DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2005/62

Stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussuaq Basin. Volcanic basins of the North Atlantic

Final report for the Sindri Group
September 2005

Larsen, M. & Nøhr-Hansen, H. (GEUS)
Whitham, A.G. & Kelly, S.R.A. (CASP)

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MINISTRY OF THE ENVIRONMENT

G E U S

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Contents

Preface

This report forms the final deliverable of the research project: “Stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussuaq Basin - Volcanic basin of the North Atlantic” jointly conducted by the Geological Survey of Denmark and Greenland (GEUS) and CASP (Formerly Cambridge Arctic Shelf Programme). A concise review of the most important findings is given in Larsen *et al.* (2005). The project was initiated in October 2002 and concluded in September 2005. It forms part of the SINDRI programme: “Future Exploration Issues Programme of the Faroese Continental Shelf” (briefly referred to at the SINDRI programme) established by the Faroese Ministry of Petroleum and financed by the partners of the Sindri Group.

The current licensees of the Sindri Group are: Agip Denmark BV, Amerada Hess (Faroes) Ltd., Anadarko Faroes Company, P/F Atlantic Petroleum, BP Amoco Exploration Faroes Ltd., British Gas International BV, DONG Føroyar P/F, Enterprise Oil Exploration Ltd., Føroya Kolvetni P/F, Petro-Canada Faroes GmbH, Phillips Petroleum Europe Exploration Ltd., Shell (UK) Ltd., and Statoil Færøyene AS.

Abstract

The Kangerlussuaq Basin in southern East Greenland exposes an approximately 1 km thick sedimentary succession below the Paleogene flood basalts. The sediments are of Late Barremian to Early Eocene age and were deposited at the western margin of the sea-way between Greenland and the UK. The depositional environments comprise: lacustrine fluvial, deltaic, estuarine, shallow marine, outer shelf, slope and deep basin.

The sediments are formally assigned to the Kangerdlugssuaq (Barremian–Paleocene) and the Blosseville Group (Paleocene–Eocene). Based on recent sedimentological, biostratigraphic and sequence stratigraphic studies a new lithostratigraphic scheme is established. The Kangerdlugssuaq Group is thus divided into the following formations: Watkins Fjord (new), Sorgenfri (redefined), Christian IV (new) and Sediment Bjerge (new) whereas the lower part of the Blosseville Group; the Vandfaldsdalen Formation is redefined. Six new members are defined within the succession.

The succession records a long history of basin evolution starting with marine transgression in the latest Barremian, shallow marine deposition during the Cretaceous, rifting and deep marine deposition in the latest Cretaceous to early Paleocene, rapid uplift and fluvial erosion in the Late Paleocene and onset of volcanism in the latest Paleocene to Early Eocene.

A rich Cretaceous macro-fauna is described and comprises Campanian–Maastrichtian species not previously described from East Greenland. The macro-fauna is correlated with palynological assemblages to form a robust biostratigraphic frame for the North Atlantic region.

With a pre-drift position only 100–150 km northwest of the present day Faroe Islands the Kangerlussuaq Basin probably forms the most important analogue for understanding the offshore sub-basaltic basins. Major unconformities in the Santonian–Early Campanian, Late Maastrichtian–Early Paleocene and mid-Paleocene may thus indicate periods of possible sediment input from the west to the Faroe-Shetland region. Studies of potential source rocks, sediment provenance and basin uplift may further improve the understanding of volcanic basin of the North Atlantic ocean and may eventually lower the risk on existing plays or lead to development of new play types for oil exploration in this frontier region.

Introduction

The magmatic influence on sedimentation and basin evolution that can be studied in the Kangerlussuaq Basin has gained renewed interest with the licensing rounds in the Faroe Islands (2000, 2005). Not only does the Faroes frontier area provide new opportunities, but it is also a high-risk area with poorly known plays and sedimentary basins in part covered by basalts. In order to minimise risk it is fundamental to achieve as much information on the evolution of sedimentary basins on the rifted volcanic margins. Plate reconstructions of the North Atlantic region indicate the former proximity of Greenland to the Faroe Islands region (Fig. 1) and the Kangerlussuaq Basin probably constitutes the most important field analogue with regards to stratigraphy, major unconformities and basin evolution. The study of the sedimentary succession in Kangerlussuaq may thus help to constrain the source rock and reservoir sand distribution and eventually lead to development of new play types in this frontier region.

Field work by the Geological Survey of Denmark and Greenland (GEUS) in the Kangerlussuaq region indicated the presence about 700 m of Cretaceous and Paleogene strata beneath the plateau basalts with important developments of sandstone units (Larsen *et al*. 1999a; Larsen *et al*. 1999b; Larsen *et al*. 1996). Field work by CASP (formerly the Cambridge Arctic Shelf Programme, but now known only by its acronym) on the Cretaceous succession has indicated the presence of sequence boundaries in the Upper Cretaceous succession and also between the Cretaceous and Paleogene successions (Jolley & Whitham 2004a; Whitham *et al.* 2004), which may have important bearings on the supply of sandstone to the adjacent region. The potential for cross rift supply of sediments were further stressed by studies of tectonic lineaments showing that a major sandstone input point may have existed in Kangerlussuaq in the Early Paleocene (Larsen & Whitham 2005). The cross rift supply of sands came to an end with the period of rifting, which preceded continental separation and flood basalt extrusion some time between the mid-Maastrichtian and earliest Eocene (Jolley & Whitham 2004a). This rift event and the later extrusion of flood basalts created a barrier between Greenland and Cretaceous basins along the NW-European margin. Both events are critical in determining the potential for Greenland-derived, Upper Cretaceous and Paleocene reservoir development in the adjacent basin.

This study is focused on stratigraphy and sedimentology of the pre-basaltic succession of the Kangerlussuaq basin. It presents a new lithostratigraphic frame based on detailed observations and tied to the existing biostratigraphic charts (macrofossils and palynological) of the North Atlantic, northern Europe and West Greenland. The interpretation of the depositional systems and the identification of unconformity bounded units forms the basis for unravelling the basin evolution, tectonic events and developing a sequence stratigraphic model for the region. Finally the Kangerlussuaq succession is compared with the volcanic basins of the Faroes and West of Shetland and the implications for petroleum exploration (source and reservoir rocks) are discussed.

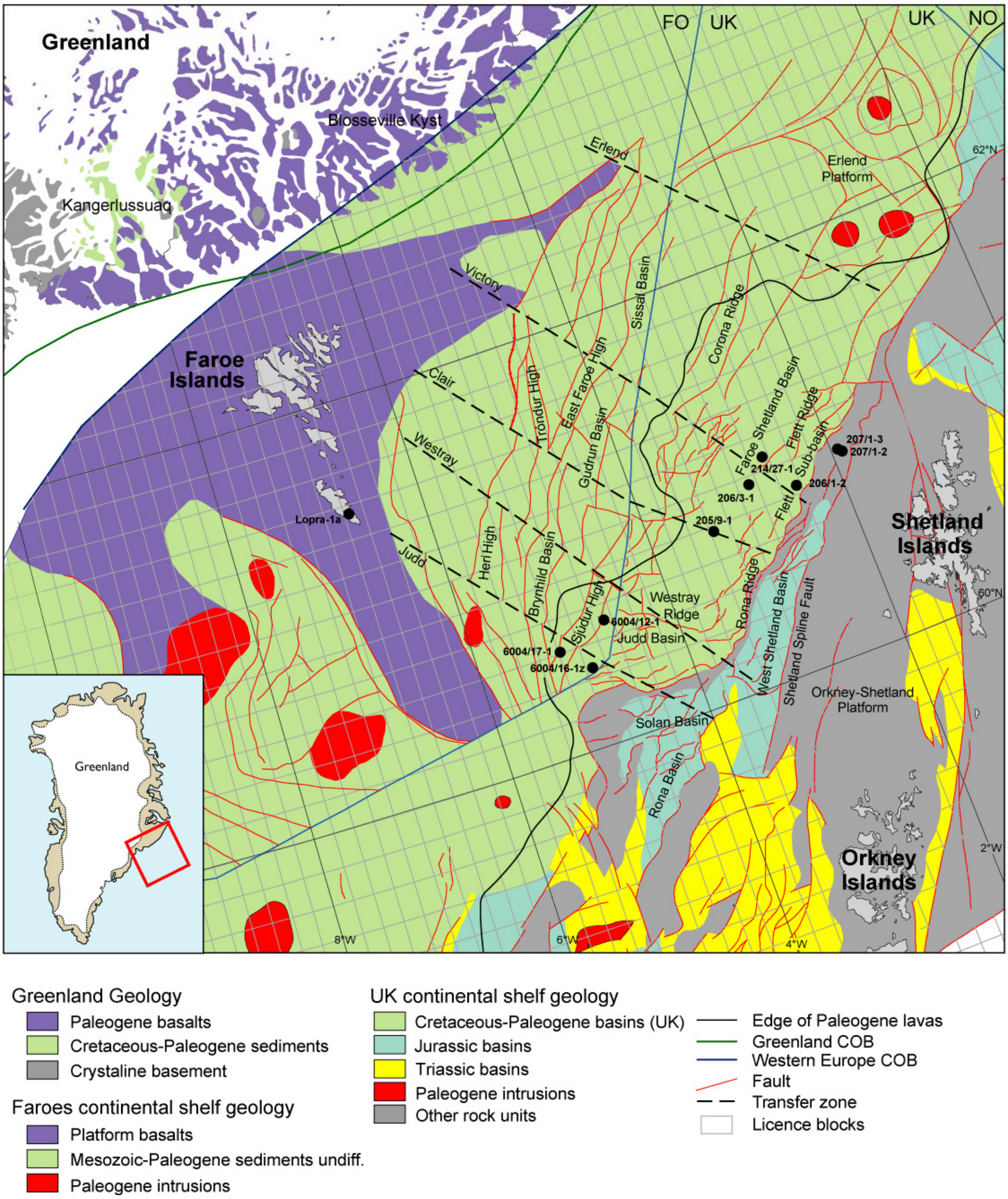

Figure 1. *Location map of East Greenland and the Faroe-Shetland region showing on- and offshore geology, main structural elements, transfer zones and wells used in the correlation chapter. Note that the position of Greenland relative to the Faroe-Shetland region is shown prior to Paleogene sea-floor spreading. Greenland geology from Escher & Pulvertaft (1995); Faroe geology from Keser Neish (2003); UK geology courtesy of Robert Hooper (Conoco Phillips).*

Previous investigations

The harsh coastline of the Blosseville Kyst and the heavily glaciated terrain contributed to the initial geological neglect of the Kangerlussuaq region (Fig. 2), while more readily accessible and less glacially active areas north from Scoresby Sund (Kangertittivaq) were being actively investigated in the late nineteenth century. It was not until the Carlsberg Foundation Expedition to East Greenland in 1898–1900, under G. Amdrup (MOG vols 27–30) that the first geological observations were made on the Blosseville Kyst.

The sedimentary rocks of the Kangerlussuaq Basin were not discovered until visited by L.R. Wager (1934), then of Reading University, during the British Arctic Air-Route Expedition of 1930–31, under the leadership of H. Gino Watkins. Wager revisited the area with the Scoresby Sound Committee's 2nd East Greenland Expedition to King Christian IX Land, under Captain Ejnar Mikkelsen, in 1932. Although Wager's main interest in the area was the layered intrusion of the Skaergaard (Wager & Deer 1939), he (Wager 1934) provided the first description of the pre-basaltic Kangerdlugsuak Series from just north of Miki Fjord (Fig. 2). He identified a succession of about 75 m of sandstone-dominated sedimentary rocks, with concretions, sandy shales, mudflakes and conglomerates. The series was recognised as resting unconformably on the metamorphic complex and was overlain by plateau basalts. Biologists of the 1932 expedition found the first fossil, stated to be a pectinid bivalve. Initially dating was a problem, and Wager (1934) believed that the sediments were 'slightly older than the Eocene rocks of Kap Dalton'.

Wager then lead his own expedition, the British East Greenland Expedition of 1935–36 (Wager & Deer 1939). He identified sediments to the north and east of the Skaergard intrusion, recognising in Vandfaldsdalen over 180 m of ferruginous sandstone, cross-bedded often calcareous sandstones, sandy shales and conglomerate. Although the base was not seen the succession was seen to be overlain by plateau basalts (Fig. 3).

During sledging trips deeper inland, belemnites were collected from what is now known to be Sortekap Passet, and a suite of plant fossils obtained from a further inland. The belemnites were initially identified by Swinnerton (in Wager & Deer 1939) as of 'Senonian' age, which was the first recognition of Cretaceous sediments in the area. Swinnerton (1943) described the belemnites in more detail and confirmed his earlier belief of a Senonian age. The plant macrofossils were initially believed to be of Late Cretaceous to Early Eocene age, but were later described by Seward & Edwards (1941), who concluded an Early Eocene age.

Wager (1947) expanded his description of the succession and provided a geological map to show that the distribution of sedimentary rocks, of what he then called the Kangerdlugssuaq Sedimentary Series, stretched from the Skaergard east to Ryberg Fjord. He identified further sites at Pyramiden, Sortekap Passet, Narren, Trillingerne, Sediment Bjerge [originally termed the Sedimentary mountains and renamed here; located between the Sorgenfri and Christian IV glaciers], to the north of Kulhøje, and east to Korridoren. Brooks (1985) reviewed Wager's work in East Greenland in considerable detail.

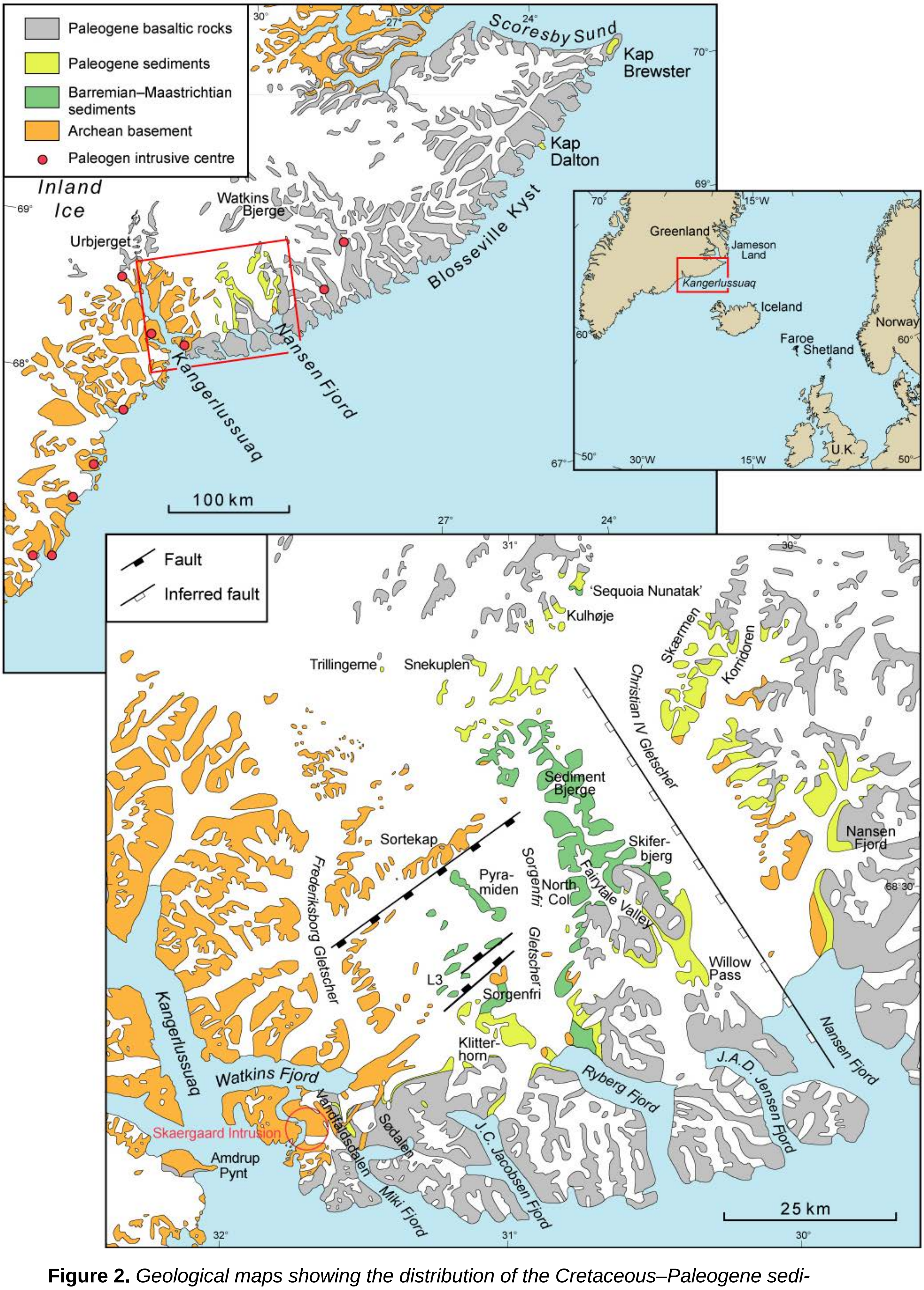

Figure 2. *Geological maps showing the distribution of the Cretaceous–Paleogene sediments and the Paleogene flood basalts of the southern East Greenland volcanic province.*

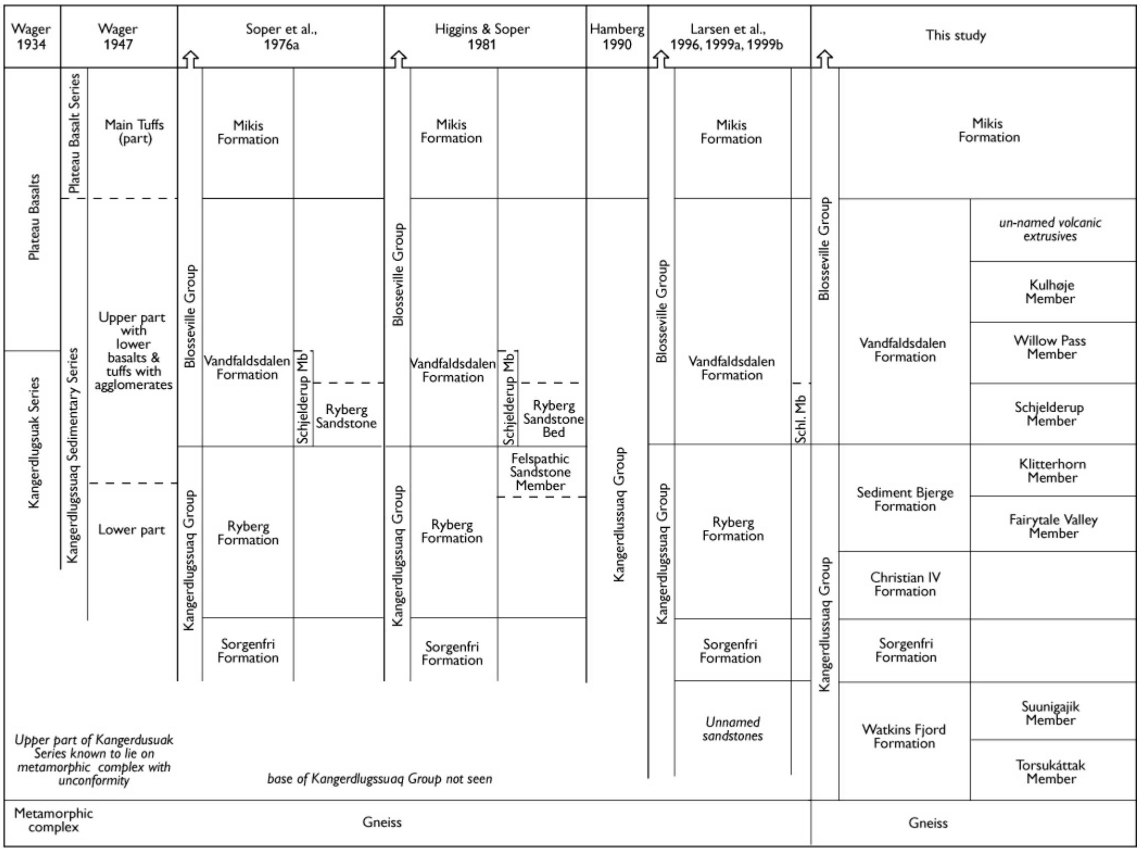

Figure 3. *Generalised history of the stratigraphic nomenclature for the pre-basaltic sedimentary succession in Kangerlussuaq*

Interest in the opening of the North Atlantic Ocean induced P.E. Brown to lead the British Universities East Greenland Expedition of 1974 to the southern part of the Kangerlussuaq Basin. Jack Soper, of the University of Sheffield, co-ordinated studies on the lower part of the basaltic succession and the underlying sediments to obtain a date on the onset of volcanism. The pre-basaltic Kangerdlugssuaq Group sediments were lithologically divided into the Sorgenfri and Ryberg formations by Soper *et al.* (1976a) (Fig. 3).

Above the Kangerdlugssuaq Group, the Blosseville Group was established (Fig. 3). It consisted of mixed sedimentary and volcaniclastic rocks at the base followed by hyaloclastic breccias and basalt flows above. The basal sediments to the "Lower Basalts" were placed in the Vandfaldsdalen Formation, the lower part of which was placed in the Schjelderup Member. The base of the Schjelderup Member was marked by a conspicuous sandstone unit with the confusing name of the Ryberg Sandstone Bed (i.e. not related to the Ryberg Formation) (Fig. 3). Both macrofauna and microbiota were collected and cited mainly from the Kangerdlugssuaq Group. Ammonites, identified by Jake Hancock of London University, indicated the presence of Cenomanian and Maastrichtian sediments and dinoflagellate cysts, identified by Charles Downie (Sheffield University), showed the presence of the Late Albian, Cenomanian–Senonian, Early Maastrichtian, Danian (Early Paleocene) and Early Sparnacian (Early Eocene) stages. The onset of volcanism was believed to be no older than 52 or 55 Ma.

Soper *et al*. (1976b) gave more biostratigraphic data on the dating of the basalts. Following NERC (Natural Environmental Research Council, U.K.) sponsored field work in 1977, Higgins & Soper (1981) recognised uplift in the Late Paleocene, before the onset of volcanism, and attempted a delimitation of the distribution of Cretaceous and Lower Paleocene deposits, and coals and non-marine sediments of the Miki Formation. They recognised a new unit, Feldspathic Sandstone Member, in the upper part of the Ryberg Formation (Fig. 3).

C. Kent Brooks, of the University of Copenhagen, co-ordinated much work on the Kangerdlugssuaq Project from 1972, with substantial funding from the Danish Natural Science Foundation and from the Carlsberg Foundation. He examined processes at the rifted continental margin which culminated in three significant volumes of conference papers (Brooks 1990; Brooks & Stærmose 1991; Brooks *et al*. 1992) and a massive bibliography (Brooks 1994), much of which is related to the intruded and extruded rocks, but which includes some data on the pre-basaltic sedimentary succession and earliest volcanogenic sediments (Hamberg 1990). Hamberg included all of the pre-basaltic sediments, i.e. including all of the Vandfaldsdalen Formation, within the Kangerdlugssuaq Group (Fig. 3).
Nielsen *et al*. (1981) prepared a detailed geological map at 1:40,000 of the well exposed SW inliers of the Kangerlussuaq Basin covering the Vandfaldsdalen, Sødalen and I.C. Jacobsen Fjord areas, providing a detailed sedimentary section through the last mentioned site. They recognised the diachronous nature of the unconformity at the base of the pre-basaltic sedimentary succession, which they believed was only about 300 m in thickness.

Nørgaard-Pedersen (1991, 1992) made sedimentological contributions at Sequoia Nunatak describing delta sequences in the Paleocene. He also recognised the furthermost inland and northernmost marine Cretaceous rocks of the basin on the presence of scaphitid ammonites (Nørgaard-Pedersen 1991). Hoch (1983, 1990, 1991) and Hoch and Hamberg (1989) gave some general accounts of the palaeontology of the Pyramiden and Fairytale Valley areas, recognising the presence of Albian/Cenomanian, Turonian and Paleocene biotas. Christensen & Hoch (1983) described Middle Turonian belemnites and Hoch (1992) postulated predation by fish on inoceramid bivalve beds in the Turonian of Pyramiden.

The growing interest in the NW European Atlantic Margin as a potential hydrocarbon province generated interest in the Kangerlussuaq area because of its proximity to the former position of the Faroe-Shetland Basin. It greatest value is that it is one of the few areas on the Atlantic margin of Greenland where Upper Cretaceous strata are exposed. It is the only site in the whole northern North Atlantic where Maastrichtian rocks are exposed and is probably the best site for Upper Cretaceous studies. The present study commenced with M. Larsen who visited Kangerlussuaq in 1995 and 2000 with GEUS and the Danish Lithosphere Centre (DLC) making detailed sedimentological studies including sequence stratigraphy and basin evolution (Larsen *et al*. 1996). The analysis of the basin succession provided outcrop analogues to the deep-water offshore areas of the North Atlantic (Larsen *et al.* 1999a, 1999b). Larsen was able to revisit the southern part of the area with geologists from Norsk Hydro in 2000 in connection with a major project supported by the Danish Natural Science Research Council and the Bureau of Minerals and Petroleum in Nuuk. This project concentrated on the Paleocene succession on the East Greenland continental margin and its relationship to plume-related continental break-up (Nielsen *et al*. 2001; Larsen *et al*. 2001; Ukstins *et al.* 2003).

