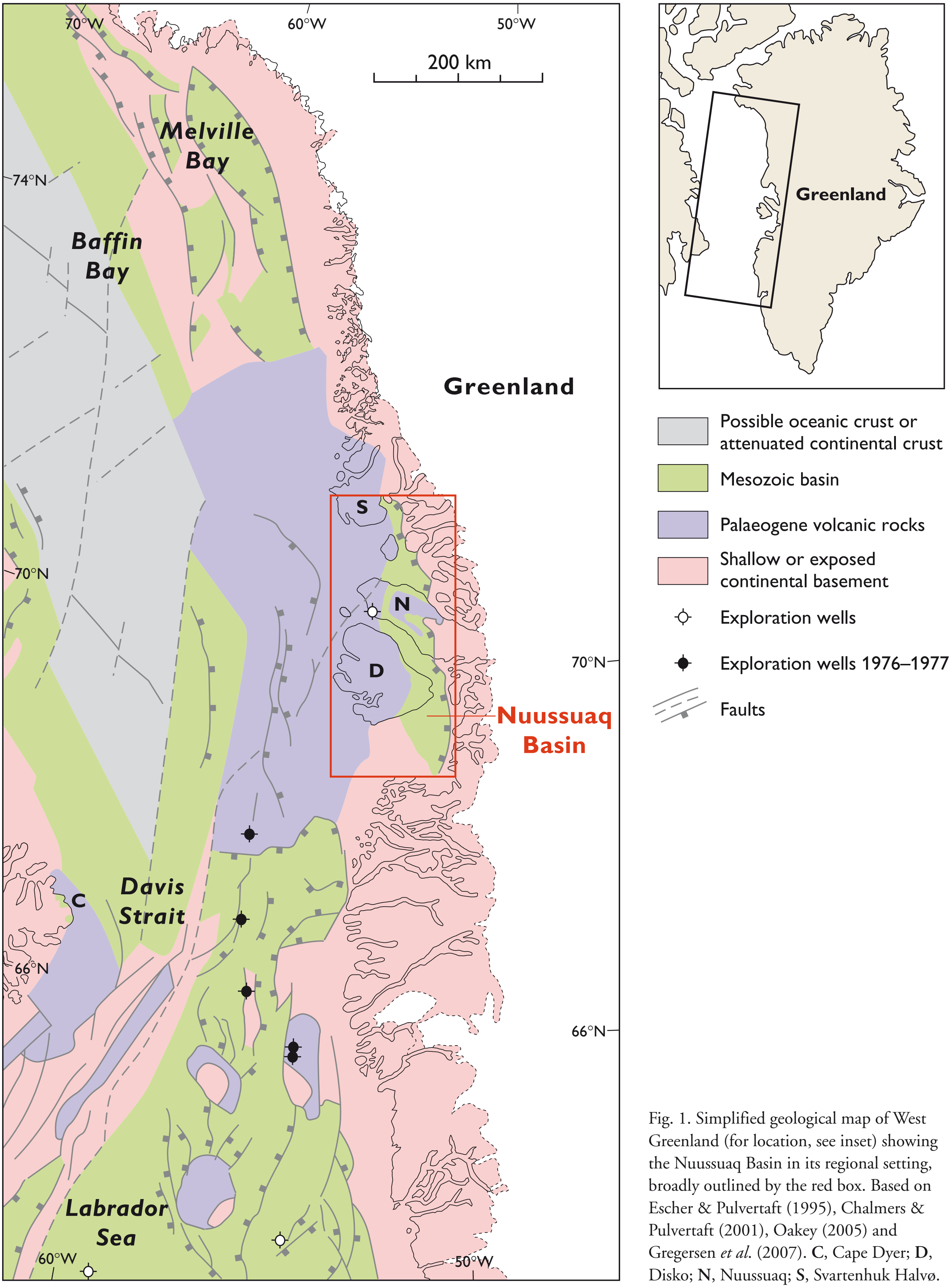


Fig. 1. Simplified geological map of West Greenland (for location, see inset) showing the Nuussuaq Basin in its regional setting, broadly outlined by the red box. Based on Escher & Pulvertaft (1995), Chalmers & Pulvertaft (2001), Oakey (2005) and Gregersen *et al.* (2007). **C**, Cape Dyer; **D**, Disko;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