CASP first visited the Kangerlussuaq with a reconnaissance party in Sødalen in the late summer of 1997, supported by a consortium of oil companies. Extensive spring fieldwork across the whole basin followed from 1998–2001, collecting sandstones for provenance and reservoir studies and mudrocks and macrofossils for biostratigraphy. CASP studies resulted in a number of unpublished reports and recently publications on the age of the sub-basaltic succession (Jolley & Whitham 2004a) and provenance of sandstone units (Whitham *et al.* 2004) have been published. As part of this Sindri project GEUS and CASP agreed to pool their data collected on the Kangerlussuaq Basin. This makes much information available, which had been the basis for a number of hitherto unpublished CASP reports.

Myers *et al*. (1985) provide the only geological map which covers the whole Kangerlussuaq Basin at a small scale of 1:500,000. This map was based in part on the map at the same scale by Wager and Deer (in Wager 1947, plate 6). This scale did not allow for the differentiation of Cretaceous and Paleocene strata. The only detailed geological map available is of the southern part of the Kangerlussuaq area at a scale of 1:40,000 by Nielsen *et al.* (1981). A new geological map is being created in this project and uses the advantages of Geographical Information Systems (GIS) (Fig. 4). The Department of Mapping in GEUS created the topographic base for the map from aerial photographs.

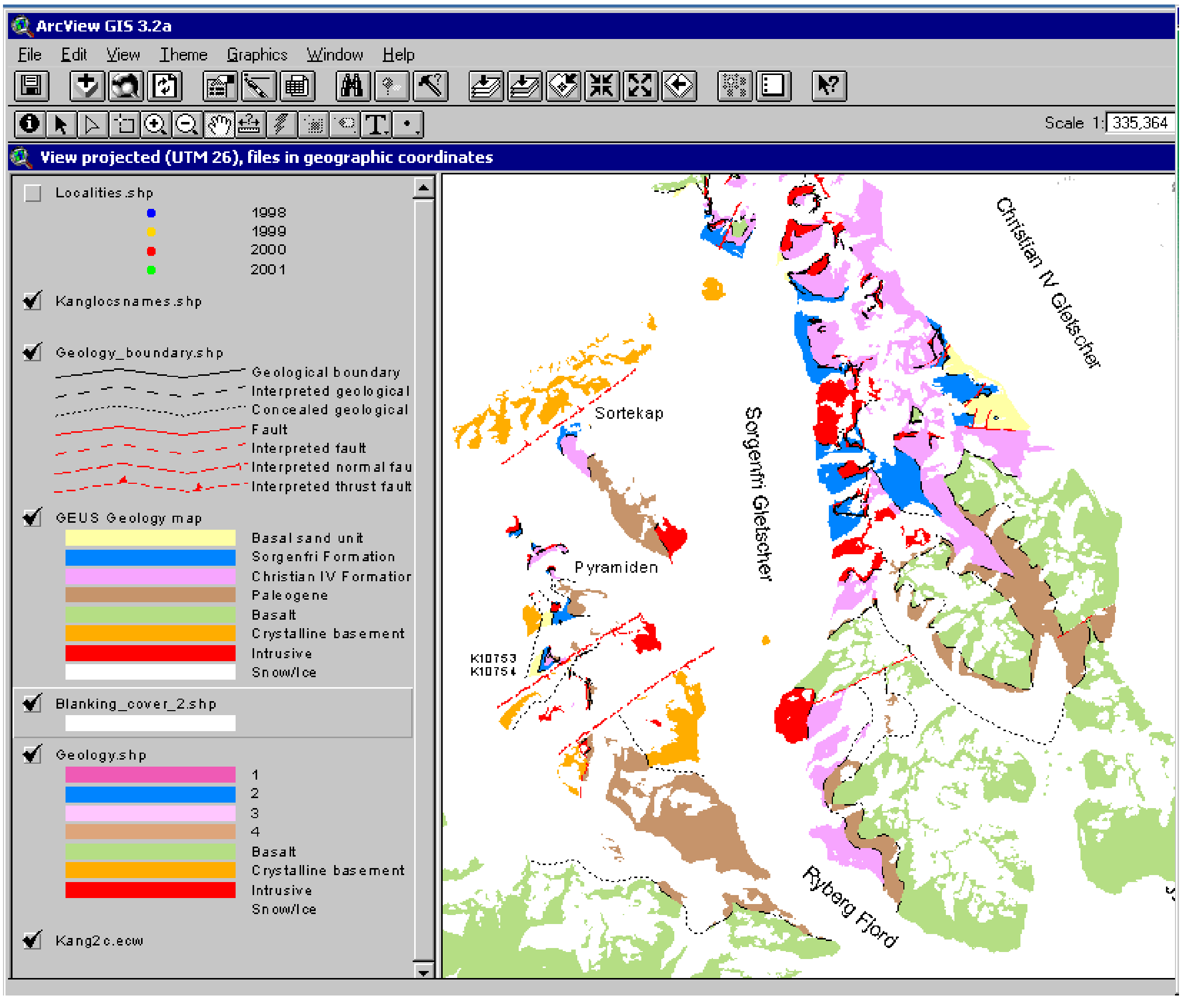

Figure 4. *Screenprint showing detail of the new GIS based geological map developed for the Sindri stratigraphy and provenance projects.*

Geological setting

The Kangerlussuaq Basin is situated at the southern East Greenland coast at 68° 30’ North (Fig. 2). The onshore exposures cover c. 10,000 km^2. However, the basin margin to the northeast is not exposed and the basin may continue below the Paleogene flood basalts along the Blosseville Kyst. The continuation of the basin into the offshore areas to the south and southeast is unknown. The basin consists of predominantly northwest dipping fault blocks bounded by southwest–northeast striking normal faults. The most prominent of these faults is the Sortekap fault, which has Cretaceous mudstones in the hangingwall to the southeast faulted against crystalline basement (Fig. 2). The resistant crystalline rocks in the footwall rise today more than 800 m above the soft mudstones indicating a normal displacement of 800–1000 m (Wager 1947). The Sortekap fault probably controlled the position of the northwestern basin margin during Early Cretaceous and mid-Paleocene sea-level lowstands. Towards the west and north, beyond the margins of the Lower Cretaceous basin, Archean crystalline basement highs are onlapped by Upper Cretaceous and Paleocene sediments.

In areas south of the Sortekap fault, crystalline basement locally crops out below a cover of Cretaceous sediments (Fig. 5). These basement windows are probably related to exhumed crests of tilted fault blocks, but little is known about the Mesozoic structural development and the timing of faulting in the region (Wager 1947; Higgins & Soper 1981; Nielsen 1975).

Figure 5. *Crystalline basement in the front overlain by Cretaceous and Paleogene sediments (centre). The crystalline basement forming the footwall block of the Sortekap Fault is seen in the background. Photo towards the north.*

According to Larsen *et al*. (1996) and Larsen & Saunders (1998) the first period of rifting in the Kangerlussuaq region is thought to have occurred in the Early Cretaceous and was associated with the deposition of basement-derived clastics in a series of fault-bounded basins floored by Precambrian crystalline basement. Whitham & Kelly (1999) have since documented a period of mid-Albian rifting. There is no evidence for earlier phases of Cretaceous rifting, but by analogy with NE Greenland where the mid-Albian phase also occurs, earlier Cretaceous rifts are thought likely. The next documented period of rifting was coincident with the onset of deep marine sedimentation in the latest Cretaceous–earliest Tertiary (Whitham & Kelly 1998). The onset of this rift phase has been constrained as mid-Maastrichtian on the basis of a major influx of reworked dinocysts at this time (Kelly *et al*., 1999). Recent studies suggest that northeast–southwest oriented faults created during this rifting phase controlled the position of a major sediment input point to the northern North Atlantic in the Late Cretaceous and Paleogene (Larsen & Whitham 2005).

The presence of a major, northwest-southeast oriented tectonic lineament northeast of Nansen Fjord in East Greenland (Fig. 2) is suggested by a number of observations. First, a marked change in the distribution and thickness of the Upper Cretaceous succession shows that two sub-basins with different subsidence history may have existed in the area. Second, Paleogene sediments, which underlie the thick plateau basalt succession, are thickest along the axis of the eastern sub-basin. The dominantly coarse-grained marine and fluvial sediments show south- and southeasterly palaeocurrents parallel to the lineament (Larsen *et al*. 1999a). Lastly the Paleogene volcanic succession shows important changes across the lineament. To the east of the lineament subaerial plateau basalts rest directly on basement or fluvial sediments, whereas to the west the basal lavas are interbedded with marine sediments and hyaloclastite foreset breccias up to 100 m thick.

The late Cretaceous–Early Paleogene rifting was followed by a period of regional uplift in the mid-Paleocene and the creation of a widespread subaerial unconformity, which was related to the onset of volcanism (Hamberg 1990; Dam *et al*. 1998, 1999).

In the Kangerlussuaq region the Paleogene continental break-up was accompanied by the development of a large-scale, coast-parallel flexure with dykes and normal faults (Nielsen 1975). Faulting occurred in a system of coast-parallel antithetic faults related to the Sortekap fault and the sediments today strike northeast–southwest, parallel to these tectonic lineaments and dip 6–22° towards the southeast or northwest.

The coast-parallel structural trend of the region is also reflected in the position of a number of large Lower Eocene–Oligocene intrusive centres including the Skaergaard Intrusion formed along a southwest–northeast line (Fig. 2). During this time interval several generations of dykes and sills were intruded in the sediments, and sills are prominent in the inland areas (Tegner *et al.* 1998).

Stratigraphy

The lithostratigraphic framework used here for the pre-basaltic sedimentary rocks of the Kangerlussuaq Basin consolidates the previous lithostratigraphic schemes first established by Wager (1934, 1947) and supplemented by Soper *et al.* (1976a). The new framework covers the whole of the Kangerdlugssuaq Group and the lowest part of the Blosseville Group. Younger rocks of the Blosseville Group exposed to the north of Kangerlussuaq are composed of dominantly basaltic extrusive rocks whose lithostratigraphy was established by Bird *et al.* (1985) and Pedersen *et al*. (1997) and are not discussed further herein. In order to retain parts of the original scheme for the sedimentary succession, it has been necessary to redefine some of the original lithostratigraphic terms. To avoid confusion the unrelated but similarly termed Ryberg Formation and Ryberg Sandstone Bed have been replaced. The generalised history of the stratigraphic nomenclature of the pre-basaltic rocks of the basin is shown in Figure 3.

Larsen *et al*. (1999a) recognised four major facies associations in the Kangerdlugssuaq Group: 1) alluvial plain and shallow marine (?Late Aptian); 2) fluvio-estuarine (Late Aptian–Early Albian); 3) offshore marine (Late Cretaceous–Early Paleocene); 4) submarine fan and channel-levee (Early Paleocene). In the overlying Vandfaldsdalen Formation of the Blosseville Group two associations were recognised: 5) fluvial (mid-Paleocene) and 6) volcanic (Late Paleocene). These associations and the biostratigraphic data collected by CASP and GEUS now form the basis for a lithostratigraphic division (Figs 3 and 6). The new formations and members are described below and a log correlation chart is given in Appendix 3.

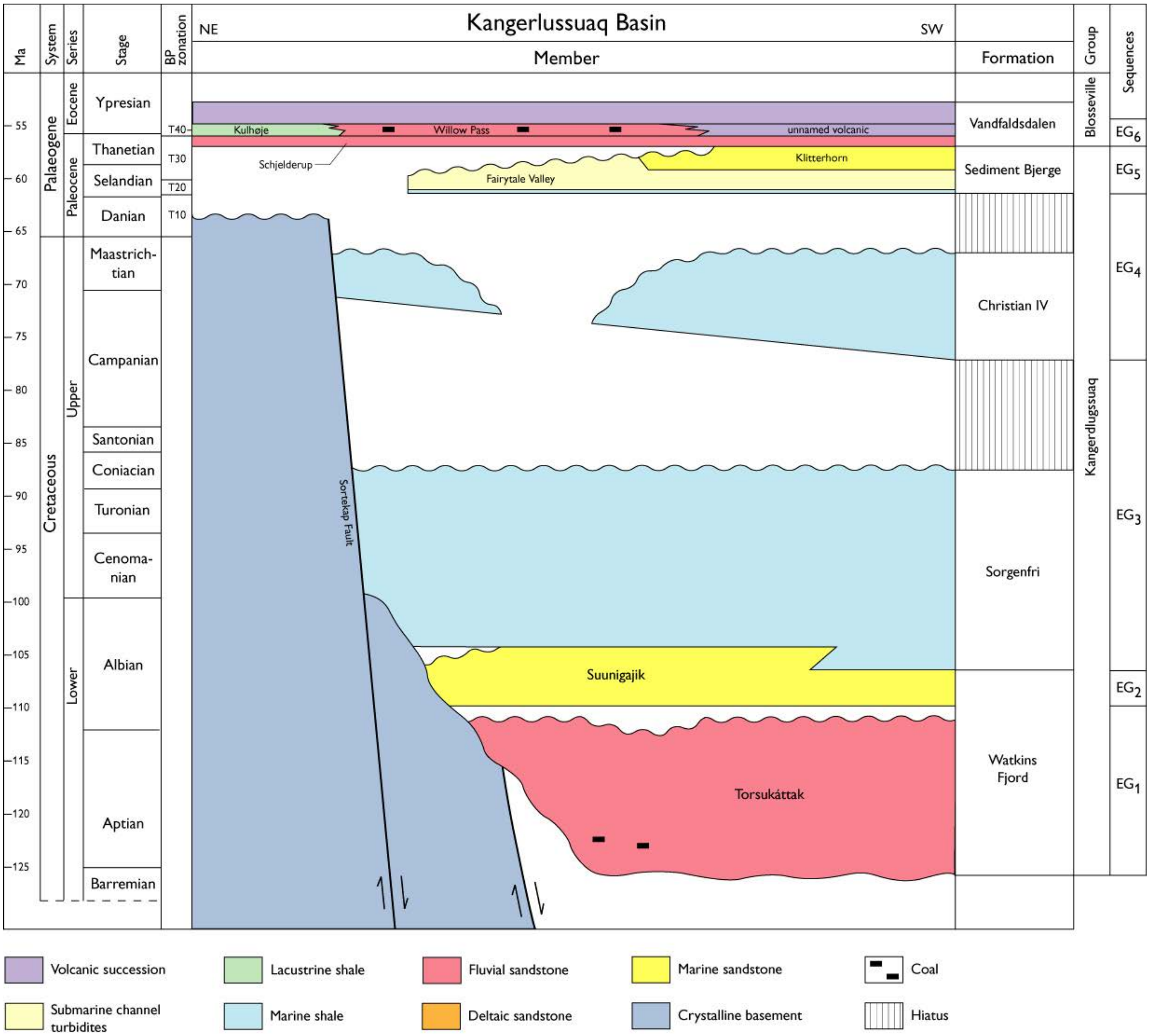

Figure 6. *Simplified stratigraphic scheme for the sedimentary succession in the Kangerlussuaq Basin with proposed new formations and members. Time scale from Gradstein et al. 2004.*

Kangerdlugssuaq Group

Redefined

History. The unit was introduced as the Kangerdlugsuak [sic] Series by Wager (1934, p. 25), and was subsequently referred to as the Kangerdlugssuaq Sedimentary Series (Wager, 1947). Soper *et al.* (1976a) modified the name to group level as the Kangerdlugssuaq Group which was followed by Nielsen *et al.* (1981) and Larsen *et al.* (1996, 1999a,b, 2001).
Name. The group is named after Kangerdlugssuaq (original spelling of the modern name: Kangerlussuaq), the principal fjord (opening into the sea at 68º 30'N) in southern East Greenland and which lies immediately to the west of the Kangerlussuaq Basin.
Type area. The group is exposed from the Kangerlussuaq fjord in the west eastwards to the Christian IV glacier and the western flanks of the Watkins Bjerge.
Thickness. The total thickness of the group is approximately 700 m.
Lithology. The group is characterised by sandstone and mudstone sedimentary rocks. The middle of the group is mainly a mudstone-dominated succession (Sorgenfri and Christian IV formations), but the lowermost part (Watkins Fjord Formation) and some parts of the uppermost units, particularly the Klitterhorn Member, are sandstone-dominated (See formations and members).
Biota. The group is characterised by a wide range of organisms including marine mollusca, echinoderms, worms, corals, acritarchs, dinoflagellate cysts, foraminiferids, fish, reptiles and trace fossils; transported nonmarine spores, pollen and plant macrofossils.
Depositional environments. A broad range of environments is represented from nonmarine, fluvio-lacustrine, through marginal marine, to mid- and outer shelf (See component formations and members). There is no volcanic influence.
Boundaries. The base of the Kangerdlugssuaq Group lies unconformably on Archean gneiss and is diachronous. At different places across the basin different units are represented at the base. To the SW of the Sorgenfri Glacier, the basal unit is the Watkins Fjord Formation, while on Pyramiden Ridge, the basal unit is the Sorgenfri Formation (W4299)[1]. The top of the Kangerdlugssuaq Group is marked by the unconformity at the base of the Blosseville Group. Locally at the margins of the basin the Kangerdlugssuaq Group may be cut out and the Blosseville Group rest directly on the basement (e.g. Narren, W4232; Korridoren, W4256).
Subdivision. From the base upwards the following units comprise the group: Watkins Fjord, Sorgenfri, Christian IV and Sediment Bjerge formations.
Distribution. The group crops out across the whole Kangerlussuaq Basin, from Watkins Fjord in the west to the Watkins Bjerge in the east, and from inner Ryberg Fjord near the coast, inland and northwards to Sequoia Nunatak and Urbjerget (North of the head of Kangerlussuaq inlet).
Geological age. Late Barremian (Early Cretaceous) – Selandian (Paleocene).

[1] Five digit locality numbers e.g. W4232 refers to the GIS project giving exact coordinates, year of fieldwork/sampling and geologist.

Watkins Fjord Formation

New formation

History. The formation consists of a hitherto un-named sandstone-dominated succession forming the base of the sedimentary succession. It underlies the mudstone-dominated Sorgenfri Formation and includes Facies Associations 1 and 2 of Larsen *et al.* (1999a,b). The formation is divided into a lower fluvial dominated unit (Torsukáttak Member) and an upper marine unit (Suunigajik Member). These sands were not recognised by Wager (1934, 1947) or Soper *et al.* (1976a). The first descriptions of the basal sandstone unit appeared in the paper by Larsen *et al.* (1996).
Name. It is named after the fjord into which falls the unnamed glacier passing the northwest side of the type locality.
Type locality. The well-exposed cliff section, 'L3' (Larsen *et al.* 1999a) (M9511, W4260), 20 km NNE Sødalen, is designated type locality (Fig. 7).
Reference localities. Important reference localities occur in eastern Sediment Bjerge along Christian IV Gletscher, localities W4233, 4234, 4244, 4269.
Thickness. The formation is up to *c* 180 m in total thickness. The precise thickness cannot be stated because the base and top are not seen in any single section.
Lithology. The rock type is sandstone-dominated; see constituent members.
Biota. Marine molluscan macrofaunas are present locally in the upper part of the formation in association with dinocyst assemblages. See constituent members.
Depositional environment. Environments range from fluvio-lacustrine at the base to marginal and shallow marine at the top.
Boundaries. The base is unconformable on Archean Gneiss 8 km S of Pyramiden. The top is overlain by a break in sedimentation with the overlying Sorgenfri Formation, where the sediment becomes mud-dominated. At L3 this is recognisable as an unconformity.
Subdivision. From the base upwards the formation is subdivided into the Torsukáttak and Suunigajik members.
Distribution. Today the member reach maximum thickness at L3 and sandridge (M0017), whereas thin deposits are present at Sill City (W4271) and in Windy Valley. A small outcrop of channelled sandstones adjacent to the basement surface north of Nansen Fjord may represent the most easterly development of the member. It is absent on NW Pyramiden ridge and in northernmost Sediment Bjerge northwards.
Geological age. Molluscan ages from the middle of the formation are Late Barremian– Aptian, and Middle Albian in the upper part.

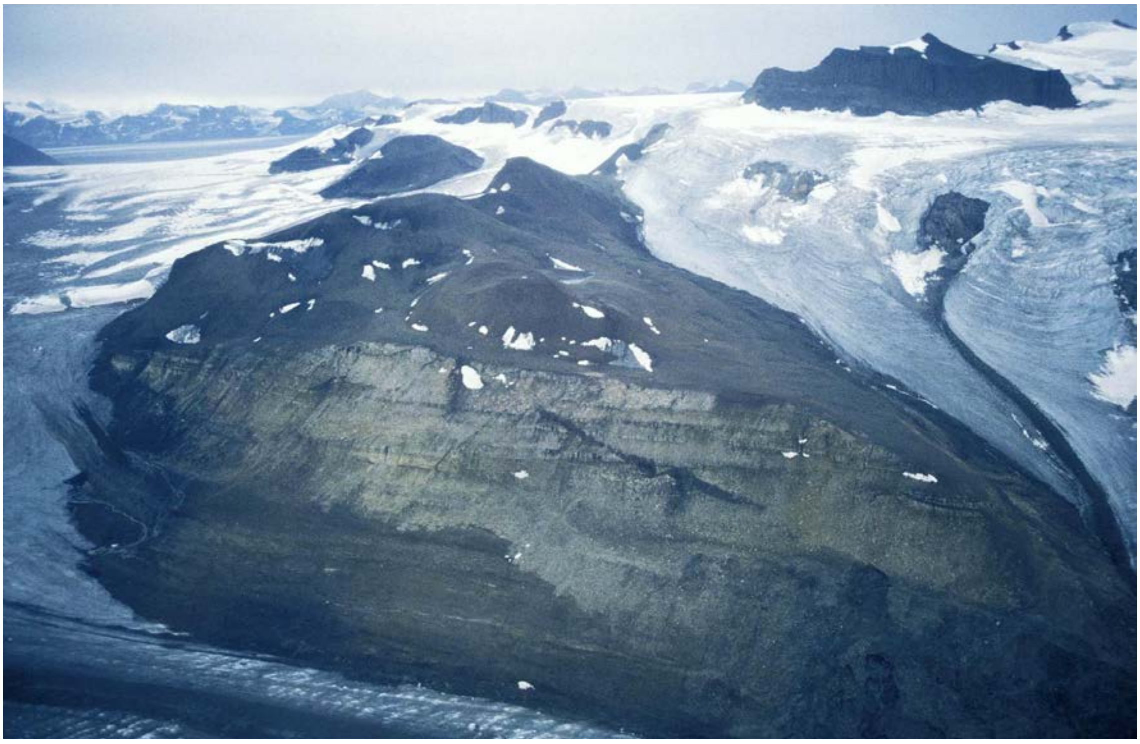

Figure 7. *Type section (L3) for the Watkins Fjord Formation. Light grey sandstones (Suunigajik Member) in the centre of the photo are approximately 100 m thick. Photo looking northeast.*

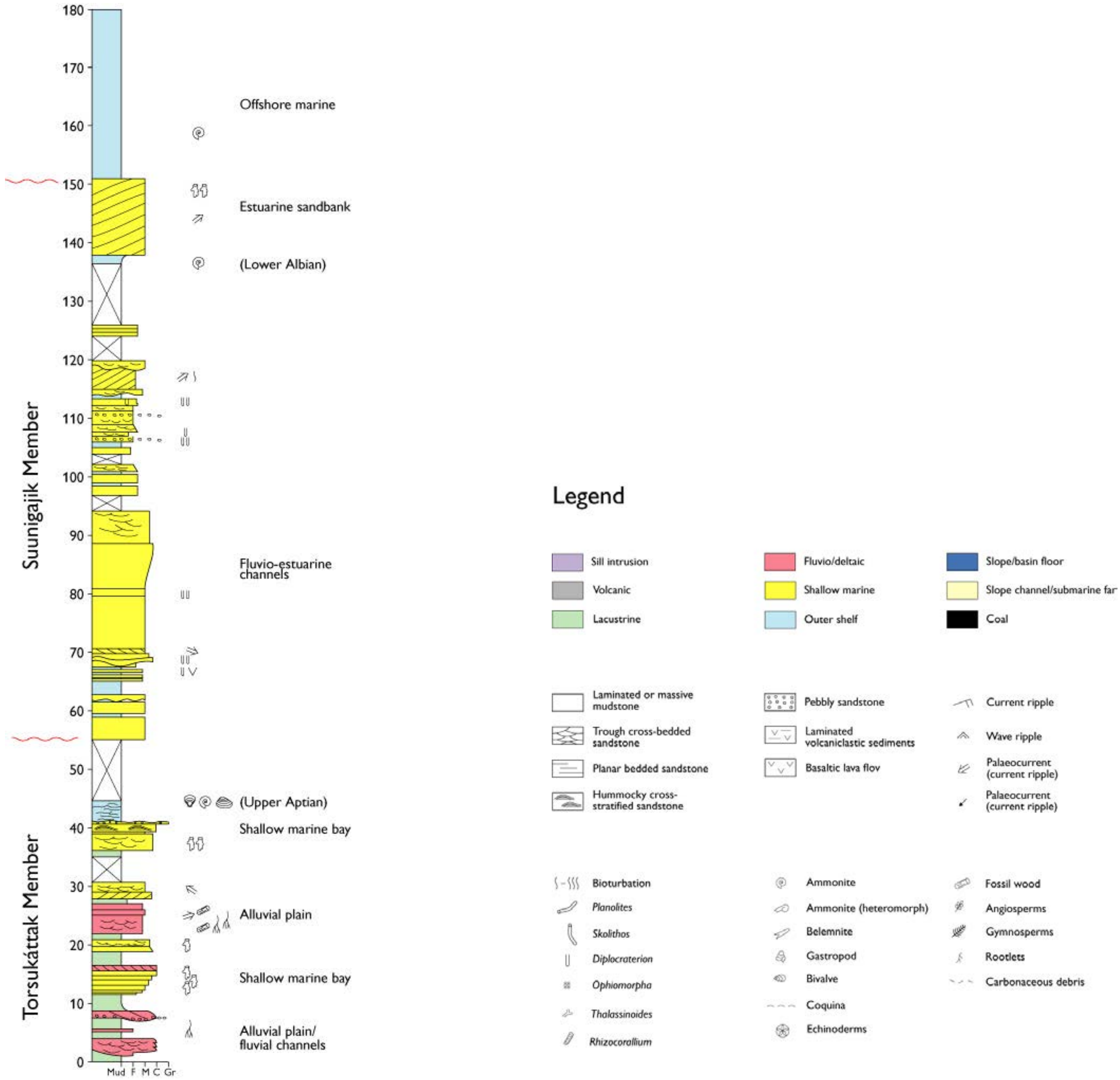

Figure 8. Type section of the Watkins Fjord Formation including the two members: Torsukáttak and Suunigajik.

Torsukáttak Member

New member

History. The sediments include Facies Association 1 of Larsen *et al.* (1999a,b)
Name. After the Greenlandic name for Watkins Fjord (Grann 1992).
Type locality. The type locality is at 'Larsen 3' (M9511, W4260), 20 km NNE Sødalen.
Reference localities. Eastern Sediment Bjerge, locality W4250.
Thickness. The thickness is greater than the 55 m exposed at the type locality where the base is not seen (Fig. 8). At Sandridge on the western side of Christian IV Gletscher a poorly exposed sandstone succession of more than 75 is assigned to the member.
Lithology. The Torsukáttak member is characterised by fine to medium grained sandstones and mudstones. The sandstones are feldspathic litharenites (Folk 1980), and locally contain coalified wood fragments and abundant disseminated carbonaceous debris. In the lower part of the succession silty mudstones and lenticular sandstone bodies occur, up to 2 m in thickness and 5–20 m in lateral extent. Sandstones commence with a gravel lag and fine upwards from coarse to fine-grained sandstones and siltstones, which are capped by rootlet horizons. The sandstones commonly exhibit trough cross-bedding (unidirectional towards east), with local epsilon-cross-stratification. In the upper part of the succession interbedded coarsening and thickening upward units up to 2 m in thickness which grade upwards from parallel laminated siltstones to medium-grained, trough cross-laminated and cross-bedded sandstones and hummocky cross-stratified sandstones (Fig. 9). The degree of bioturbation increases upwards, and the tops of the units are characterised by abundant *Ophiomorpha* isp. An erosion surface at 41 m in the type section (Fig. 8) is overlain by 0.3 m conglomerate with symmetrical ripples and in turn is overlain by calcareous silty mudstones.
Biota. Mudstone-dominated beds in the lower part of the member are barren of macrofauna, but some contain plant rootlet horizons. The oldest macrofauna was collected only from 42.2 m in the upper part of the Torsukáttak Member in the type section (Fig. 8). It contains the small heteromorph ammonite *Parancyloceras bidentatum* (von Koenen), the zonal index of the latest Barremian in NW Europe. It also contains common *Lytoceras polare* (Frebold) and the bivalve *Arctica* sp. With poorly preserved *Entolium orbiculare* (J. Sowerby). *L. polare* also occurs at 43.7 m (Fig. 8). The second principal macrofauna only occurs at 3.8 m above the first assemblage. It contains the large heteromorph ammonite, *Tropaeum subarcticum*, which characterises the *Acanthoplites nolani* Zone (formerly *Parahoplites nutfieldiensis* Zone), the older part of the Late Aptian, together with abundant bivalves, *Entolium orbiculare* (J. Sowerby) (reported as *Camptonectes sp.* by Larsen et al., 1999a), *Arctica* sp. occasional calcareous worm tubes: *Rotularia sp.* and an asteroid. The associated palynology of these faunas is unknown.
Depositional environments. The environments represented are predominantly fluvio-lacustrine with minor marginal marine influence. They show meandering channel fill sandstones on low gradient alluvial surface interbedded with lacustrine and floodplain fine-grained sediments, overlain by shallow marine deposits. The sediments of the lower part of the succession shows fining-upward channel fills with abandonment shown by plant rootlet horizons on the tops. Stacking of the channel sandstones reflects changing sea levels in the adjacent bay. The change to coarsening-upwards cycles represents bay-fill and shallow marine sediments, which drowned the alluvial plain (Fig. 8). The wave-rippled conglomer-

ate at 41 m may represent a wave ravinement surface formed during transgression of the former coastal plain. The hummocky cross-stratified sandstones beneath the conglomerate indicate deposition between fair weather and storm wave base. The benthic mollusc fauna of thin-shelled active swimming *Entolium* and shallow burrowing, thick-shelled *Arctica* are typical of forms occurring in a relatively high energy, mobile sandy bottom environment.

Boundaries. The base is seen in unconformable contact with Precambrian gneiss, 8 km S Pyramiden. The top of the member is unconformable (SB2) to the Suunigajik Member and is placed at the erosional base (SB2) of the massive sandstone unit 54 m in the type section (Fig. 8).

Distribution. The unit is exposed in small outcrops across the central part of the basin, including W of Pyramiden and the Sediment Bjerge, but is absent on NW Pyramiden ridge and has not been recognised in the northern Sediment Bjerge.

Geological age. There is no biostratigraphic control available yet on the lower part of the member. The upper part is Late Barremian based on small heteromorph ammonite *Parancyloceras bidentatum* to Late Aptian (Nutfieldiensis Zone) based on a single specimen of *Tropaeum subarcticum* Casey

Figure 9. *Bedded sandstones forming a coarsening-upward unit (bay-fill succession) in the upper part of the Torsukáttak Member.*

Suunigajik Member
New member

History. The Suunigajik Member forms the upper part of the Watkins Fjord Formation and includes Facies Association 2 of Larsen (1999a,b).
Name. After the Greenlandic name for a headland in Watkins Fjord (Grann 1992).
Type locality. At the type locality, L3 (=W4260), 20 km NNE Sødalen, the member is almost fully exposed from base to top, with only minor unexposed but measurable intervals within the succession (Figures 8, 10, 11).
Reference localities. W4269 (West of Pyramiden); W4244, W4247, W4248, W4253 (eastern Sediment Bjerge; W4293 (western Sediment Bjerge).
Thickness. The member is c100 m in thickness at the type locality (Fig. 8).
Lithology. Coarse to very coarse-grained sandstones are lithic arkoses. They form lenticular bodies up to 20 m in thickness and several hundred metres in width and, to the north and northeast pass laterally into silty mudstones (Fig. 11). In the lower part of the type-section the sandstone bodies are amalgamated, probably channelized, with erosional lower boundaries with a relief up to 3 m. In the upper part of the succession very large scale to giant-scale cross-bedded units are up to 12 m in thickness (Fig. 10). They have conformable bases and form isolated sandstone bodies separated by thin marine mudstones. At the northeast of the exposure, the upper sandstone bodies show bi-directional cross-stratification (to NE and SE) and double mud drapes. The sandstones contain scattered trace-fossil burrows, mainly *Diplocraterion habichi* and *Arenicolites*. The top surface is marked by *Ophiomorpha*. Growth faulting seen at W4273 where mudstone units thicken from 8 to 25.5 m across the fault.
Biota. From just below the upper sandstone unit at the type locality, sandy mudstones contain ammonites: *Euhoplites loricatus, E*. sp.? *aspasia* Spath, *Anahoplites* sp. *planus* group, *Phylloceras* sp.; echinoid; crustaceans: *Meyeria* sp.; and bivalve *Actinoceramus* sp.
Depositional environment. Environment interpretations range from sandbars in fluvio-estuarine channels to shallow marine sandy mudstones. The abundant burrowing and lateral interfingering of the sandstone bodies with heteroliths showing double mud drapes and laminated mudstones suggest a tidally influenced environment. The large-scale cross-bedded sandstones are interpreted as migrating large-scale alternate bars with major slip faces in a fluvial setting (Larsen et *al.* 1999a). This is supported by lack of coarsening upwards grain-size, and the consistent foreset dip azimuths at approximately 45º to the direction of progradation of the channel axis. The change from amalgamated channel sandstones to large-scale cross-bedded sandstones suggests an increase in accommodation depth with time.
Boundaries. At the type locality the base of the Suunigajik Member is incised into the top of the Torsukáttak Member. At other localities the boundary forms an apparent conformity. The unconformable base of the Sorgenfri Formation, SB3, marks the top of the member.
Distribution. The Member is exposed in small outcrops across the central part of the basin, including L3 and sandridge, Sill City and Windy Valley, but is absent on NW Pyramiden ridge where mudstones of the Sorgenfri Formation onlap the crystalline basement.
Geological age. Ammonites indicate a Mid Albian age. This is based on the presence of the *Anahoplites intermedius* Subzone of the *Euhoplites loricatus* Zone, and association with dinoflagellate cysts of the *Chichauadinium vestitum* Subzone of the *Rhombodella paucispina* Zone IV(2).

Figure 10. *Large-scale cross-bedded sandstones of the Suunigajik Member. Photo towards the east. Cliff face shown is c. 100 high. Note Paleogene intrusion.*

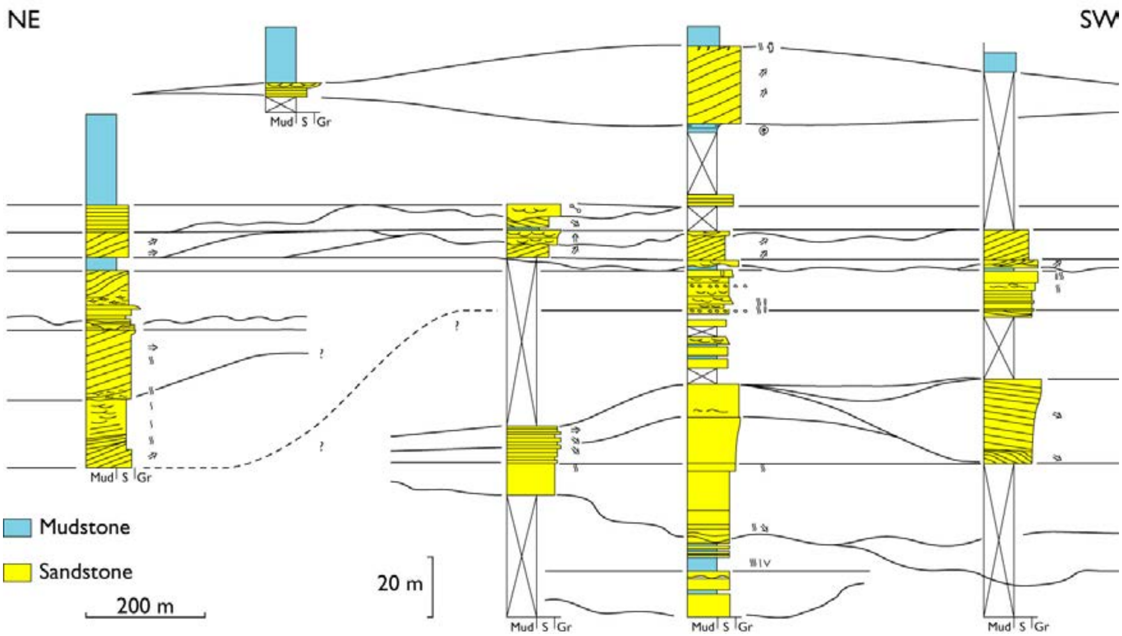

Figure 11. *Correlation chart of sections through the Suunigajik Member at the type locality. For legend see Fig. 8.*

Sorgenfri Formation

Revised

History. The Sorgenfri Formation was introduced by Soper *et al.* (1976a) for the then lowermost known unit of the Kangerdlugssuaq Group.
Name. The formation is named after the Sorgenfri Glacier.
Type section. The original type section is a 30 m succession of mudstones isolated by igneous sills on the east side of the Sorgenfri Glacier Soper *et al.* (1976a). During the course of fieldwork the authors attempted to locate the type section, but were unable to do so owing to an inadequate description of the section location. A more or less complete section through the formation is to be found at 68°37.2'N 30°51.7'W in the northern "Sediment Bjerge" and is suggested as type section for the revised Formation.
Reference localities. Well exposed sections also occur at 68°38.3'N 30°55.8'W and at the NW end of Pyramiden ridge at 68°31.5'N 31°11.2'W, but both are incomplete. The base of the section is exposed at W.4259 and at W.4247.
Thickness. The formation is 42 m thick at the type locality. At W.4225 it is more than 95 m thick and at W.4229 it is around 139 m thick.
Lithology. The formation is dominated by sandy mudstones with rare discrete sandstone beds (Fig. 12; Whitham & Kelly 1998, pl. 6). Sandstone content shows an overall increase from the bottom to the top of the unit. Dark phosphatic concretions characterise the succession; calcareous concretions and concretionary horizons, some of which are septarian, are locally common.
Facies and depositional environments. A single mudstone-dominated facies association (Fig. 12) represents the Sorgenfri Formation. The mudstones are typically dark grey and micaceous with a variable sandy content and at some localities show a bed parallel fissility. They are typically well bioturbated. Distinct burrows are rare although some concretions form after burrows. Concretions are abundant and show large size variation. Large concretions are typically elongate parallel to bedding and may form semi-continuous horizons. Many concretions are septarian. Small, rounded, phosphatic, concretions 1–5 cm diameter are also common and characteristic of the formation. Rare beds of fine-medium grained sandstone occur within the mudstones. These are typically laterally continuous although some are discontinuous and lenticular. Some sandstone beds are of up to 40 cm but most fall in the range 1–5 cm. Bed bases are typically sharp, bed tops typically gradational and bioturbated. Most beds are composed of quartz and feldspar grains sand grains, some, however, contain a large proportion of phosphatic detritus and rare small well rounded pebbles. A 50 cm bed of poorly sorted pebbly sandstone containing oncolites is found at the base of the formation at 68° 32'N 30° 32'W. The oncolites are rounded to subrounded, well laminated and reach a maximum of 13 cm diameter. Sand grains are incorporated in the laminae and are less abundant than in the matrix suggesting that oncolite formation took place at the sediment water interface rather than within the sediment. Pebbles typically form the oncolite core.
Interpretation: The lenticular sandstone beds containing phosphatic detritus are interpreted as lag deposits produced by winnowing by storms (Levell 1980). The sandstone beds with sharp bases and gradational bioturbated tops are interpreted as storm layers deposited below storm wave base, in an outer shelf setting (e.g. Snedden & Nummedal, 1991,

Brenchley, 1985). The fine grained nature of the sediment, abundant bioturbation, and biotic assemblages and the origins of sand beds support a mid-outer shelf depositional environment. This unit forms part of Facies Association 3, of Larsen *et al.* (1999a).

Fossils. Fossils are found sporadically throughout the unit and may be locally abundant. Ammonites are represented by *Hamites*, *Euhoplites, Mortoniceras (Deiradoceras), Lytoceras, Schloenbachia varians* group*, Phylloceras, Mesopuzosia.* Other cephalopods consist of nautiloids (*Nautilus*) and the belemnites *Neohibolites* and *Actinocamax*, which may be locally abundant. The bivalves found were *Actinoceramus concentricus* group, *Inoceramus crippsi*, *I. lamarcki* Parkinson group and nuculoids. The inoceramid *I. lamarcki* was generally found as fragments but at three localities complete specimens were found in life position. Vertebrates are represented by *Ptychodus* (tooth), pliosaur (tooth and bone fragments) and phosphatised fish coprolites. The boring trace fossil *Rogerella* occurs in thick inoceramid shells. There is good recovery of dinoflagellate cysts from many of the mudstones (see Appendix).

Boundaries. The base is sharp on sandstones of the Watkins Fjord Formation. An angular unconformity (SB3) is developed at Locality 3 and suggests that a tectonic phase involving block rotation took place between the deposition of the two formations. An oncolitic bed is present in the eastern Sediment Bjerge (locality W.4247).

Distribution. In addition to the type area the formation is exposed widely across the central part of the region.

Geological age. The biota indicates the presence of the Middle Albian, Late Albian, Early or Middle Cenomanian, Turonian and Coniacian stages. Representatives of the *Hoplites loricatus* and *Mortoniceras inflatum* ammonite zones occur and *Rhombodella paucispina* and *Subtilisphaera kalaalliti* dinocysts zones are represented. Miospores are prominent in the Turonian part of the formation. Thus, the formation has a mid-Albian to mid-Coniacian age. The ammonites from the base of the succession indicate that the lower boundary is diachronous ranging from the mid to Late Albian.

Remarks. Our concept of the Sorgenfri Formation differs from that in the original description of Soper *et al.* (1976a). We include in the formation all the mudstone dominated part of the succession, which contains common black phosphatised concretions, and so distinguishes the Sorgenfri Formation from the overlying Christian IV Formation. Thus we include the lower part of what Soper *et al.* (1976a) termed the Ryberg Formation, i.e. the phosphate concretion bearing beds with *Actinocamax* exposed at locality W.4229. At one locality, W.4269, to the west of Pyramiden, the formation is relatively free from the dark concretions.

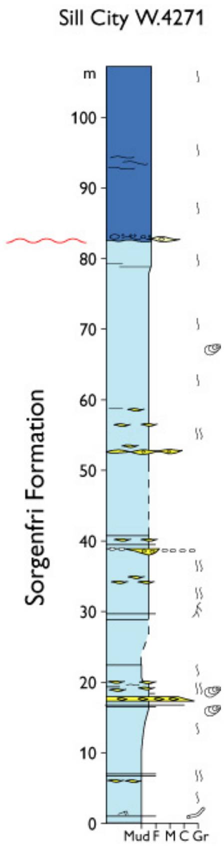

Figure 12. *Section through the Sorgenfri Formation at Sill City (W.4271). The upper boundary at this locality is a marked unconformity to the Paleocene Fairytale Valley Member. For legend see Fig. 8.*

Christian IV Formation

New

History. The Ryberg Formation was introduced by Soper *et al.* (1976a) for the uppermost division of the Kangerdlugssuaq Group. The original type area for the formation was defined by Soper *et al*. (1976a, p. 88) as 'Ryberg Fjord ... near the head of the fjord and adjacent to the Schjelderup and Sorgenfri glaciers'. We subdivide the original Ryberg Formation of Soper *et al.* (1976a) into three formations. The lowest mudstone-dominated part we transfer into the upper part of the Sorgenfri Formation (see above); whereas the younger mudstone-dominated unit is defined as a new formation; the Christian IV Formation. The mudstones of the Christian IV Formation were included by Larsen *et al.* (1999a,b) in the lower part of facies association 3.

Name. After the Christian IV Gletscher, the largest glacier in the Kangerlussuaq region.

Type locality. The thickest and best exposed section is along the Christian IV Gletscher in the eastern Sediment Bjerge (Skiferbjerg W4245) and this is chosen as the type section (Fig. 13). However, the upper and lower contacts are not exposed in the type section.

Reference locality. The base of the section is well exposed at W4282, to the NW of Pyramiden, and also at P.2383 and W.4293 in the northern Sediment Bjerge. The formation is unconformably overlain by the Sediment Bjerge and Vandfaldsdalen formations e.g. exposed at P2373.

Thickness. The maximum measured section is 250 m at the type section on the western side of Christian IV Gletscher (W4245). The formation, however, could be in excess of 500 m thick in the area around W4293 in the northern Sediment Bjerge, but this is uncertain due to faulting and intrusions.

Lithology. Well bioturbated sandy mudstones dominate the formation. At most localities strata are parallel bedded with the bedding on a 10 cm to m scale. The bedding is defined by variations in sandstone mudstone ratio with bed contacts being gradational due to the bioturbation. Some sandstone beds, typically of fine or fine to medium grade, contain sedimentary structures. Such beds reach as much as 80 cm thick and are not common. They have sharp erosive and in some cases load casted bases and gradational tops. They may also be lenticular. Beds show hummocky cross stratification (HCS) , parallel lamination and ripple cross lamination arranged sequentially. In most cases the division with HCS is absent.

Calcareous concretions are less abundant than in the underlying Sorgenfri Formation and phosphatic concretions are absent. Concretions preferentially form in the sandier units and when weathered are a characteristic ferruginous red colour. An early diagentic origin for the concretions is envisaged as calcareous macrofauna when found in concretions are uncrushed.

Strata are prone to penecontemporaneous slumping in some areas. At W4293 and at P2383, the strata immediately above the unconformity contain large slabs of sandstone 2–5 m in length, which may be folded. Bedding is difficult to recognise in these units. Dinocysts from mudstones in these units give a Campanian or Maastrichtian age indicating contemporaneous reworking of strata. At W4301, a unit of slumped strata appears to occur within the Christian IV Formation. At this location a >60 m thick unit of re-deposited sandy mudstones are exposed. Two facies characterise the unit. The first consists of dark mudstones with thin sandier units 2–20 m thick. These units are inclined to bedding and truncate at the top and bottom of the bed. Bed bases are sharp and erosive. The second facies consists of beds of sandy mudstone with large pale sandy clasts. The beds have sharp bases and are lenticular on the scale of the outcrop around 20 m. The slide block are well bedded, up to 4 m in length and typically sandier than the Maastrichtian above and below the unit. Beds are on the 4–8 m scale.

Biota. The macrofauna is characterised by ammonites, most commonly *Diplomoceras cylindraceum*, but also scaphitids, including *Clioscaphites*, *Rhaeboceras subglobosus,* and *Scaphites*, with *Saghalinites*, *Gaudryceras, Phylloceras*, *Baculites* and *Glyptoxoceras indicum*; rare nautiloids; rare belemnite *Belemnitella*, bivalves including *Tenuiptera fibrosus, Mimachlamys, Oxytoma, Protocardia,* heterodonts; gastropods; brachiopods echinoids, including holasterids, hemiasterids, spatangoids, and a conulid or galeritid; crustaceans and occasional drifted plant leaves (e.g. W4245). Microbiota includes a wide range of dinoflagellate cysts and foraminifera. In some of the bioturbated units trace fossils are preserved; *Zoophycos, Chondrites, Phycosiphon, Planolites, Teichichnus* and *Rhizocorallium* are all recorded.

Boundaries. The base is marked by an unconformity, which is planar on the scale of the outcrop. At all localities where the base is seen the underlying rocks belong to the Sorgenfri Formation. The contact is difficult to pick out unless exposure is good owing to the muddy nature of the both the Sorgenfri and Christian IV formations.

Distribution. The northernmost exposures are found at Sequoia Nunatak. There are extensive areas of exposure in the northern Sediment Bjerge between W4231 and W4254. The southernmost exposures in the Sediment Bjerge are found at W.4213. To the west of the Sorgenfri Gletscher exposures are not particularly extensive or common. The formation is found on the ridge NW of Pyramiden around W4282 and is also found further south at W4260.

Geological age. Late Campanian–Late Maastrichtian; including equivalents of the ammonite zone of *Pachydiscus neubergensis*, inoceramid bivalve zone of *Tenuipteria fibrosa* and the dinoflagellate cyst zones of *Isabelidinium cooksoniae* and *Cerodinium diebelli*.

Depositional environments. The succession was deposited in a shallow marine shelf to outer shelf depositional environment. This interpretation is supported by the well bioturbated yet sandy nature of the succession, the diverse macrofauna and hummocky cross-stratification in some sand beds indicative of storm wave processes (Brenchley, 1985) and yet an absence of wave-ripple cross-lamination. Locally, common plant debris with leaves suggest proximity to land. Chaotic units and units with matrix-supported clasts were produced by gravity induced sliding and debris flows respectively (e.g. Facies A1.2 and F2.1 (Pickering *et al.* 1986)). These probably indicate slope and base of slope environments and times of deeper water conditions.