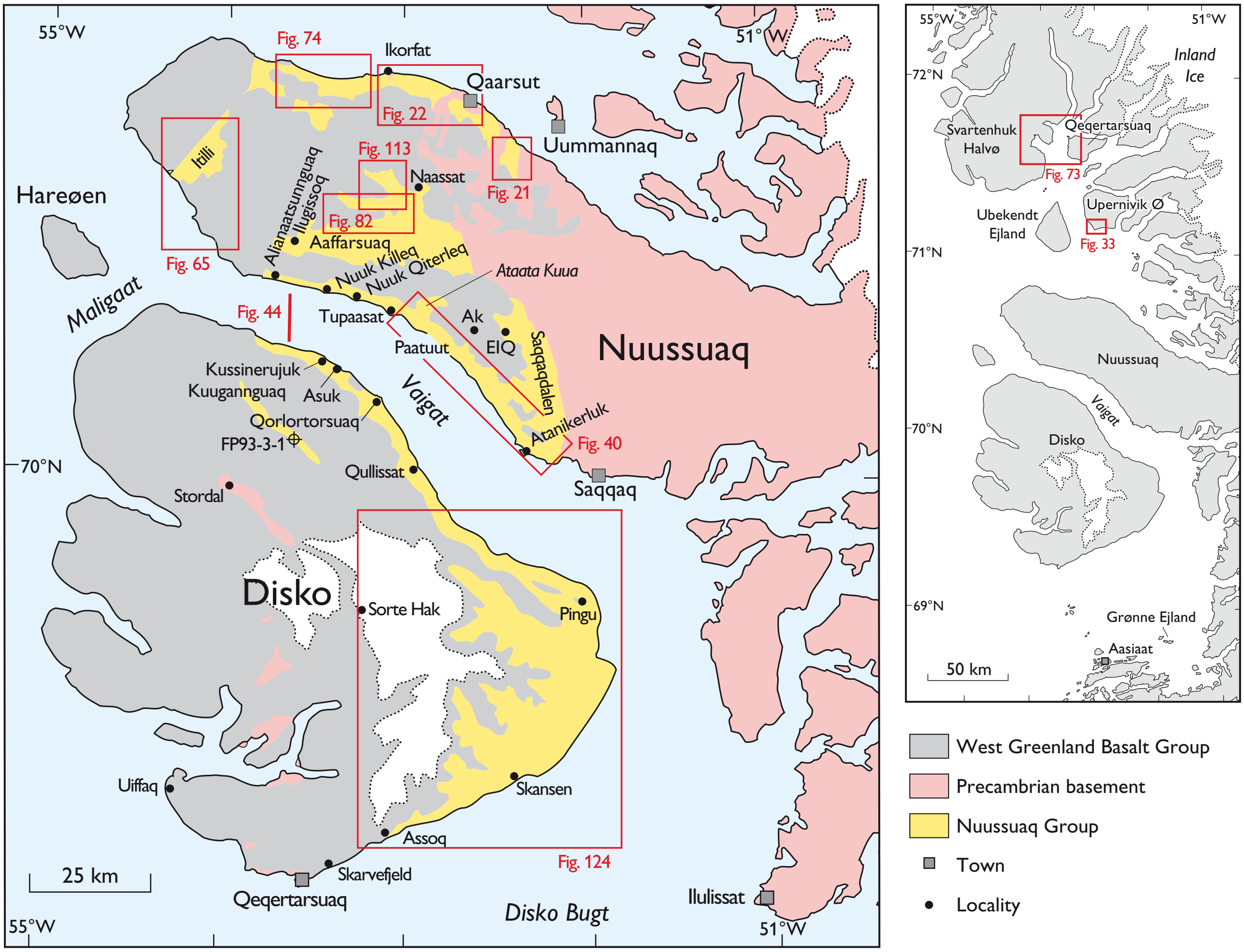


Fig. 2. Map of Disko and Nuussuaq showing the main localities and place names used in this paper. Frames and figure numbers indicate coverage of detailed maps and a seismic section. The pre-Quaternary geology is simplified from Escher (1971). The detailed maps of Upernivik Næs (Fig. 