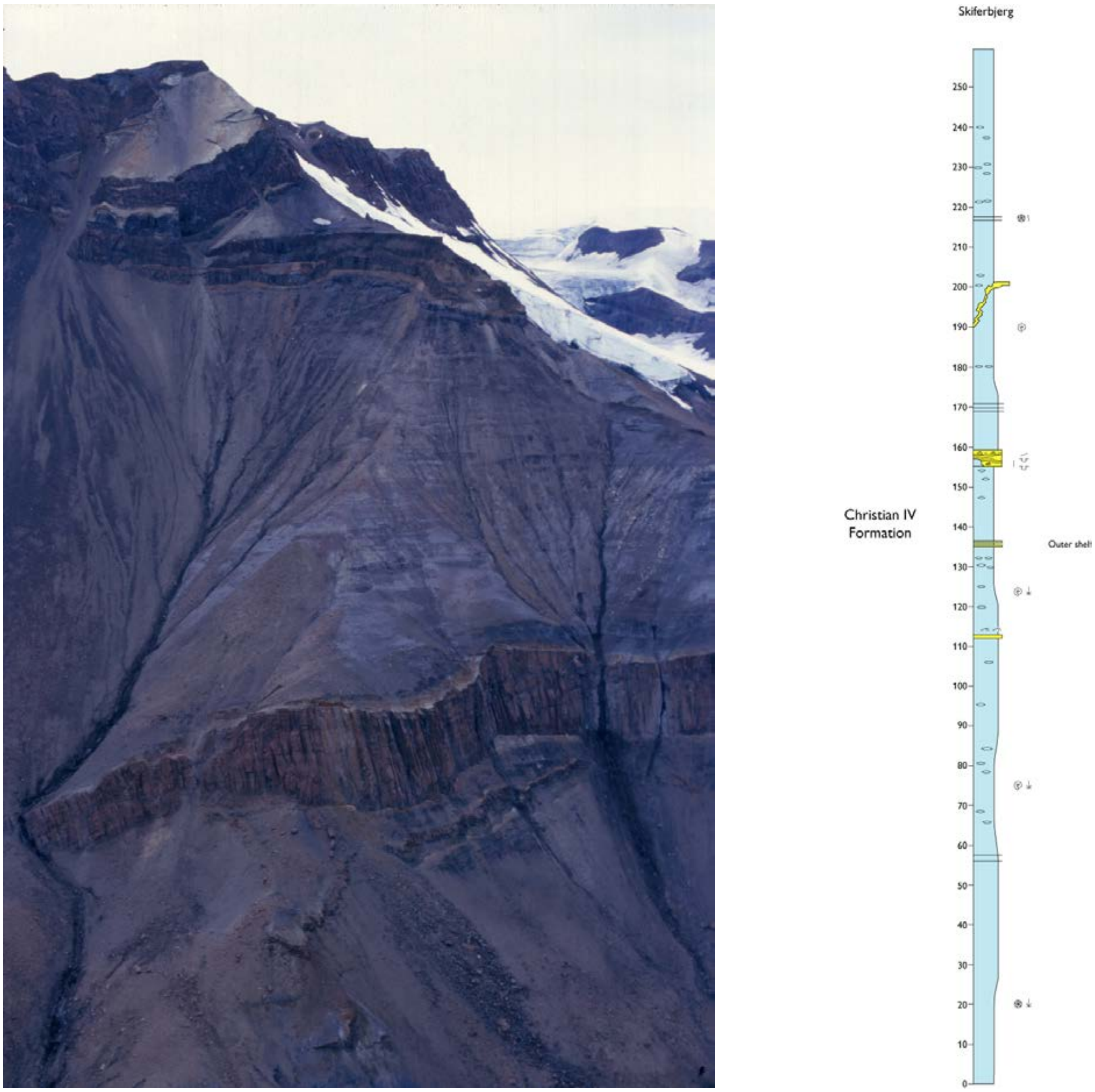

Figure 13. *Type section of the Christian IV Formation along the western side of the glacier. Height of section c. 250 m. For legend see Fig. 8.*

Sediment Bjerge Formation

New

History. The Ryberg Formation was introduced by Soper *et al.* (1976a) for the uppermost division of the Kangerdlugssuaq Group. We subdivide the original Ryberg Formation of Soper *et al.* (1976a) into three formations. The mudstone-dominated units we transfer into the upper part of the Sorgenfri Formation and the Christian IV Formation (see above); the upper sandstone dominated divisions we refer to a new formation; the Sediment Bjerge Formation, divided into a lower Fairytale Valley Member and the upper Klitterhorn members on the basis of their lithological characteristics described below. To avoid the confusion caused by the terms Ryberg Formation and Ryberg Sandstone, it has been felt better to exclude the use of Ryberg and introduce a new term.

Name. The formation is named after the Sediment Bjerge (formerly 'Sedimentary Mountains' of e.g. Higgins & Soper 1981, p. 339) which lie between the Sorgenfri and the Christian IV glaciers.

Type locality. We define the type locality based on the locality 8 described by Larsen *et al*. (1999a) on east side of Fairytale Valley, eastern central Sediment Bjerge. The section log given by Larsen *et al.* (1999a) shows that the base of the formation is not exposed in the type section.

Reference localities. The lower part of the formation is well-exposed at Sødalen and Sediment Bjerge. The upper part of the Formation is exposed at Gabbrofjeld, Vandfaldsdalen Sødalen, Ryberg Fjord and in the southern part of Sediment Bjerge.

Thickness. Soper *et al.* (1976a) originally ascribed c180 m of sediment to the Ryberg Formation, but the greatest thickness observed is 174 m at the type section where the base is not exposed (Fig. 15; Larsen et al. 1999a, pp. 1247–1252).

Lithology. The mudstone-dominated part of the formation is largely devoid of primary sedimentary structures due to intense bioturbation. Bedding, when present, is on the 10's cm to m scale and defined by variation in the sandstone mudstone ratio and by calcareous concretions that typically occur in the sandier units. Rare sandstone beds up to 80 cm thick are recorded. These show parallel lamination and ripple cross lamination. They display Ta–c and Tbc(d) divisions grading upward into flaser-bedded heteroliths and silty mudstones. The trace fossils *Zoophycos, Chondrites, Phycosiphon, Planolites, Teichichnus* and *Rhizocorallium* occur. The sandstone-dominated part consists of amalgamated massive, parallel and cross-stratified sandstones.

Biota. Macrofauna is generally scarce, with occasional poorly preserved molluscs. Trace fossils are widespread. (see Members). There is a rich reworked Cretaceous macrofauna contained in parts slumped of from the Christian IV Formation. There is also a distinctive reworked oyster-dominated assemblage in large sandstone clasts within a mass flow deposit at localities W4215–4216. Dinoflagellate cysts occur in the lower part of the formation.

Depositional environment. The lower part of the formation is marine submarine fan with channel levee having mass flow deposits and slumped strata from earlier deposits (particularly from the Christian IV Formation). The upper part is shallow marine, estuarine, with distributary mouthbars, crevasse channels, distal crevasse levees and interdistributary lagoons

Boundaries. Exposure of the base was not seen, but it is expected to be unconformable. The top is overlain unconformably by the coarse cross-bedded arkosic sandstone of the Schjelderup Member of the Vandfaldsdalen Formation.
Subdivision. From the base upwards: Fairytale Valley Member, Klitterhorn Member and Gabbrofjeld Member.
Distribution. The formation is exposed in Vandfaldsdalen, Sødalen, Ryberg Fjord, Sediment Bjerge and Nansen Fjord and show increasing thickness towards the coast (towards the southeast).
Geological age. Selandian–Early Thanetian based on dinoflagellate cysts. Reworked sediments of Late Campanian/ Maastrichtian age are based on the ammonites in particular which are from the reworked strata of the Christian IV Formation which slumped in Paleocene times.

Fairytale Valley Member

New

History. The mudstone-dominated distal facies of the Fairytale Valley Member were included in the Ryberg Formation of the Sødalen section by Higgins & Soper (1981). The first detailed description and interpretation of the deep water origin was given by Hamberg (1990) and Larsen *et al*. (1999a, Association 4).
Name. The member is named after the valley immediately west of the type section and draining southwards in the central Sediment Bjerge.
Type locality. The type locality is in the east side of Fairytale Valley, eastern central Sediment Bjerge (Fig. 14). It was described as locality 8 of Larsen *et al.* (1999a) and Locality 5 of Larsen *et al.* (1999b). The section log given by Larsen *et al.* (1999a) shows that the base of the Member is not exposed in the type section (Fig. 15).
Reference locality. The upper 35 m of the Member is well exposed at Nansen Fjord (Larsen *et al*. 1999a, locality 9) where it is in unconformable contact with the overlying Vandfaldsdalen Formation, which is also clearly exposed in the windscoop at North Col (W4212a). Localities W4215 and W4216 are important for showing very coarse clasts types (gneiss boulders up to 8 m diameter) and which include oyster-rich sandstones.
Thickness. The total thickness is in excess of the 164 m exposed in the type section, where the base is not seen.
Lithology. The member is defined from a sandstone-dominated succession in the Sediment Bjerge area. The following description and interpretation is based (lifted verbatim*) on that of the type locality (Larsen *et al.* 1999a, p.1247). The succession is dominated by stacked fining upwards sandstone units up to 35 m in thickness separated by heterolithic intervals of silty mudstones and fine-grained sandstones up to 8 m in thickness. The sandstones form large-scale lenticular bodies 300–500 m wide (Fig. 14; Larsen *et al*. 1999a). Two types of sandstones are recognised:
Type 1 sandstones dominate the succession and consist of sharp-based parallel-sided beds that are graded from medium-grained sandstones with scattered pebbles to fine-grained sandstones and siltstones (Larsen *et al. 19*99a, Figs 8, 10). The sandstones show classical Bouma $T_{a–c}$ divisions with a gradual contact to the overlying mudstones. Parting lineation and flute marks are common on bedding planes, indicating palaeocurrents toward the east–southeast (Larsen *et al.* 1999a).

Type 2 sandstones occur as subordinate massive beds, locally up to 1.5 m in thickness, with sharp, but non-erosional lower and upper boundaries. In cross section they form large scale pinch and swell beds with a wavelength of 10–20 m and an amplitude of 0.3 to 1.5 m Abrupt lateral pinch-out geometry without basal erosion may be interpreted as the product of debris flows. Thin mudstone layers occur between the sandstones, and mudstone rip-up clasts are common in the middle, otherwise massive, part of the sandstone beds.

The uppermost part of the section is mudstone-dominated., characterised by laterally persistent thin bedded turbidites, adjacent to the major sandstone units. Locally broad, shallow scours occur and are filled by conformable and locally onlapping mudstones and turbidites. The basal scour surfaces show dip angles up to 4º, and the scours are up to 3 m deep and 0.4–0.6 m wide in cross section.

The uppermost part of the member at the type locality is mudstone-dominated with thin laterally persistent thin sandstone beds. Locally broad, shallow scours occur and are filled by conformable and locally onlapping mudstones and sandstone beds.

Contorted bedding in mudstones is common in the upper part of the fining-upward successions in the type section (Larsen *et al.* 1999a, locality 8). They form discrete lenticular units of mudstone with stringers of siltstone or fine-grained sandstone showing internal contortion.

In other parts of the basin the member is mudstone-dominated with thin sandstone interbeds and remobilised and injected sandstones (Sill City W4271). Locally, large slide blocks composed of muddy sandstones of the Christian IV Gletscher Formation, complete with macrofaunas, which can easily be confused with *in situ* Christian IV Gletscher Formation in small outcrop. Concentrations of concretions and boulders also occur. The summit of W4268 shows a concentration of 100–150 mm richly fossiliferous phosphate concretions derived from the Christian IV Formation. A boulder bed at locality W4215, with gneiss clasts up to 9 m also contains clasts of pebbly sandstones up to 1.5 x 3 m of coarse sandstone with quartzite pebbles commonly in the 5–10 mm range. with a rich oyster-dominated bivalve assemblage does not match any Christian IV Formation lithologies and may therefore represent an intraformational conglomerate. Contorted bedding in mudstones is common in the upper part of the fining-upward successions in the type section (Larsen *et al.* 1999a, locality 8). They form discrete lenticular units of mudstone with stringers of siltstone or fine-grained sandstone showing internal contortion.

Biota. Sandstones of both type 1 and type 2 are characterised by the trace fossils: *Arenicolites, Monocraterion*, *Planolites, Skolithos* and *Taenidium*. Type 2 sandstones have delicate plant leaf impressions. The marine palynological assemblage is characterised by *Pterospermella, Cerodinium, Cribroperidinium, Leiosphaeridia* and microforaminiferal test linings. It is found in central and southern parts of the Kangerlussuaq Basin. At localities W4216 and W4230 a non-marine assemblage characterised by a miospore assemblage occur, which may be in part contemporary with the marine assemblage.

The unique oyster-dominated death assemblage from the boulder bed at locality W4215 contains mainly "*Ostrea*" sp., but also contains an exogyrid oyster, *Plagiostoma* sp., pectinid, ?scaphopod, gastropod and ?worm tubes. The oysters are up to 100 mm in length and up to 15 mm in thickness; commonly they are riddled with flask-shaped *Gastrochaenolites* borings, probably created by boring bivalves, and a possible clionid sponge-boring. Scattered oyster shell fragments are also present in sandstone of locality K7504.

Depositional environment. The overall fining-upward sandstone units are interpreted as the fill of turbidite channels in a proximal submarine-fan environment (Hamberg 1990). The interpretation is based on the predominance of channelised turbidites and debris-flow deposits, the overall geometry of the of the sandstone succession, the fining-upward trend, and the association with fine grained levee deposits. However, the contact to the underlying sediments is not exposed and therefore the erosional base of the channel system cannot be proved. Based on the geometry and thickness of the sandstone bodies, the individual submarine channels can be inferred to have been 300–500 m wide and over 35 m deep. The amalgamated relatively thin-bedded fill suggests that the channels acted as sediment conduits for a period of time before final infilling during multiple depositional events. Low angle erosional surfaces defining shallow scours in the associated mudstone succession suggest that deposition occurred on gently sloping depositional surfaces exposed to syn-sedimentary slumping possibly on the levee adjacent to the main channel. The levee is characterised by broad thin crevasse channel sandstones, which probably represent cut and fill by a single splay event.

The classic Bouma divisions and the well-sorted fine-grained type 1 sandstone composition suggest that the sandstones were deposited from turbidity currents. This conclusion is supported by sole marks indicative of flow turbulence. The type 2 sandstones contain delicate plant leaves, suggesting deposition from a plastic flow because the leaves would probably have disintegrated in turbulent flow. Planar clast fabric of mud clasts and leaves with long axes arranged parallel to bedding planes can be used to infer laminar flow conditions, a property common to debris flows.

Boundaries. At Sill City, the base of the member is by a mud-mud contact representing a major hiatus (Turonian–Danian). At the type locality in Fairytale Valley, the base of the member is not exposed, but based on the sedimentology it is envisaged that the channelled sandstones are incised into the top of the Christian IV Formation, SB4. The top of the member is unconformably overlain by basal sandstones or conglomerates of the Vandfaldsdalen Formation.

Distribution. The member crops out in central and southern parts of the Kangerlussuaq Basin.

Geological age. The oldest part of the member is found at Sill City and L3 where the dinoflagellate cysts *Spiniferites “magnificus”* and *Palaeocystodinium bulliforme* indicate presence of Late Danian strata. Dinoflagellate cysts from the type section suggest a Selandian age for the Member. *Areoligera* spp. and *Palaeoperidinium pyrophorum* are common in the lower successions at Fairytale Valley (GEUS sample 413108, 94m) and present in the upper succession, where a distinct *Spinidinium* sp. and a distinct *Suttilisphaera* sp. have their first occurrence (GEUS sample 413144, 141m). *Palaeoperidinium pyrophorum* and *Areoligera* spp. are also present to common in the Sødalen/Canyondal section. The dating of the five sections suggest correlating with NP5 and with the top of sequence T20 or lower part T30 of Ebdon *et al*. (1995). The mollusca have not provided any conclusive dates from the present study. The oyster-dominated assemblage of locality W4215 appears to be reworked from the Maastrichtian because of the presence of the exogyrid oyster, which does not occur in the Paleocene (N. Malchus, pers. comm. 2003). The fine-grained sandstones locally contain coalified leaf imprints.

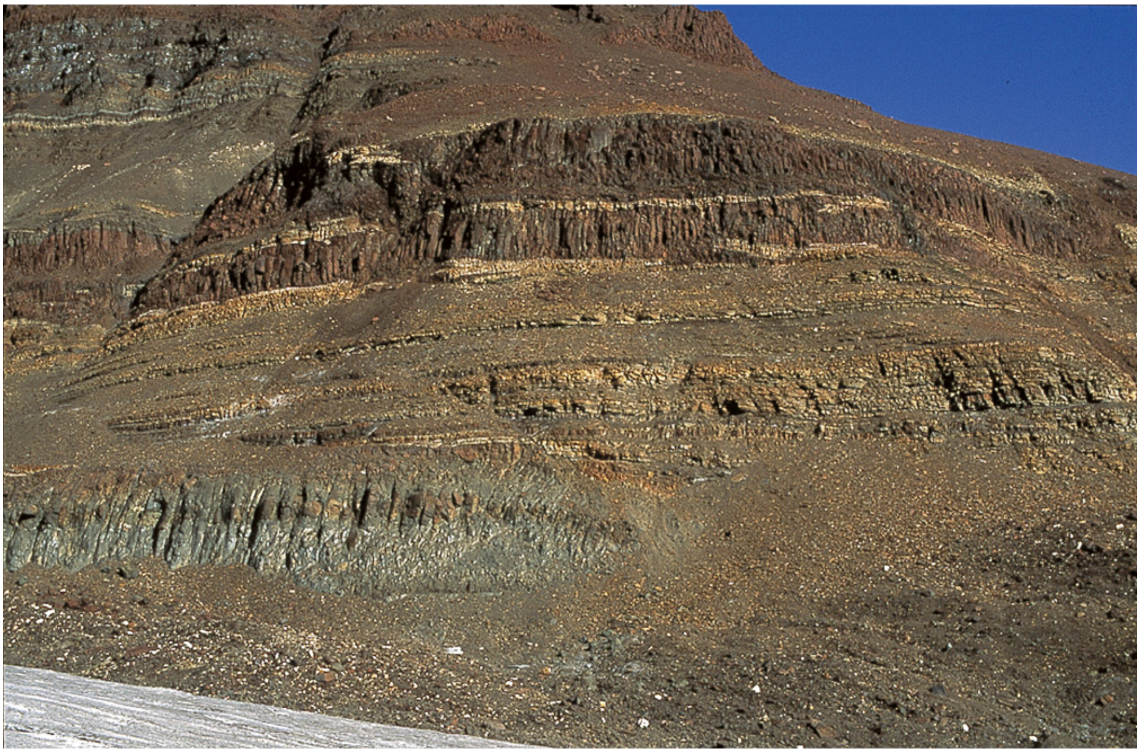

Figure 14. *Turbidite channel sandstones of the Fairytale Valley Member. Type section in Sediment Bjerge. The cliff face shown is c. 250 thick. Note the thick, Paleogene intrusions.*

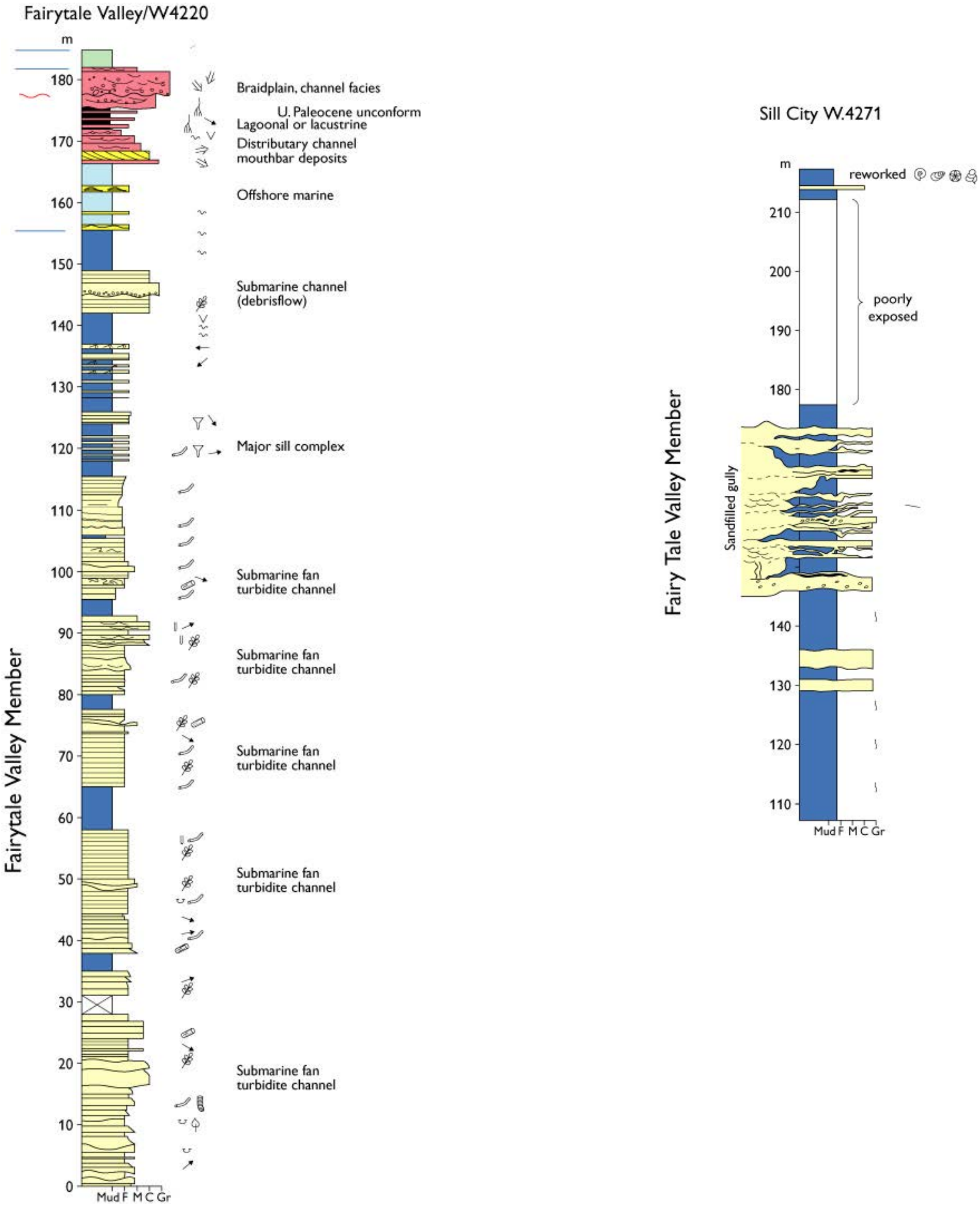

Figure 15. *Two sections through the Fairytale Valley Member illustrating the different facies . A) Type section in Sediment Bjerge interpreted as stacked turbidite channels. B) Sandstone injections at Sill City. For legend see Fig. 8.*

Klitterhorn Member

New

History. The most accessible site is at Canyondal, adjacent to the airstrip in Sødalen. The section was described by Nielsen *et al.* (1981), Higgins & Soper (1981), Hamberg (1990), Nørgaard-Pedersen (1992), Larsen *et al*. (1999a, 1999b). A thicker and more characteristic development is however present at the type locality in Ryberg Fjord (M0002). The member includes sandstone first recognised by Wager (1947) at Gabbrofjeld. Wager specifically noted the angular relations between the bedding of the sandstones and the overlying conglomerate bed (the Schjelderup Member) and interpreted this as indication for a prebasaltic tectonic event. This angular relation has later been reinterpreted as steep foreset beds being truncated by the base of the Schjelderup Member (Larsen & Saunders 1998; their Fig. 14). The succession at the Gabbrofjeld locality was described in by Soper *et al.* (1976a), who included the sandstone-dominated lower part in the Kangerdlugssuaq Group and indicated

Name. The member is named after Klitterhorn, a mountain above the Schjelderup Glacier, in the southwest of the basin (Soper *et al*. 1976a; their Fig 2).

Type locality. Cliff face along the southern inner parts of Ryberg Fjord (M0002).

Reference localities. Canyondal, Vandfaldsdalen, Gabbrofjeld.

Thickness. The total thickness varies from 110 m at Vandfaldsdalen, 50 m at Ryberg Fjord, 12m at Sødalen, 3 m at North Col, 7 m at central E Sediment Bjerge,

Lithology. The Member consists of well-sorted fine- to medium-grained sandstones interbedded with laminated mudstones. The sandstones show large scale planar cross-bedding (Fig. 16), trough cross-bedding, hummocky cross-stratification and ripple cross-lamination.

Biota. The trace fossils *Thalassionoides*, *Planolites*, *Ophiomorpha* and *Skolithos* occur in the sandstones. Coquinas with bivalve and shark teeth. Foraminifera of the genera *Globigerina* and *Globorotalia* have been described from the lower part of the succession (C. G. Adams in Soper *et al*. 1976a).

Depositional environment. The succession is interpreted as deposited in shallow marine to deltaic environment with distributary channel mouth bars.

Boundaries. The lower boundary is everywhere sharp to silty mudstones and thin-bedded sandstones of the Fairytale Valley Member (Fig. 17).

Distribution. The member crops out in western, central and southern parts of the Kangerlussuaq Basin and show increasing thickness towards the coast (south).

Geological age. The sandstone dominated facies has not yet yielded age diagnostic fossils. It is suggested to be of Late Paleocene age based on the facies relation the surrounding members. The Gabbrofjeld section has not been sampled by the present authors, but the stratigraphic position and genetic relations with the surrounding members are consistent with a late Selandian or possibly Thanetian age. Soper *et al*. (1976a) indicated a Danian age in their Fig. 2, although the text refers to “not specifically determinable” foraminifera of Paleocene or early Eocene age (C. G. Adams in Soper *et al*. 1976a).

Figure 16. *Cross-bedded shallow marine sandstones of the Klitterhorn Member in Vandfaldsdalen. Cross-set is c. 5 m high.*

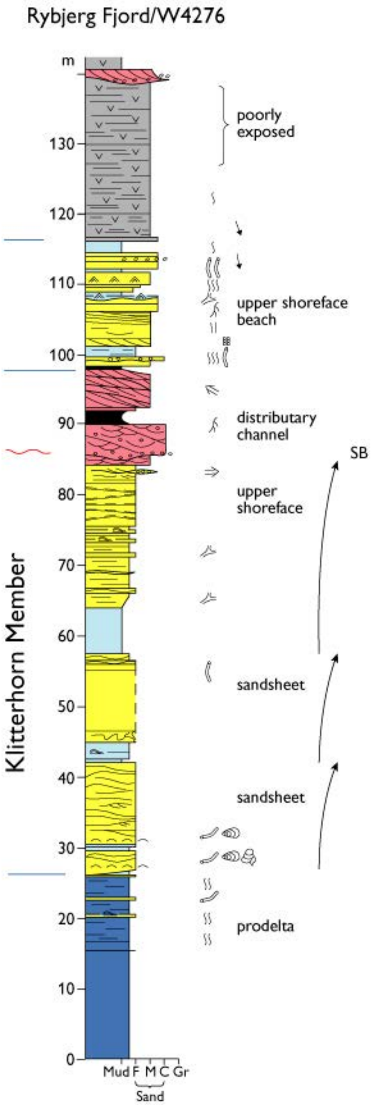

Figure 17. *Type section of the Klitterhorn Member in the inner part of Ryberg Fjord. For legend see Fig. 8.*

Blosseville Group

Redefined

History. The unit was originally defined as the Blosseville Group by Soper *et al.* (1976a).
Name. The name is based on Blosseville Kyst, which stretches from Kangerlussuaq to Scoresby Sund.
Type area. The type area for the whole group is the coastal mountain range of the Blosseville Kyst between Scoresby Sund and Kangerlussuaq.
Reference localities. Only the primarily sedimentary rocks of the Vandfaldsdalen Formation and component members are studied here. For higher units, from the first extrusive lavas in the upper part of the Vandfaldsdalen Formation and in the Miki, Hængefjeldet and Irminger formations see Bird *et al.* (1985) and Pedersen *et al*. (1997).
Thickness. A total thickness of about 9 km of succession is ascribed to the group.
Lithology. The lithology of the group is predominantly plateau basalt; the basal pre-basaltic sediments include: pale conglomerates, pale arkosic sandstones, reworked dark volcaniclastic sandstones (upper parts), arkosic sandstones, mudstones and minor coals.
Biota. Plant debris is most common; but poorly preserved mollusca, with some fish remains are very sparse. Moulds and charred remains of tree trunks and branches occur in hyaloclastic flow-breccias.
Depositional environments. Environments range from marginal marine to fluvio-lacustrine with subaerial ash fall into an aqueous environment as well as basaltic lava flows and hyaloclastic breccias showing subaqueous and subaerial emplacement.
Boundaries. The base of the group lies unconformably on the Kangerlussuaq Group in most of the central part of the basin, and where this is cut out near the margins of the basin, the group lies directly on Archean gneiss at Narren and Korridoren.
Subdivision. From the base upwards the Blosseville Group is subdivided into: Vandfaldsdalen, Miki, Hængefjeldet and Irminger formations. Only the Vandfaldsdalen Formation is described below.
Distribution. The group is widely exposed between the south side of Scoresby Sund and Kangerlussuaq, occurring across most of the Kangerlussuaq Basin and extending well to the north and northeast of the basin. One small outcrop occurs west of Kangerlussuaq at Amdrup Pynt (Wager 1947, p. 14).
Geological age. The sedimentary and volcanic rocks range from Paleocene to Oligocene, of which only the Thanetian and Ypresian are recognised in this study.

Vandfaldsdalen Formation

Redefined

History. The Vandfaldsdalen Formation was originally named by Soper *et al.* (1976a). Since that time it has been placed in the Blosseville Formation by all workers apart from Hamberg (1990) who placed all the pre-basaltic sediments of the Kangerlussuaq Basin in the Kangerdlugssuaq Group.
Name. The formation is named after Vandfaldsdalen, a valley on the N side of Miki Fjord in the southwest of the basin, where sedimentary rocks were discovered by Wager (1934).
Type locality. North side of Miki Fjord (Soper *et al.* 1976a).
Reference locality. Ryberg Fjord, Kulhøje
Thickness. Soper *et al.* (1976a) gave the thickness as up to *c* 925m at Ryberg Fjord, but this includes c 500 m of hyaloclastic breccias etc.
Lithology. Sandstones range from pale, arkosic and volcaniclastic-free to dark with much volcaniclastic debris; mudstones are subordinate; the upper part is dominated by plateau basalts and hyaloclastic breccias.
Biota. Poorly preserved carbonaceous wood fragments and tree trunks.
Depositional environment. Distal fluvial, lacustrine and shallow marine all influenced by volcanic activity.
Boundaries. The base of the Formation is marked by the base of a widespread fluvial sheet sandstone marking a regional unconformity (Figs 17, 18). The Vandfaldsdalen Formation lies unconformably on Archean basement and sediments of Early Cretaceous to Early Paleocene age.
Subdivision. Three members are recognised from the base upwards: the Schjelderup, Willow Pass and Kulhøje members. In addition a thick package of volcanic sediments and extrusives are present in the upper part of the formation. No attempt to subdivide these into formal members has been made in this study.
Distribution. The formation is exposed throughout the basin, but is thickest developed in the coastal region.
Geological age. Palynological dating ranges from Thanetian to Ypresian in the pre-basaltic sediments (Kelly *et al*. 2000; Jolley & Whitham 2004a). The earliest date of the basaltic volcanism in southern East Greenland is 61 Ma (Hansen *et al.* 2001).

Schjelderup Member

Redefined Member

History. The Schjelderup Member as used here corresponds to the Ryberg Sandstone Bed of Soper *et al*. (1976a). The term ’Ryberg Sandstone Bed’ is not recommended for use because of its confusion with the term Ryberg Formation which was introduced by Soper *et al.* (1976a) at the same time and for a separate unit (see above). The member is used in a somewhat restricted way compared to the original definition. In this study it refers specifically to a pale coarse-grained sheet sandstone unit up to 20 m thick which have been recognised as a marker bed throughout the basin.

Name. The member is named after the Schjelderup Glacier, between the heads of J.C. Jacobsen Fjord and Ryberg Fjord.

Type locality. Locality 3 of Larsen *et al.* (2001) (W4276), 0.5 km W of the western head of Ryberg Fjord, at the eastern head of the Schjelderup Glacier.

Reference localities. Sødalen, Nansen Fjord, W4212a, W4230, W and N Sediment Bjerge.

Thickness. The thickness of the Schjelderup member varies from: 12m (Ryberg Fjord), 10.5 m (W4212a) to 20 in the Nansen Fjord area.

Lithology. Sheet-like pale coarse-grained sandstones are the dominant lithology (Fig. 18). The conglomerates and pebbly sandstones have an arkosic sandstone matrix and pebbles dominated by subrounded and rounded clasts between 2–9 cm (maximum 20 cm). The clast composition varies between localities from monomict assemblages of either vein quartz or gneiss to polymict assemblages of gneiss, vein quartz and reworked sedimentary rocks. Fine-grained carbonaceous detritus is common and locally imprints of rafted logs up to 3 m long occur. The sandstones are associated with overbank heteroliths, lacustrine mudstones and coarse-grained crevasse channel-fills (Fig. 19). The fluvial sandstones are locally associated with minor deltaic mouthbar deposits. The clast-supported conglomerates are strongly cemented whereas the pebbly sandstones are generally unconsolidated, suggesting decemented matrix. In the west and south of the region a conglomeratic unit occurs at the base of the succession. Exposures to the north of Sortekap Fault contain beds of conglomerate with clasts up to 20 cm in diameter.

Biota. No fossils apart from coalified wood fragments and logs have been preserved in the coarse-grained facies.

Depositional environment. The widespread multi-storey sheet sandstones composed of trough cross bedded sandstones and pebbly sandstones of the Schjelderup Member represent a fluvial system with proximal braid-plain river channels from 15– 30 m in width and 3–6 m in depth (Larsen *et al.* 1999a, part of Facies Assemblage 5). They were characterised by migrating dunes and downstream accretion on large scale compound longitudinal or transverse sandbars (Miall 1985). Foreset azimuths and trough axes show dominant palaeocurrents towards the east and southeast. Periodic failure of channel margins caused formation of slumped beds of sandstones and overbank mudstones. Vegetation probably formed in interchannel areas, but the immature soil horizons and lack of autochthonous coal beds suggest that interchannel areas were unstable. Furthermore, the low ratio of overbank deposits relatively to bedload-dominated channel-fill deposits, suggests, that repeated channel migration cannibalised most of the fine-grained sediment within the floodplain. The sheet sandstone is interpreted as amalgamated, channel-fill deposits formed on a proximal braidplain during a period of low subsidence rate.

Boundaries. The base of the bed is sharp and erosional on the Sediment Bjerge Formation which may be cut out and it rest on units from the Christian IV Formation in northern Sediment Bjerge (P.2373) down to the Archean gneiss basement at Amdrup Pynt and Mellemø (Higgins & Soper, 1981), Korridoren (W4256) and Narrren (W4232). The top of the unit is placed at the top of the sheet sandstone corresponding to the basal mudstones of the Willow Pass Member.

Distribution. The Schjelderup Member has been recognised throughout the outcrop area Mellemø east to Nansen Fjord (west) and north to the Nunatak Narren and south to the Fjord region.

Geological age. The member has not been dated, but is referred to the latest Paleocene – earliest Eocene based on datings of the Fairytale Member below and the Willow Pass and Kulhøje members above.

Figure 18. *Sheet sandstone composed of amalgamated fluvial channel sandstones c. 20 m thick northeast of Nansen Fjord. The sheet sandstone forms the Schjelderup Member of the Vandfaldsdalen Formation. Photo towards the East.*

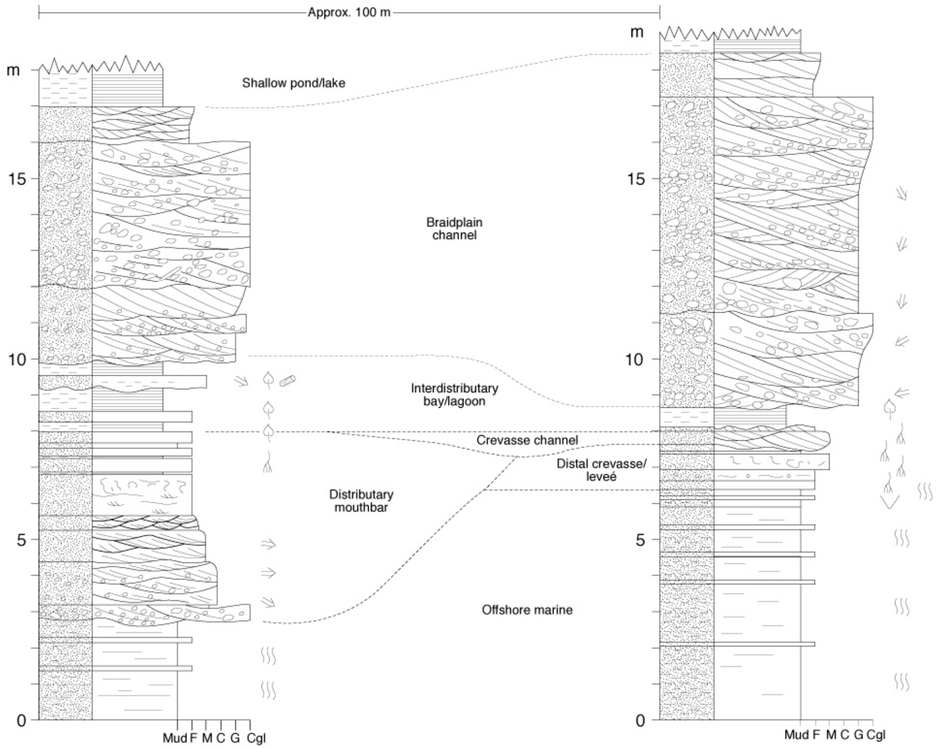

Figure 19. *Amalgamated channel sandstones of the Schjelderup Member in Fairytale Valley (M9503). For legend see Fig. 8.*

Willow Pass Member

New member

History. The Willow Pass Member includes that part of the original description of sedimentary rocks of the Vandfaldsdalen Formation of Soper *et al*. (1976a), which lay above the 'Ryberg Sandstone Bed' (i.e. above the present Schjelderup Member) and are characterised by a mixture of siliciclastic sediments and pyroclastic debris.

Name. The Willow Pass Member takes its name from Willow Pass, southern Sediment Bjerge as defined by Higgins & Soper (1981).

Type locality. Willow Pass (M0004)

Reference locality. Nansen Fjord, Ryberg Fjord

Thickness. 40 m at the type section.

Lithology. The Willow Pass Member consists of a mixed succession of sandstones and carbonaceous mudstones with strong influence of volcanic activity (Fig. 20). Some sandstones are sheet-like and bioturbated. Coals occur at the top of the succession at locality W4230. At this locality the succession is dominantly lenticular fining upwards units of cross-bedded and ripple cross-laminated sandstones. The cross-bedded sandstones show mudstone drapes on foresets, but are unbioturbated.

Biota. Finely comminuted plant debris is common; occasionally leaves are preserved. Poorly preserved marine faunas contain bivalves, including *?Garum* and *?Dosiniopsis*, gastropods, *?Siphonalia.* Palynologically the member is characterised by a non-marine assemblage P3 containing abundant *Inaperturopollenites hiatus* and restricted to localities W4233b and W4256 in the north of the Kangerlussuaq Basin. Bioturbation (*Planolites* sp.) is common in the thin sheet-like sandstone bodies.

Depositional environment. The member is a genetic continuation of the underlying fluvial Schjelderup Member reflecting a gradual flooding of the area. The depositional environment of the mudstone dominated Willow Pass member is predominantly a low-lying floodplain, dissected by small fluvial channels. The bioturbated sheet-like sandstone bodies represent episodic shallow marine incursions (Fig. 20).

Boundaries. The Willow Pass Member rests with apparent conformity on the coarse-grained sheet sandstone of the Schjelderup Member. The top is conformable or interfingers with parallel bedded mudstones of the Kulhøje Member. Sharp upper boundaries are present where the member is overlain by volcaniclastic facies and lava flows of the Vandfaldsdalen Formation.

Distribution. The member is exposed widely in the southern part of the basin and in the Sediment Bjerge.

Geological age. The dominantly terrestrial Willow Pass Member has yielded a spore pollen assemblage that correlates with the Brito-Arctic Igneous Province flora. The member is thus Thanetian or Ypresian (earliest Eocene) in age (Boulter & Manum 1989; Hjortkjær & Jolley 1999). New studies by Jolley & Whitham (2004a) suggest an early Eocene T40 age for the member.

Comment. In poorly exposed sections it may be difficult to distinguish channel sandstones of the Willow Pass Member from the sandstone unit forming the Schjelderup Member. In general the Schjelderup Member is coarser-grained, contains several amalgamated channel units, and the unit is laterally continuous.

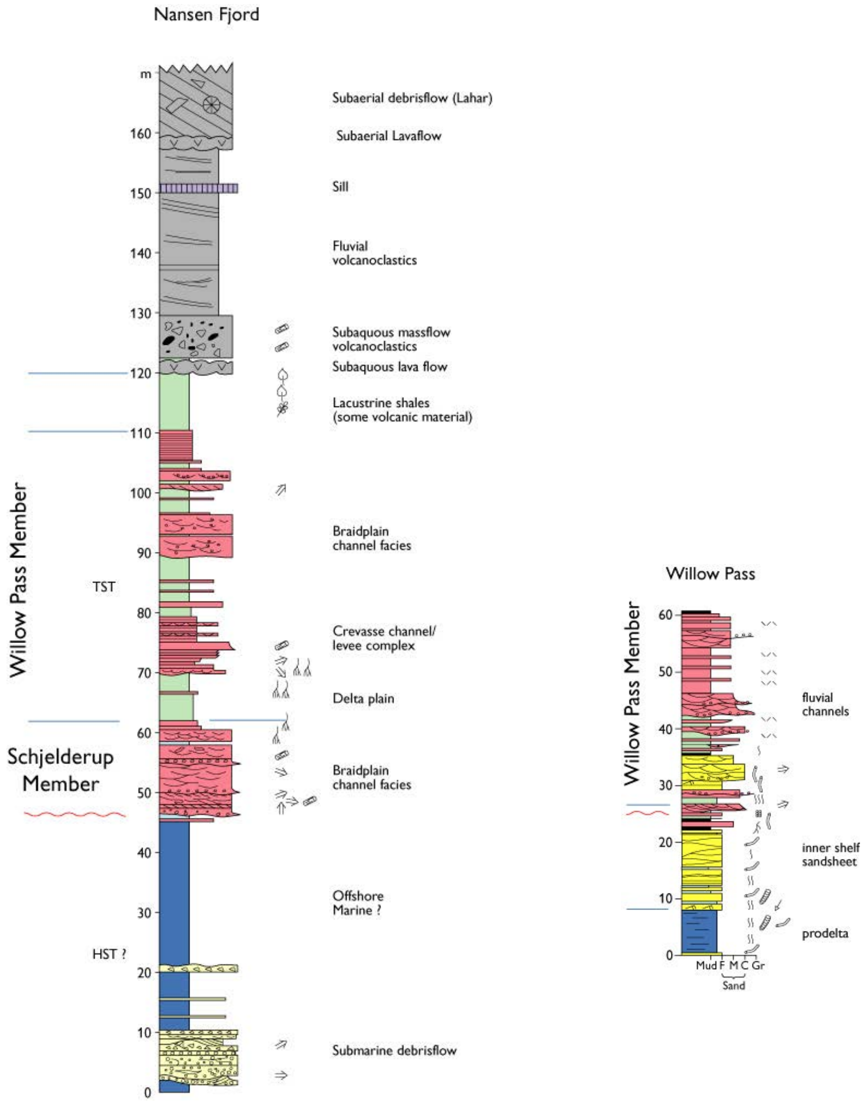

Figure 20. *Two sections through the Willow Pass Member. Note the periodic marine incursion in the lower part of the Member at the type locality; Willow Pass. For legend see Fig. 8.*

Kulhøje Member

New Member

History. Lacustrine sediments above the Schjelderup Member were first recognised by Nørgaard-Pedersen (1991). These sediment are the basis of the member. The Kulhøje Member was originally included in the upper part of the original description of the Vandfaldsdalen Formation of Soper *et al.* (1976a), which is otherwise characterised by basaltic rocks.

Name. The member is named after the Nunatak area Kulhøje, northwest of Christian IV Gletscher.

Type locality. At the northernmost nunatak of the Kulhøje area (informally named "Sequoia Nunatak" by Nørgaard-Pedersen 1992)

Reference locality. Good exposures of the member are also found at P2374 in the northern Sediment Bjerge. The base of the member is seen at W4230 and Nansen Fjord.

Thickness. The thickest developments of the member are in the Sediment Bjerge and north to "Sequoia Nunatak". At its type section the member is around 100 m thick. It is 10 m thick to the East of Nansen Fjord > 25 m thick at W4311 and around 150 thick at P2373

Lithology. The succession is dominated by parallel-bedded dark fissile mudstones showing parallel lamination, which are interbedded with beds or laminae of pale silt-sand grade volcaniclastic material (Fig. 21).

Biota. There are no macrofauna found in the unit. Leaf fossils are found in some units showing a varied flora assemblage. Hoch (1992) figured an leaf assemblage from Kulhøje comprising: *Metasequoia occidentalis* (Newberry) Chaney, *Cercidiphyllum arcticum* (Heer) Brown, *Nordenskioeldia borealis* Heer and *Paranymphaea crassifolia* (Newberry) Berry dated as Late Paleocene. Hoch (1990) also recorded *Macclintockia* from the Sediment Bjerge of similar age and found the specimen comparable to West Coast Greenland records of Koch (1963). Pollen are abundant in the sediments at "Sequoia Nunatak".

Boundaries. The lower boundary is sharp but probably conformable on the Schjelderup or Willow Pass member (Fig. 22). It is placed at the point where sandy or muddy fluvial or flood plain deposits are overlain by black parallel laminated mudstones or graded airfall deposits. The top is placed at the first subaerial lava bed or coarse conglomeratic unit.

Distribution. The member is found in the Sediment Bjerge and north to Kulhøje. It is thinly developed to the east of Nansen Fjord and not present to the west of the Sorgenfri Gletscher.

Geological age. The member was first dated by Hjortkjær & Jolley (1999) as Late Paleocene (T38) but this age was later revised by Jolley & Whitham (2004a) to earliest Eocene (T40). Studies of spores and pollen by McIntyre (this study) suggest a Paleocene age compared to the Canadian palynological zonation (Appendix 2).

Facies and depositional environments. Interbedded dark mudstones and pale volcaniclastic siltstones and sandstones characterise the member (Fig. 21) Mudstones vary in colour from dark grey to greenish and may develop a bedding parallel fissility. The units vary from mm to 10's cm thick and have sharp or gradational bed bases. Interbedded with the mudstones are sandstones. These sandstones are up to medium sand grade, but typically very-fine grade sand or finer. The sands are sharp based and have sharp or gradational tops and show well developed grading. Although the succession generally shows a well-developed parallel bedding, scours may be developed. Sand beds drape these scours without obvious thickening in the lows. Thick parallel-sided beds up to 1m are also developed at P2373. These are composed of contorted and folded sandstones and mudstones and have sharp upper and lower contacts. Other units have a more homogeneous nature and contain isolated matrix-supported folded and contorted clasts.

The parallel-bedded sandstones and mudstones, which make up this succession, were largely deposited by suspension fall-out processes. The dark mudstones represent the background sedimentation the sandier beds represent airfall ash deposits and fall out of muddy sediment from suspended plumes in the surface layers of the lake following flood events. A turbidite origin for some of the sand beds cannot be ruled out. Beds showing contorted strata and homogeneous beds with isolated clasts were produced by gravity induced sliding and debris flows respectively (e.g. Facies A1.2 and F2.1 (Pickering 1986). Isolated scours in the succession were probably formed by slope failure. The absence of a macrofauna and any bioturbation in the formation suggests non-marine possibly lacustrine sedimentation. Slide and deposits and debris flows deposits indicate the presence of slope and base of slope environments at some localities.