33) and Svartenhuk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

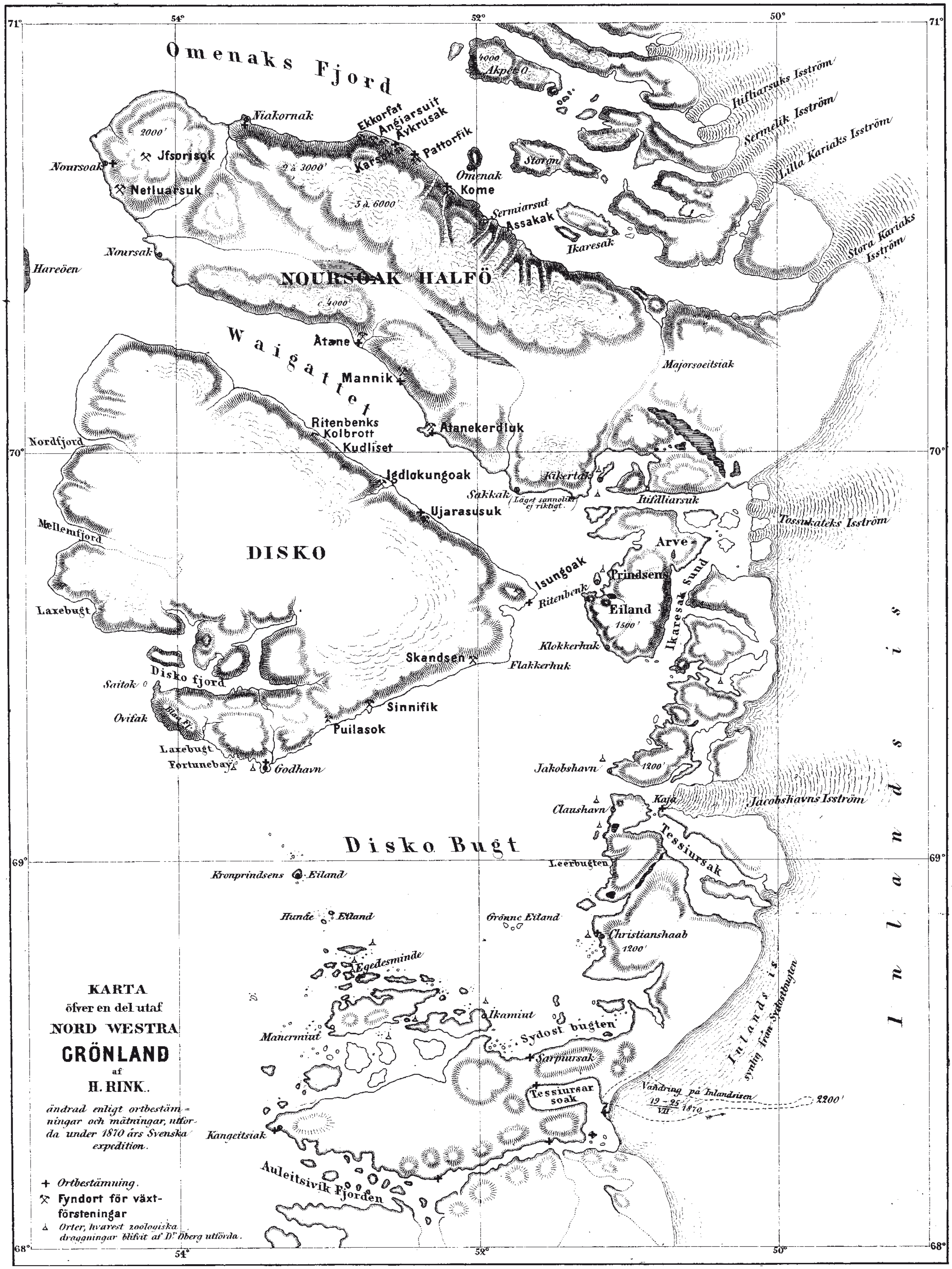


Fig. 3. Topographical map by Rink (1857) reproduced by Nordenskiöld (1871), showing the location of Kome, Atane and other named features given lithostratigraphic significance by Nordenskiöld.

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).