Figure 21. *Interbedded dark mudstones and pale volcaniclastic siltstones and sandstones of the Kulhøje Member. Lens cap for scale.*

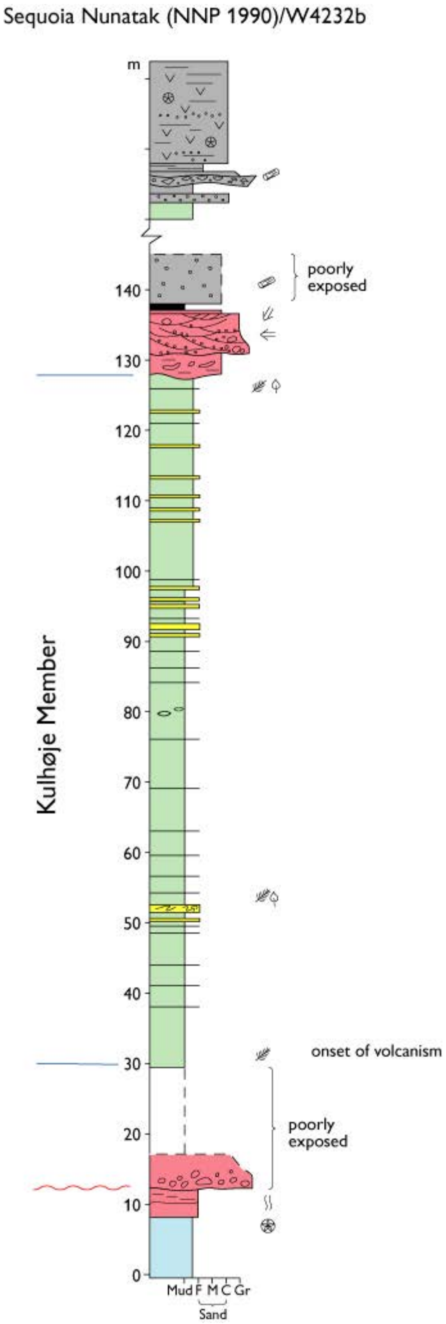

Figure 22. *Type section of the lacustrine Kulhøje Member at "Sequoia Nunatak". For legend see Fig. 8.*

Unnamed volcanics

History. The Sequoia Nunatak and the Willow Pass Members interfinger with a succession of pyroclastic rocks, hyaloclastites and thin-bedded basalt flows. The volcanics were included in the original description of the Vandfaldsdalen Formation, Soper *et al.* (1976a) and have been described in detail by Ukstins *et al.* (2003). As the succession is dominated by volcanic rocks the present authors have not attempted to subdivide the remainder of the Vandfaldsdalen Formation into members. A short description is included for completeness.
Name. Not assigned
Type locality. Not assigned
Reference localities. The unit is well exposed in the coastal region along the Miki, I.C Jacobsen and Ryberg Fjord (see Ukstins *et al.* 2003).
Thickness. The volcanic rocks are up to 820 m at Ryberg Fjord.
Lithology. The basaltic rocks include: fine-grained vesicular basalt flows, some with pillowed bases and some with reddened polygonally jointed or rubbly tops (Ukstins *et al*. 2003). Laminated mudstones and siltstones contain volcanic ash; fine sandstones are purely volcaniclastic detrital tuffs, well-bedded with grading and cross bedding; green to purple siltstones are ripple laminated. Intrabasaltic siliciclastic sandstone beds are present at Sødalen and Ryberg Fjord.
Biota. 60 m above the base of the hyaloclastic breccia in Ryberg Fjord, Soper *et al*. (1976a) recorded *Wetzeliella homomorpha.* Taxonomic revisions know refer the Wetzeliella to *Apectodinium* and the flora probably follows the Late Paleocene Thermal Maximum (LPTM) leading to a flooding by *Apectodinium* species in the succession.
Depositional environment. The subaerial extrusive volcanic, including pyroclastic rocks, hyaloclastites and thin-bedded basalt flows created a topography on which ephemeral lacustrine deposits formed. In Sødalen and around Ryberg Fjord two sandstone marker beds up to 5 m thick are developed in the lowermost part of the volcanic succession. The beds consist of almost pure siliciclastic material and were deposited in fluvial and shallow marine environments.
Boundaries. The lower boundary interfingers and is conformable with the Willow Pass and Kulhøje members. The upper boundary is conformable with the hyaloclastites of the Hængefjeldet Formation (Soper *et al.* 1976a).
Distribution. The Lower volcanic succession is widespread in the coastal region of the Kangerlussuaq area. A significant thickness variation across the basin suggests that deposition in the early volcanic phase was still controlled by the old tectonic lineaments delineating the underlying sedimentary basin.
Geological age. The member has not been dated, but based on the proposed Early Eocene age of the correlative Kulhøje Member it is tentatively referred to the earliest Eocene. The *Wetzeliella* flora indicates an early Sparnacian age (Soper *et al.* 1976a, p. 95) corresponding the Ypresian (early Eocene). This early Eocene (T40) age is supported by Jolley & Whitham (2004a) based on correlation with the North-East Greenland flora assemblages.

However, the palynological evidence contrasts with radiometric datings of basalts belonging to the Urbjerget Formation (Hansen *et al.* 2001). The lava flows are dated to 61 Ma (latest Danian) and form the oldest known volcanic rocks of the Paleogene East Greenland flood basalt province.

Biotas and Biostratigraphy

The fossils collected during this study have three principal uses. Firstly they provide a biostratigraphic framework; secondly they contribute to palaeoecological and palaeoenvironmental interpretation; and thirdly through reworking, they may also give indication of strata which have been adjacent to, or are no longer present *in situ*, in the Kangerlussuaq Basin. Particularly important during this work has been the integration of micro- and macro-palaeontological studies to refine the biostratigraphy. Working in isolation on certain groups can easily lead to serious biostratigraphic misinterpretations. There has been large scale slumping and reworking of Cretaceous strata during the Early Paleogene. For example, the assemblages of Maastrichtian ammonites and dinoflagellate cysts may also contain spores and pollen of Tertiary age. The ammonites may contribute to the knowledge of the local history of deposition in the Cretaceous, but the associated microflora may indicate local reworking of the original sediment at a later time. Microbiota are readily collected in the Kangerlussuaq Basin from the poorly consolidated mudstone-dominated sediments. However, they may not be preserved locally because of the thermal metamorphism caused by the many intruded sills and dykes. Macrofaunas are not usually abundant, but locally, biostratigraphically important ammonites belemnites and bivalves will proved accurate dating, and may be preferentially preserved in areas of contact metamorphism, especially in the sediments immediately overlying sills.

The distribution of the principal Kangerlussuaq biotas according to the lithostratigraphic units in which they were collected has been cited in the formal lithostratigraphic descriptions above. The biostratigraphically significant biotas are reviewed here first by major taxonomic group and then stage by stage (Fig. 23).

Ammonites

Ammonites were first collected from the Kangerlussuaq area in 1974 in the Sorgenfri Formation and Ryberg (now Sediment Bjerge) Formation. Although unnamed, ammonites of the lower level were attributed by Hancock (in Soper *et al*. 1976a) to the *Mantelliceras saxbii* Subzone of the *Mantelliceras mantelli* Zone, Cenomanian. The higher levels produced *Pachydiscus gollevillensis* (d'Orbigny), which was believed to be of Late Campanian to Early Maastrichtian age, although the species is currently the Early Maastrichtian standard zonal indicator in the European succession Hancock 1991). The first illustrated specimen was an unidentified ammonite by Hoch (1983, fig. 2) from the Sediment Bjerge. Nørgaard-Pedersen (1991) first recognised scaphitid ammonites at Sequoia Nunatak. The Late Aptian substage was first recognised on the presence of *Tropaeum subarcticum* Casey in the lowest sandstones of the basin (Callomon in Larsen *et al.* 1999a). At a slightly higher level yielded Lower Albian ammonites (Larsen *et al.* 1999a) but the age is not substantiated in the present work and the ammonites are believed here to be of Middle Albian age.

New records indicate the presence of at least the following nine assemblages (Fig. 23):

9. *Discoscaphites aff. angmartussutensis, Diplomoceras cylindraceum* (Defrance) (Late Maastrichtian)

8. *Acanthoscaphites tridens, Jeletzkytes* sp*., Hoploscaphites* sp. nov.*, Neophyloceras greenlandicum, Saghalinites wrighti; Anagaudryceras cf. leuneburgense, Pachydiscus* sp*. Diplomoceras cylindraceum, Baculites* sp*.* (Early Maastrichtian; *Acanthoscaphites tridens* Zone former *Pachydiscus neubergensis* Zone)

7. *Gaudryceras (Mesogaudryceras) leptonema* (Mid– to Late Cenomanian)

6. *Phylloceras (Hypophylloceras) lombardensis, Gaudryceras (G.) casssisianum, Gaudryceras (Mesogaudryceras) leptonema, tetragonitid* gen. et sp. nov.*, Parapuzosia (Austiniceras) austeni, Schloenbachia varians* (Early Cenomanian; *Mantelliceras mantelli* Zone, *Mantelliceras saxbyi* Subzone).

5. *Mortoniceras* (*Deiradoceras*) sp., *Euhoplites boloniensis* (Spath), *Hamites* sp. (Late Albian; *Mortoniceras inflatum* Zone, *Hysteroceras orbignyi* Subzone,).

4. *Euhoplites loricatus*, *E*. sp. *?aspasia* Spath, *Anahoplites* sp. *planus* group, (Middle Albian; *Euhoplites loricatus* Zone, *Anahoplites intermedius* Subzone).

2. *Tropaeum subarcticum* Casey (Late Aptian; *Acanthoplites nolani* Zone former *Parahoplites nutfieldiensis* Zone).

1. *Parancyloceras bibentatum* (von Koenen), *Lytoceras Polare* (Late Barremian; *Parancyloceras bibentatum* Zone)

Belemnites

Belemnites were originally collected by Wager from Sortekap Passet and were initially dated by Swinnerton (in Wager and Deer 1939) as 'Senonian'. The fauna was originally described (Swinnerton 1943) as containing *Actinocamax* cf. *blackmorei* Crick, *A.* cf. *plenus* (Blainville) and *A.* sp., indicating a Senonian age. Christensen & Hoch (1983) reinterpreted the fauna as an assemblage of *A.* cf. *manitobensis* (Whiteaves) which indicated a Middle Turonian age. Hoch (1983, 1990) gave further records from Pyramiden and the Sediment Bjerge.

We now recognise the presence of three belemnite assemblages in the Kangerlussuaq area. We confirm the occurrence of *A*. cf. *manitobensis* and note the association with *Inoceramus lamarcki* group bivalves, which suggests a Late Turonian age. The records are in agreement with the occurrence of *Actinocamax* in Turonian strata of Hold with Hope (Kelly *et al*. 1998).

New records of belemnites include the group of *Neohibolites minimus* (Miller) from several sites in western Sediment Bjerge. They occur in association with ammonites of the *dentatus* to *inflatum* ammonite zones and with *Rhombodella paucispina* Zone to *Wigginsiella grandstandica* dinoflagellate cyst Subzone, ranging from Middle to Late Albian (Nøhr-Hansen 1993). *Neohibolites minimus* ranges from late Early Albian to early Late Albian of northwestern Europe (Mutterlose 1990).

Belemnitella sp. of probable Early Maastrichtian age have been found in association with *Diplomoceras* and scaphitid ammonites. It is the youngest belemnite recorded from Greenland. The record post-dates the belemnite records of *Actinocamax* and *Belmnoteuthis* of West Greenland (Birkelund 1956).

Bivalves

A probable pectinid bivalve was the first fossil reported from the Kangerlussuaq area (Wager 1934). An unidentified large species of *Inoceramus* was illustrated by Hoch (1983, fig. 2) from the Sediment Bjerge and from Pyramiden (Hoch & Hamberg 1990, figs 6, 7). Fragmentary specimens of large *Inoceramus lamarcki* group were recorded by Hoch (1991, 1992) and their relationship with the potential fish predator, the crushing tooth armed ray, *Ptychodus decurrens*. Cf. *"Pteria"* (*Oxytoma*) sp. was also recorded from the Late Cretaceous. D. Curry (in Soper *et al*. 1976a) identified *?Garum* sp. and *?Dosiniopsis* sp. in the Schjelderup Member and Nielsen *et al*. (1981) recorded *Hippopodium* sp. in tuffaceous sandstones of the Vandfaldsdalen Formation at Sødalen.

The most stratigraphically important Cretaceous bivalves in the Kangerlussuaq Basin are the inoceramids. The succession includes:

5. Spyridoceramus tegulatus (Early Maastrichtian)
4. Inoceramus lamarcki group (Late Turonian)
3. Inoceramus cuvieri (Late Turonian)
2. Inoceramus crippsi group (Early– Middle Cenomanian)
1. Actinoceramus sp. (Albian)

Other new records from the present studies include current accumulated shell pavements rich in *Arctica* and *Entolium orbiculare* in the Watkins Fjord Formation. *Mimachlamys cretosus* subsp. *denticulata* are particularly useful in the Christian IV Formation reworked into the Fairytale Valley Member of the Sediment Bjerge Formation. In northern Europe this taxon is only known from the Early Maastrichtian (Dhondt 1973).

In the Paleocene strata the marine mollusc fauna drops rapidly to being rare, with only one exception. The boulder beds at the base of the Sediment Bjerge Formation, in the Fairytale Valley Member, locality W4215, contain sandstone blocks rich in marine bivalves, particularly *Isognomon*, and oysters, some with clionid sponge borings. In addition some of the uppermost sands of the Klitterhorn Member at Sødalen contain small thin shelled but indeterminate bivalves.

Echinoids

Rich new faunas of irregular echinoids are typical of the Christian IV Formation and include spatangids, holasterids, hemiasterids, and conularids or galeritids. They are currently investigated by John Jagt. There are also new records of echinoids from the Sorgenfri Formation.

Vertebrates

Vertebrate material is scarce, but Hoch (1989) and Hoch & Hamberg (1990) illustrated a crushing tooth of *Ptychodus decurrens* and recorded chondostrean vertebrae from the Turonian. This study includes new records include lamnid(?) shark teeth from the base of the Vandfaldsdalen Formation.

Other macrobiota

Gastropods

Gastropods make up a small proportion of the Cretaceous and Tertiary faunas. D. Curry (in Soper *et al*. 1976a) identified *?Siphonalia* in the Schjelderup Member.

Small gastropods and the nautiloid *Eutrephoceras* are present in the Late Maastrichtian sediments.

Crustacean

Crustacean carapaces are often associated with phosphatised concretions in the Albian and Maastrichtian. Calcareous worm tubes and a possible scaphopod occur associated with the bivalves in the Fairytale Member boulders.

Plant macrofossils

Plant macrofossils were originally collected by Wager from Sequoia Nunatak and compared to the Mull Leaf Bed by Seward (in Wager & Deer 1939) and believed to be of Late Cretaceous to Early Eocene age. They were described by Seward & Edwards (1941) who identified leaves of *Sequoia*, *Elatocladus*, *Platanus* and *Cercidiphyllum* and fruits of *Cercidiphyllum* and *Palaeanthus*, who concluded an Early Eocene age. This material is now believed to come from the Sequoia Nunatak Formation and is now believed to be of Sparnacian (earliest) age. Nørgaard-Pedersen (1991) identified leaves of *Sequoia/Metasequoia* and *Cercidophyllum* in the lower part of the section at Sequoia Nunatak which he believed was Late Cretaceous to Paleocene, but which may belong to the Christian IV Member and thereby be Late Cretaceous in age (Larsen *et al*. 2001, p. 101).

Hoch (1992) figured an leaf assemblage from Kulhøje comprising: *Metasequoia occidentalis* (Newberry) Chaney, *Cercidiphyllum arcticum* (Heer) Brown, *Nordenskioeldia borealis* Heer and *Paranymphaea crassifolia* (Newberry) Berry dated as Late Paleocene. Hoch (1990) also recorded *Macclintockia* from the Sediment Bjerge of similar age and found the specimen comparable to West Coast Greenland records of Koch (1963).

New collections include pine cones from the Watkins Fjord Formation and drifted leaves including those of angiosperms from the Maastrichtian.

Oncoliths

Local conglomeratic lenses rich in oncoliths occur at the base of the Sorgenfri Formation in the eastern part of Sediment Bjerge (W4248, W4249). These are nucleated on rock fragments and quartz pebbles. They are of probable algal/cyanobacterial origin and are typical of high energy photic zone in clear water.

Palynology

Dinoflagellate cysts were first recorded in the Kangerlussuaq area by Downie in Soper *et al.* (1976a). A substantial microflora was recovered by Soper *et al*. (1976a, p. 87) from the Upper Albian of the Sorgenfri Formation, and in the former Ryberg Formation (now Christian IV Formation) of ascribed Cenomanian–Danian age. L. Costa (in Nielsen *et al*. 1981) recognised what she believed were Campanian to Danian dinoflagellate cysts from this unit in Sødalen. In the Vandfaldsdalen Formation a *Wetziella* flora was obtained, and attributed to the Sparnacian (Soper *et al*. 1976a)

The dinoflagellate cyst succession of the Greenland Cretaceous, proposed by Nøhr-Hansen (1993, 1996) for the Early Cretaceous on the East Coast and Late Cretaceous of the West Coast respectively, has been a very valuable biostratigraphic tool. However we have made some revisions to the ages originally attributed by Nøhr-Hansen (1993), particularly with regard to zones which he originally placed in the Albian Stage, and which we would recalibrate as Albian to Turonian in age (Kelly *et al*. 2002). Nøhr-Hansen's (1993, 1996) stratigraphies were not originally applied to the Kangerlussuaq area. However, we have applied Nøhr-Hansen's schemes in the area with considerable success and recognised zones from the *Rhombodella paucispina* Zone to the *Wodehouseia spinata* interval of Mid Albian to earliest Late Maastrichtian age.

In the Early Paleogene sedimentary rocks of the Kangerlussuaq Basin, the most valuable biostratigraphic tool is palynology, but it lacks integration with other taxonomic groups, although there is correlation with magnetostratigraphy elsewhere (Jolley & Whitham 2001; Jolley & Whitham 2004a).

In this study palynological work by Nøhr-Hansen have proven dinoflagellate cysts of Danian, Early Selandian and Late Selandian–Early Thanetian age in the Sediment Bjerge Formation (Appendix 1). This is in contrast with previously published ages given by Jolley & Whitham (2004a). They believed that in all sections in the Sediment Bjerge Formation and in the Schjelderup Member of the Vandfaldsdalen Formation are represented by the T40 assemblage and are of undifferentiated Thanetian– Sparnacian age. Recent work on sections in Fairytale Valley member, however, has confirmed the Early Paleocene ages and the member is now assigned to the Selandian (Jolley & Whitham 2004b).

Data by Braham (in Kelly *et al*. 1999) from the Vandfaldsdalen Formation indicated three marine to non-marine palynofloras, which were perhaps overlapping, and ascribed an age range of Thanetian to Ypresian age. Hjortkjær & Jolley (1999) thought they recognised an unequivocal Thanetian T36– T38 palynoflora (Ebdon *et al*. 1995) from Kulhøje, but this age has later been revised to T40 (Jolley & Whitham 2004a). The Willow Pass Member, which contains the earliest volcanic ashes, is also attributed to the T40 assemblage, but it is of Sparnacian (earliest Eocene) age. McIntyre (this study) compared the spores and pollen from the Kulhøje Member with the Canadian palynostratigraphic charts and concluded an unequivocal Paleocene age of the succession (Appendix 2).

The final conclusion on the age of the palynological assemblages awaits the results from the ongoing Sindri project that will focus on critical Cretaceous–Paleogene transition.

Foraminiferids

Foraminiferid studies from the Cretaceous rocks of Kangerlussuaq, and indeed from Greenland are very limited and restricted mainly to unpublished reports. Soper *et al*. (1976a, p. 91) recorded *Globigerina* and *Globorotalia* from the marine upper part of the Ryberg Formation near Gabbrofjeld. Drilled sections from formerly nearby offshore areas including the Shetland area, the North Atlantic (both commercial and ODP drill legs) and the North Sea allow a comparative zonation to be used. The most relevant Cretaceous and Tertiary zonations, developed for the North Sea area, were published by Gradstein *et al*. 1988, King (1989) and King *et al*. (1989). The Cretaceous was also investigated from offshore wells selected between East Greenland and Norway by Gradstein *et al*. (1999). This zonation utilises most of the datums selected by King *et al*. (1989), as well as some new Late Cretaceous markers for agglutinate-rich samples.

Within the Paleogene, the standard zonation is based on the distribution of planktic foraminiferids (e.g. Berggren & van Couvering 1974; Berggren *et al*. 1985), which were not commonly recovered in the sections so far studied in southern East Greenland. As with similarly dated sections from the North Sea and Atlantic areas, agglutinating foraminiferids were dominant. Where possible the ranges of the agglutinating foraminiferids have been correlated to these planktic foraminiferid zonations in deep water basinal areas of NW Europe (e.g. Gradstein *et al*. 1994; Charnock & Jones 1990). However, it must be noted that agglutinating foraminiferids are more likely to be affected by facies dependent distribution patterns than the planktic taxa.

Microfossil recovery from the small number of spot samples selected for the Kangerlussuaq micropalaeontological pilot study was found to be variable, from poor to moderately diverse. However, most samples yielded microfaunas, indicating that at the very least marginal marine conditions existed for the samples analysed. The microfaunas were dominated by agglutinating foraminiferids. However, calcareous benthic foraminiferids, planktic foraminiferids, rare diatoms, radiolaria, ostracods and miscellaneous microfossils (including bivalve fragments and woody material) were also recovered. Within the Cretaceous three distinctive associations can be ascribed to a *Recurvoides* spp. event (Middle to Late Albian), the *Uvigerinammina una* Zone (early Late Albian), and the *Hedbergella delrioensis* event (early– mid Cenomanian).

Radiolarians

Rare radiolarians, *Cenodiscus* spp. and *Orbiculiforma* sp., occur in the upper part of the *S. kalaalliti* Zone (*Hapsocysta bentea* Subzone), and may herald a biosiliceous event in the late Cenomanian/Turonian. *Cenosphaera minuta* from the upper part of the succession is no older than Danian, and association with Cretaceous fossils indicates reworking.

Diatoms

The diatom *Fenestrella bellii* occurs in the upper part of the *Wigginsiella grandstandica* Subzone although the genus first appears in the *Leptodinium hyalodermopse* Subzone in East Greenland. *Coscinodiscus* spp. from the upper part of the succession indicates a Tertiary age.

Group	Formation	Member	Macrofaunal assemblages	Ammonite zone	Ammonite subzone	Belemnite Zone	Bivalve Zone	Palynology Zone/ Assemblage*	Palynology Subzone	Substage	Stage	Sub-Period	Period
Blosseville Group	Sedimentbjerge Fm	Fairy Tale Valley Mbr									Selandian	Paleocene	Paleogene
			Not recognised								Danian		
Kangerlussuaq Group	Christian IV Fm		Ammonites: *Discoscaphites* aff. *angmartussutensis, Diplomoceras cylindraceum*					***Wodehousia spinata***		Late	Maastrichtian	Late	Cretaceous
			Ammonites: *Acanthoscaphites tridens, Jeletzkytes* sp., *Hoploscaphites* sp. nov., *Neophyloceras greenlandicum, Saghalinites wrighti; Anagaudryceras* cf. *leuneburgense, Pachydiscus* sp. *Diplomoceras cylindraceum, Baculites* sp.; belemnites; bivalves: *Spyridoceramus tegulatus, Mimachlamys cretosa denticulatus, Lucina sp., Protocardia* sp.; scaphopods; brachiopods; echinoids; crinoids	*Acanthoscaphites tridens*			*Spyridoceramus tegulatus*	***Cerodinium diebelli***		Early			
								Isabelidinium cooksoniae		Late	Campanian		
										Mid			
										Early			
										Late	Santonian		
			Not recognised							Mid			
										Early			
										Late	Coniacian		
										Mid			
	Sorgenfri Fm							***Arvalidinium scheei***		Early			
			Belemnite: *Actinocamax* cf. *manitobensis*; bivalve: *Inoceramus lamarcki* gp.; trace fossils: *Rogerella* sp.			*Actinocamax* cf. *manitobensis*	*Inoceramus lamarcki*	***Subtilisphaera kalaalliti***	***'Epilepidosphaeridia spinosa'***	Late	Turonian		
										Mid			
										Early			
			Gaudryceras (Mesogaudryceras) leptonema							Late	Cenomanian		
										Mid			
			Ammonite: *Phylloceras (Hypophylloceras) lombardensis, Gaudryceras (G.) casssisianum, Gaudryceras (Mesogaudryceras) leptonema*, tetragonitid gen. et sp. nov., *Parapuzosia (Austiniceras) austeni, Schloenbachia varians*; bivalves: *Inoceramus crippsi*.	*Mantelliceras mantelli*	*Mantelliceras saxbyi*		*Inoceramus crippsi*		***Ovoidinium* sp. 1**	Early			
									Odontochitina ancala				
									Wigginsiella grandstandica				
			Ammonites: *Mortoniceras (Deiradoceras) sp., Euhoplites boloniensis, Hamites* sp., ; belemnite: *Neohibolites* sp., bivalve: *Actinoceramus* sp.	*Mortoniceras inflatum*	*Hysteroceras orbignyi*					Late	Albian	Early	
			Hoplites sp.	?				***Rhomboidella paucispina***	*Chichauadinium vestitum*	Mid			
			Hoplites spp.; belemnite: *Neohibolites minimus* gp.	?		*Neohibolites minimus*							
	Watkins Fjord Fm	Sunnigajik Mbr	Ammonites: *Euhoplites loricatus, Euhoplites ?aspasia, Anahoplites planus* gp.; bivalves: *Actinoceramus concentricus, Entolium orbiculare, Arctica* sp.;	*Euhoplites loricatus*	*Anahoplites intermedius*		*Actinoceramus concentricus*						
									Litosphaeridium arundum				
			Not recognised							Early			
	Watkins Fjord Fm	Torsukattak Fm	Ammonite: *Tropaeum subarcticum*; bivalves: *Entolium orbiculare, Arctica* sp.; trace fossil: *Teredolites* sp.	*Acanthoplites nolani*				*Circulodinium brevispinosum*		Late	Aptian		
										Mid			
			Not recognised							Early			
								Pseudoceratium nudum					
			Ammonite: *Parancyloceras bidentatum, Lytoceras polare;* bivalves: *Arctica* sp.	*Parancyloceras bidentatum*				*Batioladinium longicornutum*		Late	Barremian		
										Early			

*only bold zones recognised in Ksngerlussuaq Basir

G E U S **Figure 23.** Macrofauna assemblages of the Kangerlussuaq Basin

Biostratigraphic summary

In this section the significant biota present stage by stage are briefly reviewed.

Pre-Aptian

Reworked dinoflagellate cysts occur particularly in Cenomanian strata and in Late Campanian/Early Maastrichtian. These occurrences indicate the former presence of sedimentary rocks in the Kangerlussuaq Basin, or adjacent to it, of the following ages:

Permian–Triassic
Striate bisaccate pollen

Triassic
?Aratrisporites spp., *?Limbosporites lundbladii*

Early/Middle Jurassic
Chasmatosporites (Triassic– Mid Jurassic), *?Kylindrocysta spp*. (Early– Mid Jurassic)

Late Jurassic
?Goniacaulacysta eisenacki (Late Callovian– Late Oxfordian), *Leptodinium cf. mirabile* (Oxfordian– Early Kimmeridgian), *Scrinodinium luridum* (Middle Oxfordian– Early Kimmeridgian sensu anglico)

Neocomian
Cassiculosphaeridia magna (Late Jurassic?/Ryazanian– Late Barremian), *Chlamydophorella nyei* (Neocomian– Early Santonian), *Gochteodinia villosa* (Middle Volgian–Valanginian/Early Hauterivian).

The nearest known outcrops of sedimentary rocks of Permian – Early Cretaceous age are in Jameson Land and Milne Land, about 400 km to the northeast (Clemmensen 1980; Piasecki 1979; Birkelund *et al.* 1984; Surlyk *et al*. 1973, 1984, Surlyk 2003), making these reworked specimens the southernmost records of Late Palaeozoic and Early Mesozoic age from Greenland.

Barremian

The oldest macrofauna was collected only from 42.2 m in the upper part of the Torsukáttak Member in the Watkins Fjord section. It contains the small heteromorph ammonite *Parancyloceras bidentatum* (von Koenen), the zonal index of the latest Barremian in NW Europe.

It also contains common *Lytoceras polare* (Frebold) and the bivalve *Arctica* sp. With poorly preserved *Entolium orbiculare* (J. Sowerby). *L. polare* also occurs at 43.7 m. The associated palynology of this fauna is unknown. As this occurrence lies above the base of the Watkins Fjord Formation, the precise age of the oldest Cretaceous sediments in the Kangerlussuaq Basin and their exact relationship to the Archean crystalline basement remains open.

Aptian

The second principal macrofauna only occurs at 3.8 m above the first assemblage. It contains the large heteromorph ammonite, *Tropaeum subarcticum*, which characterises the *Acanthoplites nolani* Zone (formerly *Parahoplites nutfieldiensis* Zone Casey 1960, 1961, 1980), the older part of the Late Aptian, together with abundant bivalves, *Entolium orbiculare*, *Arctica* sp. and an astartid. No associated microfauna or microflora are yet reported. However, reworked floras of *Pseudoceratium polymorpha* (Aptian) and possibly *Sirmiodinium grossi* (Bathonian– Early Aptian) at localities around Christian IV Gletscher indicate the former more widespread occurrence of Aptian or older sediments. The stratigraphic relationship with records of *Tropaeum* cf. *arcticum* from Late Aptian of Store Koldewey (Frebold 1934) and with *Sanmartinoceras* from Kuhn Ø (Bøgvad & Rosenkrantz 1934), are believed here to be not of Aptian age as originally stated, but of Late Barremian age.

Albian

The Albian of the Kangerlussuaq area is well characterised by ammonite and dinoflagellate cysts; it is also characterised by belemnites and inoceramid bivalves. The ammonites are dominated by hoplitids and occasional mortoniceratids, typical of European assemblages. But there is a frustrating lack of gastroplitinid ammonites that might have provided important correlation with other Arctic areas and the Western Interior of North America. Lower Albian ammonites are mentioned from the western part of the basin, but no details were given (Larsen *et al*. 1999a). Investigations of the GEUS ammonites by S. Kelly as part of the present study suggests that they may possibly of Middle Albian age. The presence of the Middle and Upper Albian sedimentary rocks in eastern Sediment Bjerge, are well represented at ammonite zonal and subzonal level: Middle Albian, *Hoplites dentatus* Zone, *Lyelliceras lyelli* and/or *Hoplites spathi* Subzone and *Euhoplites loricatus* Zone, *Anahoplites intermedius* Zone; and Late Albian, *Mortoniceras inflatum*, *Hysteroceras orbignyi* Subzone. For the relationship with the standard succession of NW Europe see Owen (1999). Ammonites have not yet been obtained by the present authors in proximity to the mid-Albian unconformable surface north of Watkins Fjord. Unfortunately dinocyst recovery from the ammonite levels has been poor and so direct correlation of the ammonite and dinoflagellate successions cannot always be made.

The ammonites recovered so far have been particularly important because the NE Greenland faunas listed by Spath (1946) and Maync (1949) after study in England were lost in transit between England and Denmark at the beginning of the Second World War (H.G. Owen, pers. comm. 2000). This is the first time that well-preserved hoplitid material has been obtained from similar levels and Owen's preliminary determinations herein confirm the earlier conclusions concerning the presence of these ammonites elsewhere in eastern Greenland. The Middle Albian ammonites of the Kangerlussuaq area provide some correlation with those of Svalbard (Nagy 1970).

The belemnite *Neohibolites minimus* is a useful accessory indicator for the Albian stage. The species ranges from late Early Albian to early Late Albian in northern Europe (Mutterlose 1990).

The palynological evidence for the Albian is usually less precise than that for the ammonites. No Early Albian is recognised yet in the Kangerlussuaq Basin. Nothing older than the Middle Albian *R. paucispina* Zone is seen based on records of *Litosphaeridium arundum* and *Chichaouadinium vestitum*. The Late Albian is recognised and palynological evidence, which is sparse, indicates an age no older than *W. grandstandica* Subzone based on the presence of *Dinopterygium cladoides* (cf. Nøhr-Hansen 1993; Koraini 1997). The *W. grandstandica* Subzone is also recognised beneath the occurrence of hoplitid ammonites.

Cenomanian

The Albian– Cenomanian boundary is exposed in the basin. The Cenomanian lies entirely within the dinocyst *Subtilisphaera kalaalliti* Zone. The upper part of the *Wigginsiella grandstandica* and all of the *Odontochitina ancala*, *Ovoidinium* sp. 1 and lower part of the *Hapsocysta benteae* subzones are recognised within the stage. The Cenomanian ammonite, Schloenbachia varians occurs at the top of the of the *Ovoidinium* sp. 1 Subzone, indicating a probable Middle Cenomanian age. This conclusion is supported by inoceramids of the *Inoceramus crippsi* group from just below. The Cenomanian–Turonian boundary is approximated to the upper limits of the ranges of *Litosphaeridium siphoniphorum* and *Epilepidosphaera* sp. 1 within *Hapsocysta benteae* Subzone (Koraini 1997). There is indication of a biosiliceous event in the late Cenomanian to Turonian where rare radiolarians, *Cenodiscus* spp. and *Orbiculiforma* sp., occur in the upper part of the *S. kalaalliti* Zone (*Hapsocysta benteae* Subzone).

Turonian

Dinoflagellate cysts indicate that the *Hapsocysta benteae* Subzone of the *S. kalaalliti* Zone spans the Cenomanian– Turonian in the mid-Sorgenfri Formation. *Hapsocysta benteae* has its upper range in the Turonian stage , which is otherwise characterised of other undifferentiated *S. kalaalliti* Zone forms. There is possibility that this part of the succession might be suitable for refining the dinoflagellate zonation based on detailed collecting from sites in this interval. There is also a potential biosiliceous event near the Cenomanian– Turonian boundary (See Cenomanian above). Based on the collection of macrofauna it has not been possible formally to recognise the earliest Turonian. However, the association of the belemnite *Actinocamax* cf. *manitobensis* (Christensen 1997) with bivalves of Inoceramus lamarcki group generally indicate the mid– late Turonian although this bivalve is known to range higher elsewhere. *Inoceramus cuvieri* is restricted to the mid– late Turonian, but is known only few sites (localities of NW Pyramiden). Beds rich in *Inoceramus lamarcki* can be correlated directly with the *Inoceramus lamarcki* beds of Traill Ø and Geographical Society Ø (Donovan 1953), and with upper part of the Fosdalen Member (Kelly *et al*. 1998).

Coniacian

The Coniacian is poorly delimited and is identified only in two sections in the uppermost part of the Sorgenfri Formation. The early part of the stage can be recognised by the presence of the zonal dinocysts *Arvalidinium scheii* and *Laciniadinium arcticum*. *Heterosphaeridium difficile* indicates the mid-Coniacian to earliest Santonian. The upper part of the range of the *Inoceramus lamarcki* group could indicate this stage but apart from the palynology within the Kangerlussuaq Basin no other confirmatory evidence has been obtained. The Coniacian is usually directly overlain unconformably by sediments of Late Campanian or more commonly Early Maastrichtian, *C. diebelii* interval (Nøhr-Hansen 1996).

Santonian

Substantiation of the presence of Santonian deposits in the Kangerlussuaq Basin has not been made. It appears likely that deposits of the stage, if they were deposited, have been subsequently eroded and transported seawards. The uppermost part of the range of *Heterosphaeridium difficile* lies in the Santonian elsewhere in Greenland (Nøhr-Hansen 1996), but there is no other supporting evidence for its presence in the Kangerlussuaq region. There is no trace of the Sphenoceramid assemblages, typical elsewhere in eastern Greenland, in Traill Ø, Geographical Society Ø (Donovan 1957), Hold with Hope (Kelly *et al*. 1998) and also in West Greenland (Rosenkrantz 1970).

Campanian

There is good palynological evidence for Late Campanian, *Isabelidinium cooksoniae* interval sediments in the lower part of the Christian IV Formation at Skiferbjerg, beneath the overlying Early Maastrichtian *Cerodinium diebelii* interval sediments. A loose specimen from this site of the ammonite *Rhaeboceras subglobosus* (Whiteaves) contained in its matrix *I. cooksoniae* interval dinoflagellates. In the Western Interior of Canada this ammonite occurs in the *Baculites compressus* to *B. eliasi* zones (Riccardi 1983). In addition there are tentative records of possible, very equivocal Campanian sediments with *Palaeohystrichophora infusorioides*, if *in situ*, may indicate the presence of this stage. Undifferentiated Campanian/Maastrichtian sediments also occur (see following section). Correlation of the *I. cooksoniae* interval sediments can be made with West Greenland (Nøhr-Hansen (1996).

Maastrichtian

The presence of the Early Maastrichtian is well established by the widespread occurrence of *Cerodinium diebelii*, indicating the presence of the *C. diebelii* interval. The junction with the underlying *I. cooksoniae* interval is seen at one locality. The *C. diebelii* interval is Early Maastrichtian (Nøhr-Hansen 1996). 'Undifferentiated' Campanian/Maastrichtian sediments are also present in (see also preceding section). The most abundant ammonite is *Diplomoceras cylindraceum* (Defrance) and is typical of the Maastrichtian, but the species is known to occur in the latest Campanian of Japan (Kennedy & Henderson 1992). The presence of *Acanthoscaphites tridens, Discoscaphites angmartussutensis, Hoploscaphites* sp., *Jeletzkyites* sp., and *Saghalinites wrighti* Birkelund indicates the latest Early to earliest Late Maastrichtian. *Anagaudryceras politissimum*, *Baculites* sp., *Scaphites* sp. and D. *cylindricum* that suggest an unspecified Maastrichtian age for some sediments. However, they occur together with earlier Cretaceous sediments and probably represents a collection of fossils reworked in the Paleocene.

The bivalve *Mimachlamys cretosa* subsp. *denticulata* (Dhondt 1973) confirms an original Early Maastrichtian age for the original deposition of these sediments. Inoceramid bivalves *Spyridoceramus tequlatus* that also support a Maastrichtian age based on ammonites and dinoflagellates. This probably belong to the *T. fibrosa* Zone which can be recognised widely from N.W Europe to Western Interior North America. The various molluscan dates give a general Maastrichtian age, it is the palynological data, however, which restrict the age of these sediments.

The palynomorph assemblage from the Christian IV Formation (Sequoia Nunatak) is dominated by Late Cretaceous, early Late Maastrichtian marker species (e.g. *Alterbidinium acutulum, Cerodinium diebelii, Diphyes colligerum, Hystrichostrogylon coninckii, Isabelidinium cooksoniae, Laciniadinium arcticum, Triblastula utiensis* together with a few pollen specimens, e.g. *Aquillapollenites* spp. and *Wodehouseia spinata*). Recorded reworked material is represented by specimens of Albian–Cenomanian age (*Rhombodella paucispinosa* & *Chlamydophorella nyei*) and of Campanian age (*Isabelidinium microarmum*).

The presence of the species discussed above and the absence of latest Maastrichtian markers (e.g. *Palynodinium grallator*) suggest an early Late Maastrichtian age for the lower part of the Sequoia Nunatak section. The lowermost sample (GEUS 406 765) may be correlated to the upper part of the *Triblastula utinensis* Range Zone, earliest Late Maastrichtian (Schøiler & Wilson 1993). Whereas the two middle samples (GEUS 406 767 & 406 769) may be correlated to the middle part of the Late Maastrichtian *Isabelidinium cooksoniae* Interval Zone (Schøiler & Wilson 1993).

New data from the Kangerlussuaq Basin at Skiferbjerg (Appendix 1; Enclosure 5) yields ammonite fragment throughout and an echinoderm specimen from the base. Three of the studied samples (GEUS 455 641, 1260 m; 455 646, 1280 m and 455 649 1290 m) also contain ammonites. The palynomorph assemblage is poor to very poor preserved, especially in the upper part. The presence of *Cerodinium diebelii* in the lower part (1135–1215 m) suggests an age not older than Early Maastrichtian. The upper part (1225–1315m) contain like the two “Sequoia Nunatak” sections, described above, late Cretaceous (Maastrichtian) marker species (e.g. *Alterbidinium acutulum, Cerodinium diebelii, Chatangiella* spp., *Diphyes colligerum, Hystrichostrogylon coninckii, Isabelidinium cooksoniae, Laciniadinium arcticum* together with a few *Aquillapollenites* spp. and *Wodehouseia spinata*), suggesting an early Late Maastrichtian age.

Danian–?Selandian

Based on sections in Kangerlussuaq and North-East Greenland, Jolley & Whitham (2004a) suggested that the sediments of Danian – early Thanetian age (Pre T40) were entirely missing at the western margin of the northern North Atlantic (East and North-East Greenland. The original evidence for the Danian stage provided by Soper *et al*. (1976a) is according to (Jolley & Whitham 2004a) no longer supported and this microflora can be ascribed to the Maastrichtian. The conclusion presented in their paper is based on extensive palynological work on terrestrial Paleogene sections from Kangerlussuaq and North-East Greenland which yield spores and pollen characteristic for the *Apectodinium* acme associated with the Late Paleocene Thermal Maximum (Jolley 2002; Jolley & Whitham 2004a).

However, this conclusion is disputed by Nøhr-Hansen & Piasecki (2002) who recently documented the presence of Paleocene sub-basaltic sediments from Kap Brewster at Savoia Halvø (approximately 400 km northeast of Kangerlussuaq). The dating was based on dinoflagellate cysts. The palynological content is dominated by reworked Cretaceous dinoflagellate assemblages of Early Albian to Late Maastrichtian age, together with rare Paleocene marker species. The presence of *Alisocysta margarita*, *Cerodinium striatum* and *Palaeoperidinium pyrophorum* throughout the studied section and the presence of *Palaeocystodinium bulliforme*, *Spiniferites septatus* and *Thalassiphora delicata* restricted to the upper part indicates a late Danian age for the lower part and a late Danian – early Selandian? age for the upper part of the succession.

Paleocene marine deposits have been documented in two samples (GEUS 413269 & 413271) from the shale succession (lower part of the Fairytale Valley Member) at Watkins Fjord (Fig. 24). The deposits rest unconformably on the Cretaceous Christian IV Formation and indicate the presence of a hiatus spanning the Late Cretaceous and the Early Danian (earliest Paleocene).

The lower sample (GEUS 413269) dates the lower deposits latest Danian (dinoflagellate cyst *Spiniferites magnificus* Zone DP2 of Mudge & Bujak (1996) based on the presence of *Palaeocystodinium bulliforme, Spiniferites magnificus.* The top of the latest Danian *Spiniferites magnificus* Zone was defined by the last occurrence of the *Spiniferites magnificus* in the lower part of the Maureen Formation by Mudge & Bujak (1996), who mentioned that *Spiniferites magnificus* not has been recorded outside the North Sea. Mangerud *et al.* (1999) defined the top of their Early Paleocene (Danian) Grane A Biozone by the last occurrence of the *Spiniferites magnificus* and *Alisocysta reticulata* in the middle of the Våle Formation, offshore Norway.

The upper sample (GEUS 413271) are dated as possible earliest Selandian age (lower part of dinoflagellate cyst *Thalassiphora* cf. *delicata* Subzone DP3a of Mudge & Bujak 1996) based on the presence of *Palaeocystodinium bulliforme*, common *Areoligera* spp. and common *Palaeoperidinium pyrophorum*. Mangerud *et al.* (1999) divided their early Late Paleocene Grane B Biozone into four subzones, the top of the oldest was defined by the by the last occurrence of common *Palaeocystodinium bulliforme* in the upper half of the Våle Formation offshore Norway. The subzone correlate with the lower part of the *Thalassiphora* cf. *delicata* Subzone DP3a of Mudge & Bujak (1996). Mudge & Bujak (1996) mentioned in their description of subzone DP3a, that *Palaeoperidinium pyrophorum* dominate in the subzone.

This last common occurrence of *Palaeocystodinium bulliforme* is according to Mangerud *et al.* (1999) a useful regional North Sea event. *Palaeocystodinium bulliforme* is quite common onshore Nuussuaq, West Greenland where it range from the mid to Late Danian *Palaeocystodinium bulliforme* Zone and into the Late Danian/Early Selandian *Alisocysta margarita* Zone (Nøhr-Hansen *et al.* 2002). *Palaeocystodinium bulliforme* has also recently been recorded onshore Kap Brewster, East Greenland where it co-occurs together with *Thalassiphora delicata* and *Alisocysta margarita* suggesting deposits of Late Danian/Early Selandian age (Nøhr-Hansen & Piasecki 2002). Few, possibly reworked specimens of Late Cretaceous and earliest Danian ages are also recorded from the Watkins Fjord section.

The latest Danian to earliest Selandian ages suggested here for the Fairytale Valley Member at the Watkins Fjord section (Fig. 24) correlate with the top of sequence T10 or lowermost T20 of Ebdon *et al*. (1995), according to Mudge & Bujak (2001).

Selandian

The Fairytale Valley Member at Fairytale Valley, Willow Pass, Ryberg Fjord, Ryberg Fjord North section and Sødalen/Canyondal all contain very poor preserved thermally altered low diverse and low density palynoassemblages. However the consistent occurrence of *Palaeoperidinium pyrophorum* in all five sections (Fig. 24), indicate an age no younger than latest Selandian (the *Palaeoperidinium pyrophorum* Zone DP4 of Mudge & Bujak 1996; 2001). *Areoligera* spp. and *Palaeoperidinium pyrophorum* are common in the lower successions at Fairytale Valley (GEUS sample 413108, 94m) and present in the upper succession, where a distinct *Spinidinium* sp. and a distinct *Suttilisphaera* sp. have their first occurrence (GEUS sample 413144, 141m). *Palaeoperidinium pyrophorum* and *Areoligera* spp. are also present to common in the Sødalen/Canyondal section. The dating of the five sections suggest correlating with NP5 and with the top of sequence T20 or lower part T30 of Ebdon *et al*. (1995).

A Danian to early Selandian age for part of the Sediment Bjerge Formation is also supported by a single Danian foraminifer (*Subbotina pseudobolloides* Plummer) recorded form the Fairytale Valley Member (J.A. Rasmussen pers. comm. 1998).

Thanetian to Ypresian

In all sections of the Sediment Bjerge Formation, low salinity microplankton palynofloras are restricted to chlorophycean and prasinophycean algal phycomas and in the Vandfaldsdalen Formation, in the lower part of the Schjelderup Member (former Ryberg Sandstone Bed) rich terrigenous assemblages dominated by *Inaperturopollenites hiatus* (swamp Cypresses, *Metasequoia*) and *Deltoidospora adriennis* (ferns); also common are *Alnipollenites verus* and *Cupuliferoidaepollenites liblarensis* and occasional *Caryapollenites veripites* (Jolley & Whitham 2001, 2004a). The palynofloras indicate a T40 assemblage of undifferentiated Late Paleocene to earliest Eocene age. Palynofloras from the onset of basaltic eruption in the Willow Pass Member are also of T40 assemblage, but are of Ypresian age (Fig 24).

McIntyre (this study) reported abundant spores and pollen throughout the Kulhøje Member at "Sequoia Nunatak" and ascribed the assemblage to the Late Paleocene (Appendix 2).

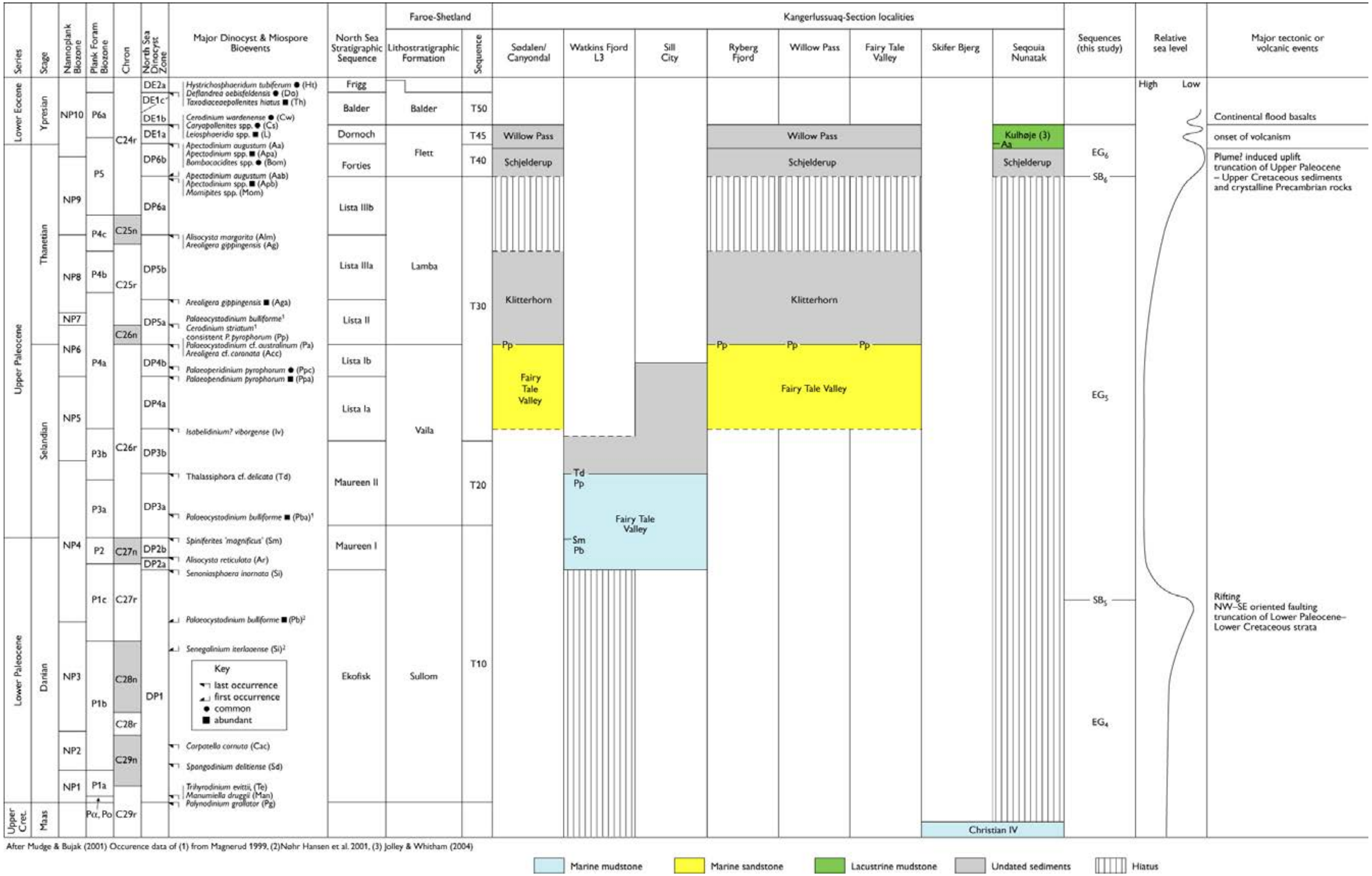

Figure 24. *Palynostratigraphy of the Paleogene sections (for details see Appendix 1).*

Sequence stratigraphic framework

Analysis of the succession in Kangerlussuaq has revealed the development of a number of major angular unconformities and hiatuses. The sequence stratigraphic significance of each of these boundaries is analysed further below, starting from the bottom of the succession and working upwards and numbered EG1–6 (Figs 6, 25).

SB EG_1 (basal onlap)

The contact between the Watkins Fjord Formation and the basement is not exposed therefore the nature and origins of the boundary remain conjectural. However, the thickness of the Watkins Fjord Formation is quite variable; the Torsukáttak Member for example is only found at L3 and to the NE of Pyramiden the Sorgenfri Formation rests directly on basement.

The origins of this boundary are uncertain and it may have been formed over many years. It may be that the thickness variations seen in the Watkins Fjord Formation are controlled by relief, with the greatest thicknesses in the low points of a topography sculpted by fluvial incision. Alternatively thicknesses variations may be due to fault movements as there is evidence for faulting during the deposition of the formation (Fig. 25).