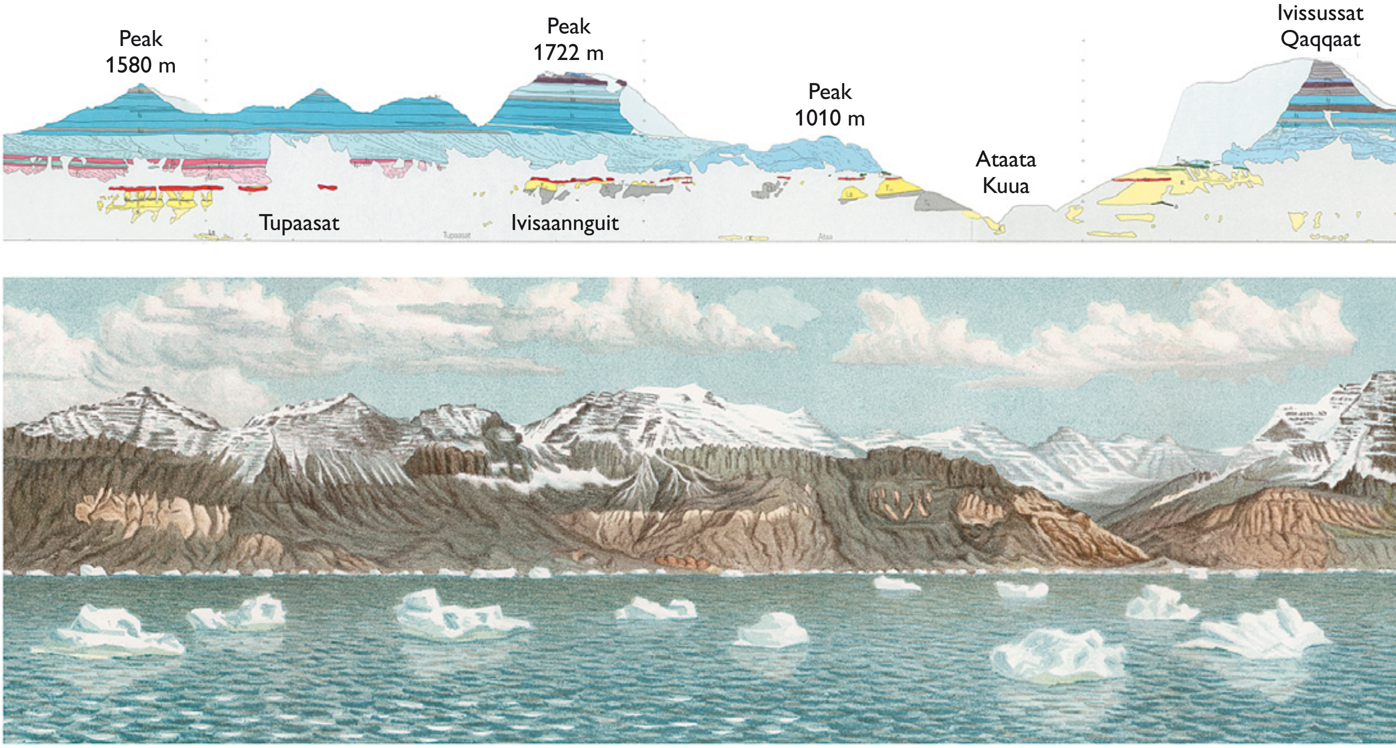


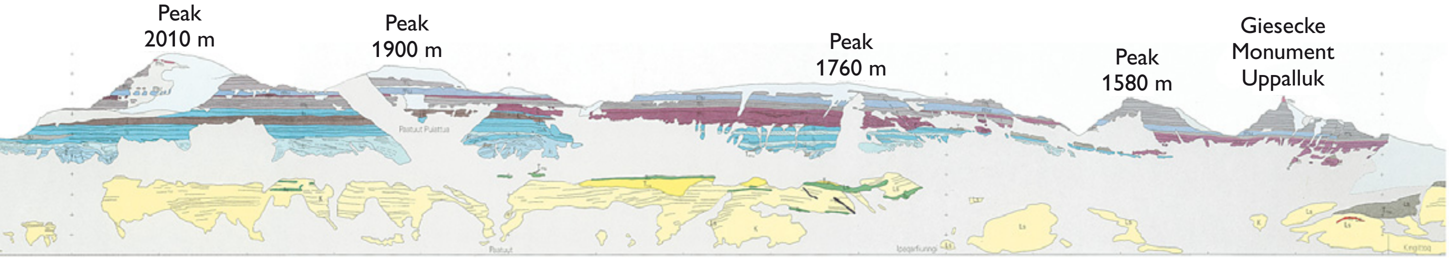
Fig. 6. The south coast of Nuussuaq around the Ataata Kuua river delta (the large valley in the centre of the profile) which is the type area of the Nuussuaq Group. **Upper panel**: Part of modern section measured by multimodel photogrammetry using oblique aerial photographs (from A.K. Pedersen *et al.* 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).

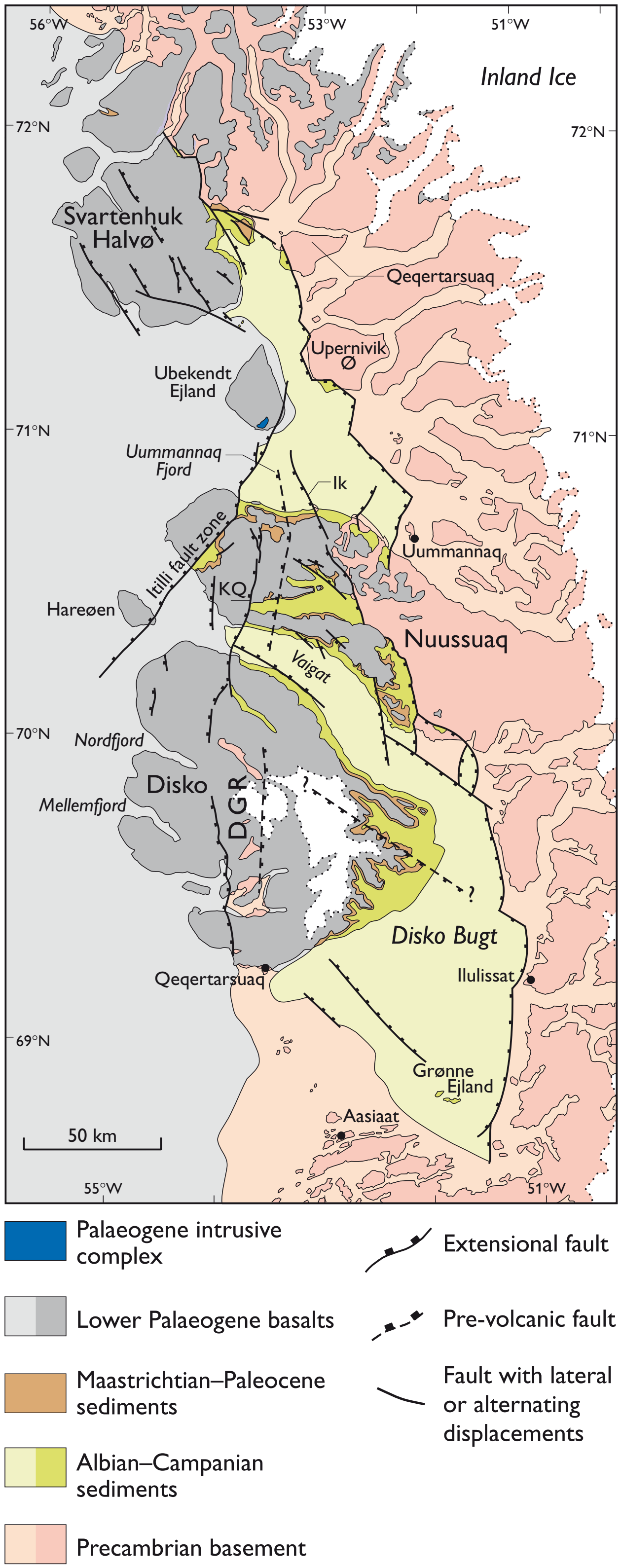
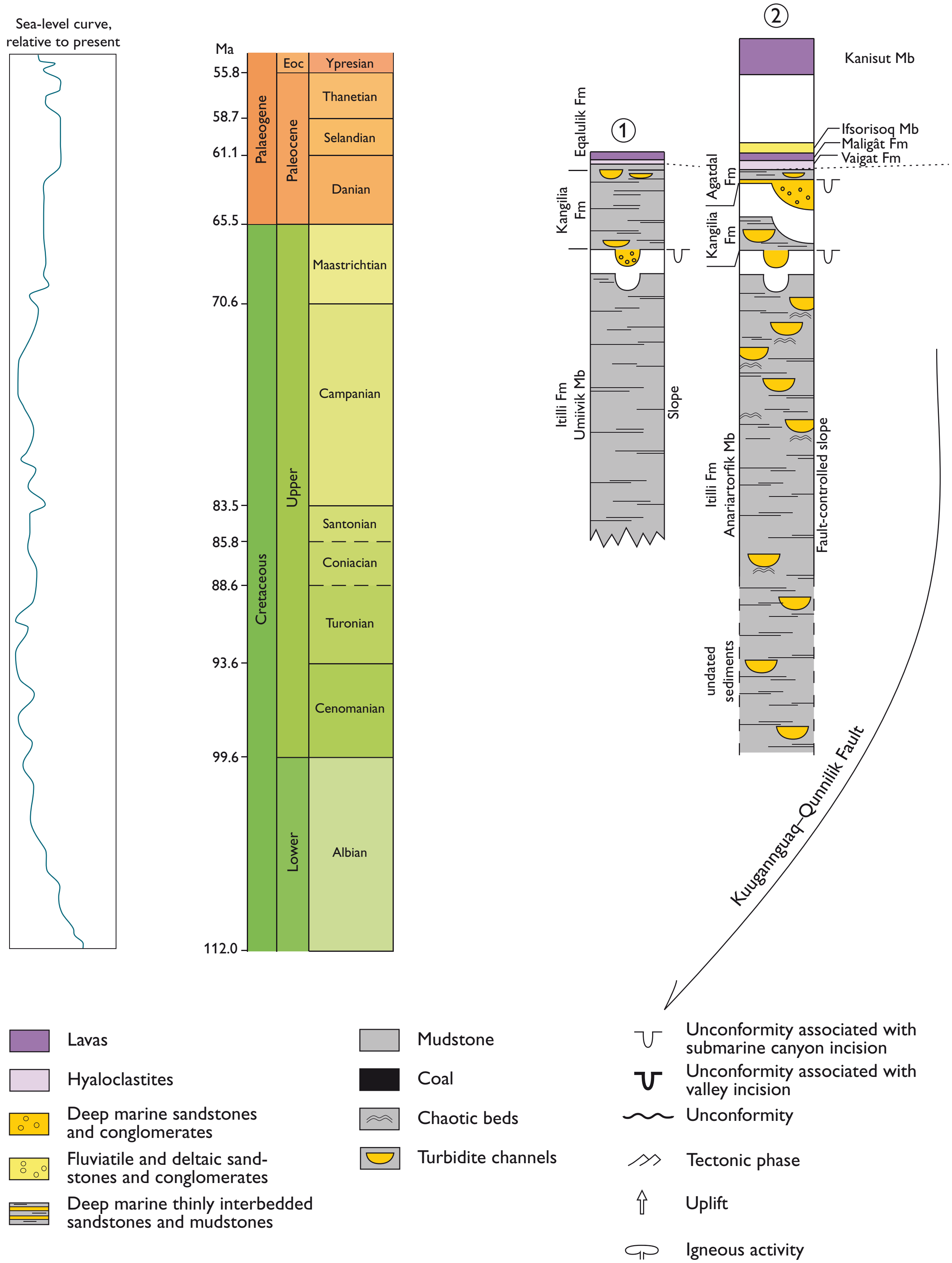
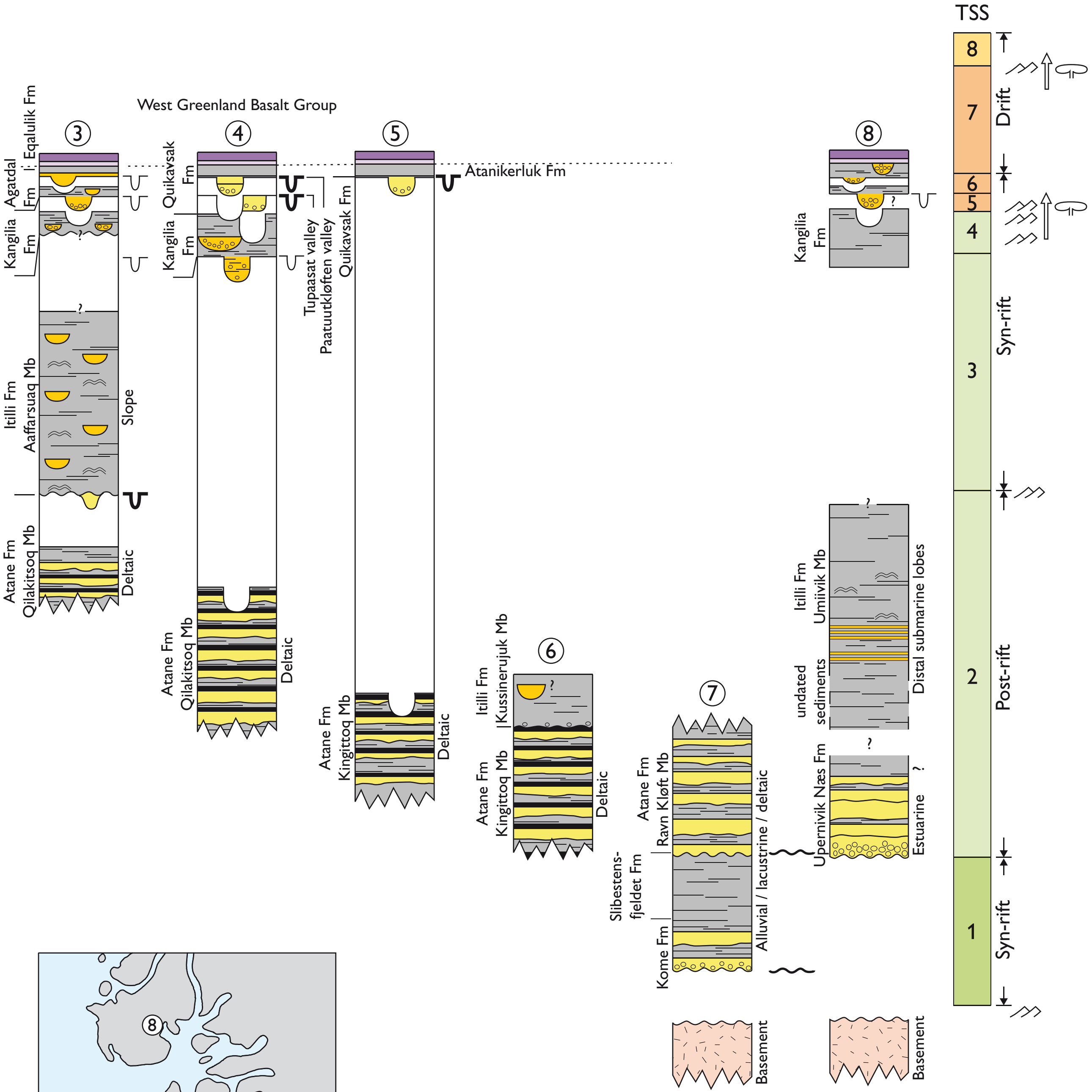


Fig. 10. Simplified geological map of the Nuussuaq Basin (after Chalmers *et al.* 1999). **Ik**, Ikorfat fault zone; **KQ**, Kuugannguaq–Qunnilik Fault; **DGR**, Disko Gneiss Ridge. The offshore geology is indicated by paler shades.



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 sand-stones 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



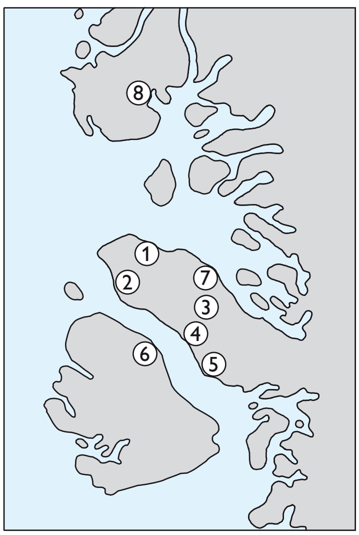


Fig. 11. Tectonic events and regional depositional units, based on Dam & Nøhr-Hansen (2001). **TSS**, tectonostratigraphic sequences; **Eoc**, Eocene. **1**: GANT#1 well; **2**: GRO#3 well and Itilli valley area; **3**: Agatdalen; **4**: Ataata Kuua and Paatuut; **5**: Atanikerluk; **6**: Kussinerujuk; 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).

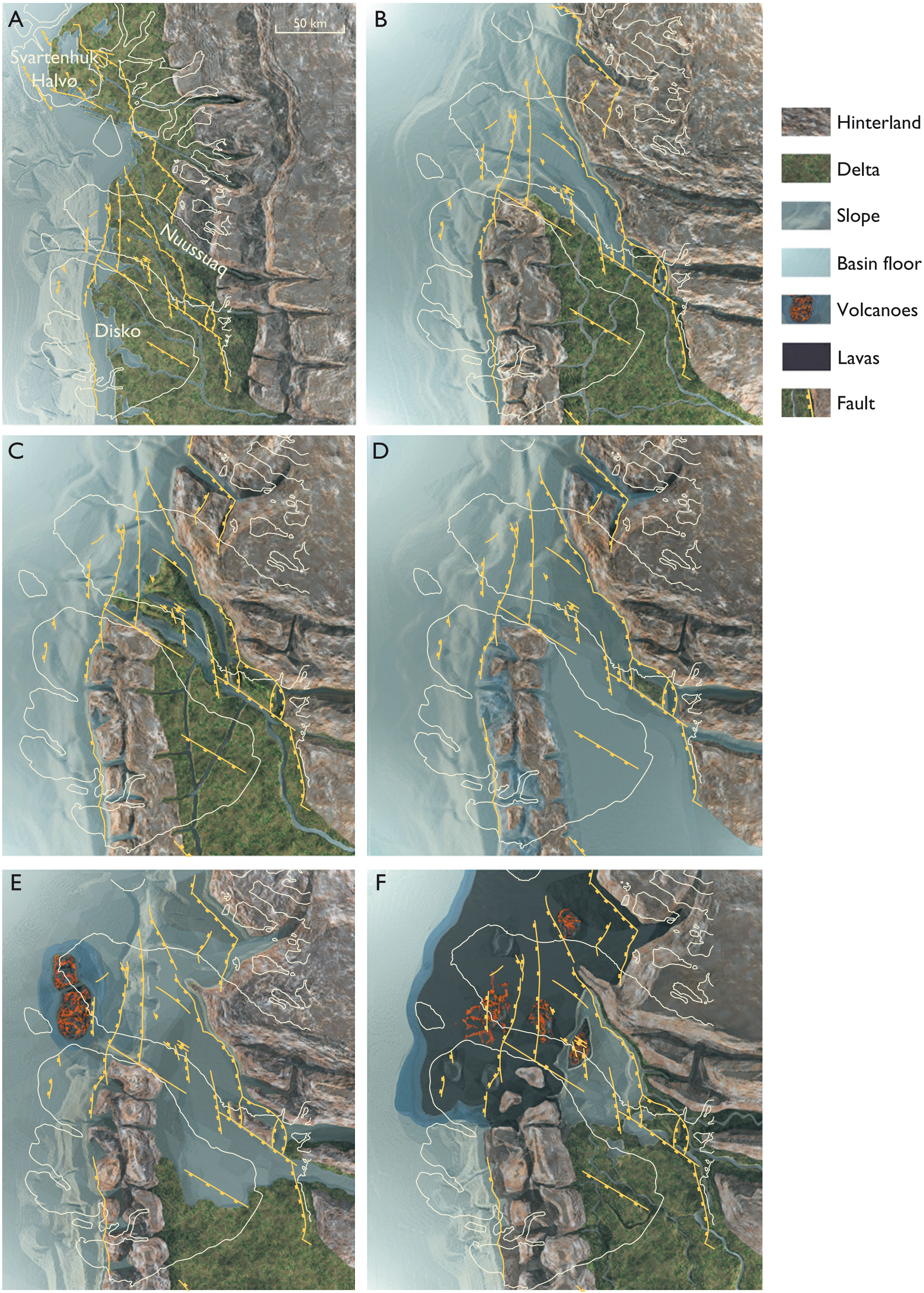
The exposed part of the succession in the Nuussuaq Basin can be divided into eight tectonostratigraphic sequences (TSS; Fig. 11); the early rift episode includes two sequences and the late episode six sequences. These sequences are mainly related to tectonic events marking discrete basin-fill phases (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
50 km
Svartenhuk
Halvø
Nuussuaq
Disko
B
C
D
E
F
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).