SB EG_2 (hiatus)

The boundary between the Suunigajik and Torsukáttak members is seen at L3 in the west of the mapped region. A channel cutting into the Torsukáttak Member is seen at the northern end of the outcrop, which may have been formed by fluvial incision prior to infilling by the Suunigajik Member. There is no apparent angular relationship between beds above and below the unconformity (Fig. 25).

The surface probably formed in the Early Albian as indicated by the fact that the Torsukáttak Member is Aptian age and the oldest marine macrofauna in the Suunigajik Member have a Mid-Albian age. This boundary would appear to have been formed by a fall in relative sea level leading to incision by rivers of the underlying member. Consequently at this time there is the potential for the development of deep marine fans in adjacent basin areas.

SB EG_3 (angular unconformity)

This boundary occurs at the contact between the Sorgenfri and Watkins Fjord formations where dark mudstones overly pale sandstones. In the east of the region the contact is a conformable a flooding surface with no apparent discordance between beds above and below. At L3 in the west of the region an angular discordance is seen and Cenomanian mudstones rest directly on Mid-Albian sandstones (Fig. 25).

The boundary at L3 was formed following tilting and erosion of the Watkins Fjord Formation (Fig. 25). The origin of this tilting to thought to be tectonic; growth faults cutting the Mid-Albian sandstones are seen in nunataks around 10 km to the north. This surface is thought to have formed sometime during the Mid-Albian and Late Albian. Sediment created during this period of erosion is likely to have been deposited in fault controlled basins and sediment transport paths are likely to have been influenced by the position of active faults.

SB EG_4 (hiatus)

This sequence boundary occurs at the contact between the Christian IV Formation and the Sorgenfri Formation. Since the boundary is marked by a subtle change in mudstone facies the geometry of the contact is difficult to define. As there is little thickness variation in the Sorgenfri Formation beneath and no relationship between the thickness of the formation and its position relative to faults, it is thought that this contact is an hiatus or disconformity and not an angular unconformity (Fig. 25).

The youngest strata in the Sorgenfri Formation have a Coniacian age and the oldest strata above the unconformity have a Late Campanian age, this constrains the formation of this boundary to the Coniacian to Late Campanian. Reworking of Santonian dinocysts in the Christian IV Formation suggests the former presence of strata of this age and suggests the sequence boundary formed in the Santonian – Late Campanian interval. The sequence boundary was formed by a fall in relative sea level and subaerial erosion potentially with the development of fans in adjacent basin areas. There are, however, no major periods of sea level fall, during the time interval represented by this hiatus, indicated by Fugelli & Olsen (2005).

SB EG_5 (angular unconformity)

The Fairytale Valley Member rests unconformably on strata showing a wide age range reaching as old as the Turonian (Sorgenfri Formation) (Figs 6, 25). The geometry of this contact is uncertain as is always a mudstone– mudstone contact and therefore poorly exposed. The Christian IV Formation thins beneath the Fairytale Valley Member towards the west from the Christian IV Gletscher, in some areas being removed completely by erosion. It is absent on the east side of the glacier. Consequently, thickness variations are thought to have been controlled by movements on a NW trending faults concealed by the glacier (Larsen & Whitham 2005) and it is thought that this contact is an angular unconformity (Fig. 25).

This boundary was formed by erosion associated with rifting some time between the Late Maastrichtian and T20 time. Substantial thicknesses of Cretaceous strata were removed during the formation of the unconformity. The facies of the Christian IV Formation and Sorgenfri Formation indicate they were deposited as widespread blankets of sediment and yet now they are only locally preserved in downfaulted outliers surrounded by crystalline basement. The products from this period of erosion would have been deposited in more basinal areas. Fan distribution would have been controlled by active normal faults that would have provided conduits for sediment transport pathways and also accommodation space in their hangingwalls. This angular unconformity conceals the intra-K98 and T20 sequence boundaries identified by Fugelli & Olsen (2005).

SB EG$_6$ (hiatus)

This boundary is recognised by an abrupt change of facies from shallow marine outer shelf to low sinuosity fluvial indicating a fall in sea-level and the development of a sequence boundary. The break in time represented by this hiatus is poorly constrained. Sediments above are dated as late T40 and those below are constrained by dates in the Fairytale Valley Member as T20 age. As discussed previously, the shallowing upward succession from the Klitterhorn Member to the Schjelderup Member probably represents the progradation of a sequence recognised in the Faroe-Shetland Basin that reached its maximum basinward extent in T40 time.

The sequence boundary indicates the development of turbidite fan systems between T20 and T40 time. The sequence boundary corresponds with the T50–40 sequence boundary identified by Fugelli & Olsen (2005).

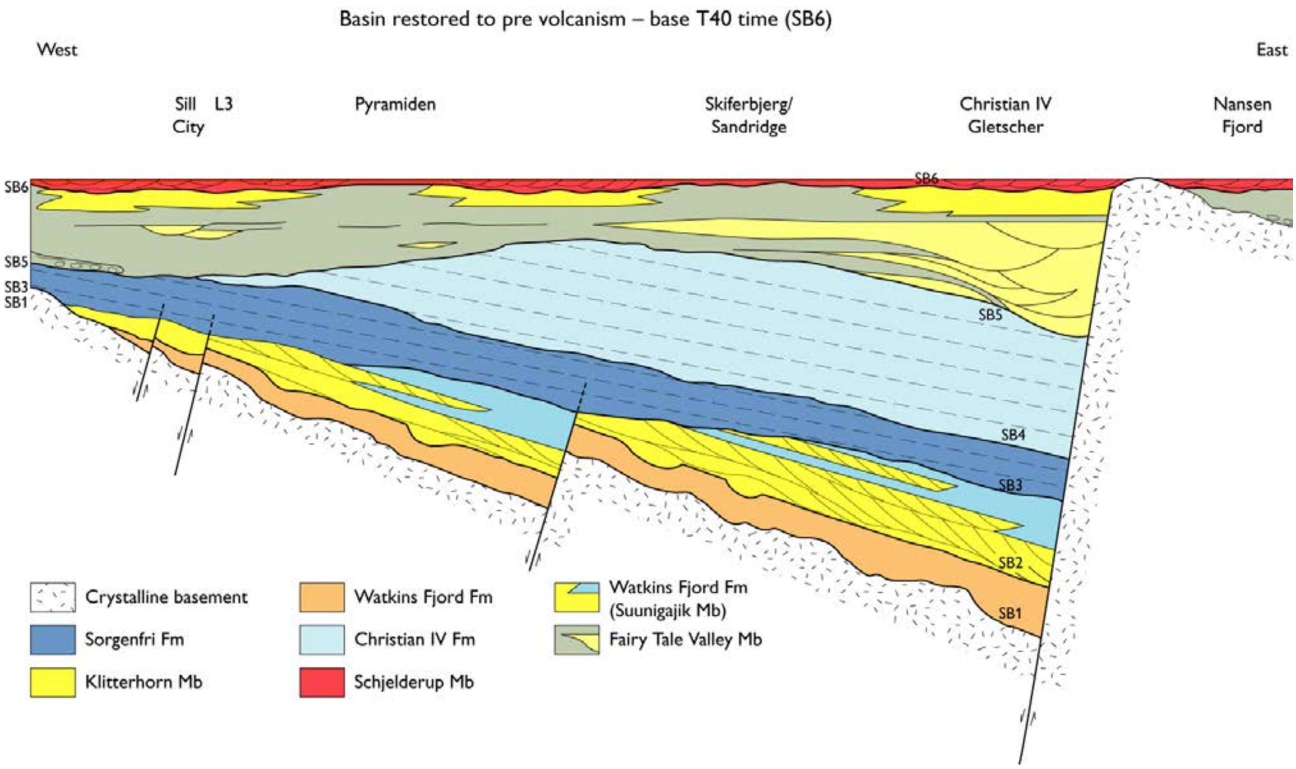

Figure 25. *Cross-section of the Kangerlussuaq Basin restored to SB$_6$ time (Base T40). See text for further discussion.*

Summary of the basin evolution in Kangerlussuaq

Pre-Aptian record

The oldest recognised sediments of the Kangerlussuaq Basin belong to the Watkins Fjord Formation and is probably of latest Barremian age. The sediments is believed to onlap the sculptured surface of the Precambrian crystalline basement EG SB_1, although the contact between the Watkins Fjord Formation and the basement is not exposed. Reworked Triassic and Jurassic palynomorphs indicate that older sediments were present in southern East Greenland at the time of the Early Cretaceous transgression.

Latest Barremian–Aptian transgression and coastal plain deposition

The area became flooded during the Latest Barremian – Aptian creating a low-lying coastal plain (Torsukáttak Member). The coastal plain was dissected by meandering channels now represented in sandy point bar successions showing epsilon cross-bedding. Palaeocurrents were mainly towards the east. Adjacent to the fluvial channels, vegetated levees and swamps were developed, as indicated by fine-grained rooted strata and coal deposits. The sea periodically flooded the low lying floodplain and clean fine-grained sandstones were deposited across the plain. Ophiomorpha burrows are common in the marine sandstones. Towards the top of the member a ravinement conglomerate overlain by HCS sandstones indicate establishment of a more permanent shallow marine environment. The shallow marine deposits are represented by very fine-grained calcareous sandstones with abundant bivalves and rare ammonites.

The thickness variations present in the Torsukáttak Member probably reflect the topography of the deeply eroded crystalline basement surface with floodplain deposited in the low-lying areas. The inherited topography may reflect a series of rotated fault blocks. According to Larsen *et al*. (1996) and Larsen & Saunders (1998) the first period of rifting in the Kangerlussuaq region is thought to have occurred in the Early Cretaceous and was associated with the deposition of basement-derived clastics in a series of fault-bounded basins floored by Precambrian crystalline basement. There is no evidence for earlier phases of Cretaceous rifting, but by analogy with the Faroe Shetland area and NE Greenland early Cretaceous rifts are thought likely.

Early Albian fluvial incision

At L3 (locality M9511), the Torsukáttak Member are truncated by a fluvial channel cutting deeply into the underlying shallow marine deposits. The base of the channel EG SB_2 marks a distinct shift in depositional environment with incoming of vast amounts of coarse-grained sandstones. The sandstone dominated succession is approximately 100 m thick and consists from below of amalgamated channelled sandstones overlain by large scale cross-bedded sandstone bodies isolated in marine mudstones (Fig. 26). The sandstones were deposited in a fluvio-estuarine environment and the upward change in depositional style suggests an upward increase in accommodation space. The Suunigajik Member thus reflects a relative sea-level fall accompanied by fluvial incision and sequence boundary formation EG SB_2. The fall in sea-level was followed by a gradual rise in sea-level and establishment of a fully marine shelf.

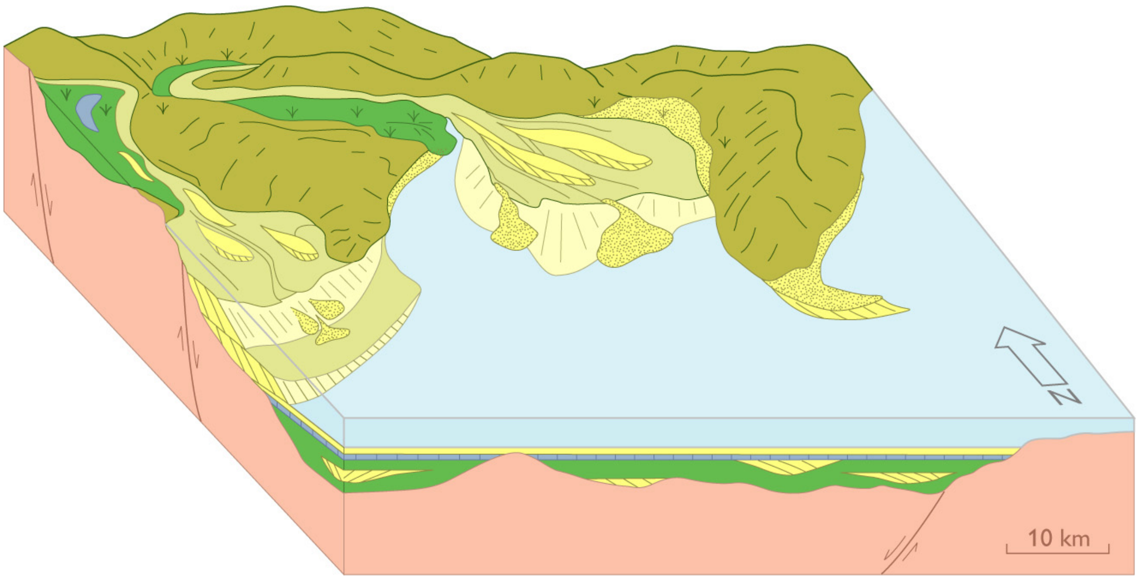

Figure 26. *Palaeogeographic reconstruction of the Kangerlussuaq Basin in Early to mid-Albian times (Watkins Formation, Suunigajik Member).*

Mid-Albian transgression and estuarine deposition

The continued rise in sea-level is reflected in backstepping of the shallow marine sandstones of the Suunigajik Member from southeast towards northwest. The shelf deposits are represented by silty mudstones with thin bioturbated sandstones (stormsands). Due to erosion below EG SB_3 the mudstones are only preserved locally, but are believed to have formed an extensive storm influenced shelf distally to the coastal sandstones. Ammonites and bivalves are common in the mudstones below the uppermost sandstone unit at L3.

At Sandridge west of Christian IV Gletscher a period of condensation on top of the sandstones (Late Albian) is indicated by the formation of an oncolite bed and intense bioturbation and carbonate cementation. The size of the oncolites indicates influence by strong bottom currents accompanied with very low sedimentation rates.

Albian tectonism

At L3 a marked angular unconformity is developed at the northern end of the outcrop. The unconformity truncates sandstones of the Suunigajik Member below and is onlapped by mudstones of the Sorgenfri Member above. The erosional surface EG SB_3 probably formed after a period of extensional tectonic activity associated with fault block rotation. The tectonic phase took place in mid- or Late Albian time. The orientation of the fault planes is roughly northeast– southwest with downthrow towards the southeast. Minor adjustments to the block movements are reflected in growth faults present in the lower part of the Sorgenfri Formation.

Late Albian to Santonian flooding and fine-grained shelf deposition

The fault relief was submerged during the mid-Albian to Late Albian. The oldest onlapping mudstones are thus of mid-Albian age at Sandridge whereas ammonites indicate a Late Albian age at Skiferbjerg. Following the transgression a long lived, stable shelf area became established and silty and sandy mudstones dominated the basin from the Late Albian and probably into the Santonian. The formation was probably deposited as a blanket across the entire basin. The abundant phosphoritic concretions and intense bioturbation suggest relatively low sedimentation rates. Thin- bedded laterally continuous sandstones with sharp bases and gradational tops represent occasional stormsand layers. The shelf was inhabited by large inoceramids and remains of ammonites, fish, *Ptychodus* and pliosaur indicate a fully marine water column with depths ranging from 20–100 metres.

Late Cretaceous sea level fall and erosion

A distinct hiatus is recorded in the macrofauna spanning the late Coniacian to mid-Campanian. Although the boundary EG SB4, which marks the boundary between the Sorgenfri and Christian IV formations, is a subtle mud–mud contact the surface indicate a significant erosional event. The hiatus probably reflect a lowering of relative sea level accompanied by extensive submarine erosion. Formation of incised valleys across the mud-dominated shelf may have taken place at the boundary, but is not present in the Kangerlussuaq area.

Late Campanian to Late Maastrichtian outer shelf deposition

Deposition of fine-grained outer shelf sediments resumed in the Late Campanian with the deposition of Christian IV Formation. The depositional environment was similar to that of the Sorgenfri Formation although both sedimentation rates and the general energy level appear higher. The sediments are thus slightly more sandy and sandstone beds representing stormsands are thicker and show complete HCS sequences. It is thus suggested that deposition took place close to storm wave base at water depth slightly less than prevailed during the deposition of the Sorgenfri Formation. The sandy mudstones are widespread across the basin and is found as far inland as Sequoia Nunatak in the Kulhøje area indicating a very wide, low gradient shelf. The shelf mudstones are strongly bioturbated indicating a well aerated seabottom.

Early Paleocene rifting

In the latest Cretaceous– Early Paleocene a dramatic change in basin configuration took place. The change was caused by intense rifting along northwest–southeast oriented faults that divided the basin into two depositional centres separated by a basement ridge (East of Christian IV Gletscher). The faulting also caused an abrupt deepening, with the basin floor now being below storm wave-base.

The block rotation was followed by erosion and a major angular unconformity EG SB5 was formed. The unconformity locally cut as deep as the Turonian strata represented by the boundary between the Sorgenfri Formation and Fairytale Valley Member at Sill City.

Selandian slope and deep marine deposition

At the basin margins, sediments were subject to syndepositional slumping and sliding down newly created slopes and along the axis of the new basins, deep marine sediments were deposited. The major sediment input took place along the major fault lineaments focussing sediment transport towards the southeast (Larsen & Whitham 2005). In the deepest, axial part of the newly formed basin a thick, sandstone-dominated succession was deposited (Fairytale Valley Member). It is characterised by amalgamated coarse to fine grained sandstones deposited in a slope channel and basin floor fan system. Outside the main turbidite channel mudstones with thin laterally persistent fine-grained sandstone prevailed. The deposits are characterised by a very low diverse flora and fauna although bioturbation is common in the sandstones. This may indicate formation of restricted marine basins during the early phase of rifting.

Selandian shallow marine and delta progradation

As rifting ceased a more stable depositional environment gradually established and shallow marine and deltaic sediments of the Klitterhorn Member started prograding from basin margins filling the former deep basin. Progradation was focused and mouthbar formed in front of major rivers are found at the southern side of Ryberg Fjord, in Sødalen and at Willow Pass.

Late Paleocene uplift and fluvial erosion

In the Late Paleocene uplift rate accelerated and eventually the entire Kangerlussuaq region became emerged. The uplift was probably controlled by the impact of hot mantle material beneath the East Greenland margin (Dam *et al.* 1998). Widespread erosion of strata ranging in age from Early Paleocene to Archean took place and vast amounts of coarse clastic sediments were shed of the East Greenland margin into basin to the south east. A distinct sheet of coarse-grained pebbly sandstones and conglomerates (Schjelderup Member) immediately overlie the erosional unconformity EG SB6. The facies and the geometry of the sandstone body suggest that deposition took place in a shallow braided river system. Muddy interfluves with space vegetation developed in between channels, but were readily eroded. The sediment source area was local, emerged basement highs and older sediments, which is confirmed by the sediment provenance analysis (Whitham *et al.* 2004).

Late Paleocene – earliest Eocene subsidence and onset of volcanism

The uplift although prominent, seems to have been short-lived and the fluvial braid plain soon became submerged as the basin subsided. The coarse, sheet sandstones of the Schjelderup Member is thus overlain by a mixed succession of carbonaceous floodplain mudstones, coarse-grained channel sandstones, mouthbar with rootlets and bioturbated, clean white sandstones of the Willow Pass Member. The bioturbated sandstones are most common in the most basinward areas of southeastern Kangerlussuaq and suggest periodically incursions of the sea. Geochemical analyses of the sediments indicate that deposition took place contemporaneously with the first volcanic activity in the area.

Early Eocene floodplain and lake deposition

During the initial volcanic phase a deep lake was formed in the inner, northern parts of the Kangerlussuaq Basin. The lake was surrounded by a dense mixed mesophytic forest as reflected in the spores and pollen of the Kulhøje Member (Hjortkjær & Jolley 1999; Jolley & Whitham 2004a). The mudstones also contain impressive imprints of leaves and fructifications (Hoch 1992). Airfall tuffs indicate a strong volcanic influence at the time of lake deposition and it is possible that formation of the deep lake was controlled by lava flows or volcanic centres damming existing river valleys.

Early Eocene volcanic deposits

The Early Eocene volcanics is eclipsed by the intensive volcanism forming local steep topographic gradients accompanied by high rates of subsidence, and abrupt, local introduction of vast amounts of volcaniclastic sediments (Ukstins *et al.* 2003). Thick hyaloclastite wedges were deposited directly above marine mudstones capping fluvial sandstones and indicate almost instantaneous creation of several hundred metres deep basins following collapse of the thermal dome (Dam *et al.* 1998). A continuing creation of accommodation space (several kilometres) is indicated by the repeated shallow marine intrabasaltic incursions that characterise the lower part of the volcanic succession (Nielsen *et al.* 1981). Relative sea-level rise due to subsidence (loading by the thick basalt pile), and perhaps eustatic sea-level rise, was able to keep pace with the high rate of basalt extrusion during the initial volcanic phase (cf. Soper *et al.* 1976b; Nielsen & Brooks 1981). In the hinterland, high rates of subsidence are indicated by the presence of up to 250 m thick volcaniclastic successions. The marked thickness and facies variation of the early synvolcanic continental deposits was probably controlled by differential subsidence of local subbasins.

Relationship to basins in the Faroe-Shetland region

The following section concentrates on the evolution of the Aptian to Eocene succession in the basins of the Faroe-Shetland region. The purpose of the exercise is to allow comparisons to be drawn between the geological evolution of basins on either side of the rift, which were formerly joined prior to the onset of sea-floor spreading in the Paleogene. Focus will be on stratigraphy, but the potential for a Greenland source of sediment to the western parts of the Faroe-Shetland region in the Late Cretaceous and Paleocene is also addressed.

Structural framework

The Cretaceous–Tertiary rift between the Faroe Island and the Shetland Islands is characterised by the presence of a number of Cretaceous–Tertiary sedimentary basins and subbasins (Fig. 1) The largest of the sedimentary basins in the region is the Faroe-Shetland Basin. The basin is bounded by the Corona Ridge to the northwest, the Westray Ridge to the southeast and the Erlend Platform to the northeast. The southeastern margin of the basin is formed by the Shetland Spline Fault, which was also the eastern margin of the Cretaceous rift. A number of smaller basins are present to the southwest such as to the North Rona Basin, the Judd Basin and the Solan Basin. Further basins are thought to exist to the northwest of the Corona Ridge, however, the number size and distribution of these basins is poorly constrained. Seismic mapping by Sørensen (2003) was focused on the post basalt evolution of the Faroes area, but observations on structural highs and existence of Cretaceous depocentres to the southeast of the Faroe Islands were also given. As part of the Sindri research programme a structural elements map was published by Jarđfrøđisavniđ in 2003 (Keser Neish 2003). The map shows the continuation of the Cretaceous rift into Faroes waters where a number of SW–NW basement ridges and basins were identified. These comprises the Sjúđur Ridge, Heri High, Tróndur High and the prominent East Faroe High and the Mesozoic–Tertiary basins; Brynhild, Guđrun and Sissal (Fig. 1). The presence of the basalts and problems with seismic imaging of sub-basalt structures means that the outline the western side of the Cretaceous rift is unclear and it is not known whether prominent intrabasinal highs may be present between East Greenland and the Faroe-Shetland basin. Most authors, however, imaging a crystalline basement high below the present day Faroe Islands and suggest that this high influenced the pre-basaltic basin history of the region (e.g. Smallwood *et al.* 2001; Ellis *et al.* 2002).

There are two fault trends apparent in the Faroe-Shetland region; a set of north–south trending faults and a set of northeast–southwest trending faults (Dean *et al.* 1999). The north–south trending fault set appears to be earlier as it is cross-cut by the northeast–southwest trending set. The later fault set moved in the Late Cretaceous–Early Paleogene but may have also moved in the Early Cretaceous. This cross cutting relationship may be due to a change in relative plate movements between the Jurassic and the Cretaceous (Doré *et al.* 1997; Doré *et al.* 1999). A further set of northwest trending structural lineaments has also been noted in the region (Rump *et al.* 1993; Doré *et al.* 1997).

These are termed transfer zones by some workers and appear to have controlled the input of sediment into the basin from the Orkney-Shetland Platform (Naylor *et al.* 1999) and may to some extent also have influenced the supply of sediment to the offshore basin from the west (Jolley & Whitham 2004b) (Fig. 1.).

Farther south the Rockall trough formed a deep Cretaceous depocentre with up to 3000 m of sediments. The Rockall Trough is bounded to the north by the NW–SE oriented Wyville-Thomson Ridge.

Rift history

Like many of the extensional basins on the Northwest European Margin, the Faroe-Shetland basin and adjacent basins had their origins in the gravitational collapse of Caledonian Orogen (Dean *et al.* 1999; Roberts *et al.* 1999). Regionally, rift events are documented in the Mid Devonian (Larsen & Bengaard 1991), Late Carboniferous (Stemmerik *et al.* 1991), Early Triassic (Clemmensen, 1980; Seidler *et al.* 2004), Late Bajocian–Valanginian (Surlyk 1977, 1978), Albian (Whitham *et al.* 1999) and Late Cretaceous–Early Paleocene (Brekke 2000). These events are all documented from the Faroe-Shetland Basin although with minor degrees of variation in duration and precise timing e.g. (Carr & Scotchman 2003; Dean *et al.* 1999)

Cretaceous–Paleocene rifting

Between the Late Jurassic and the Early Cretaceous there was a change in relative plate motions from east–west to northwest–southeast (Doré *et al.* 1999). This change led to the development of the Cretaceous rift basins of the northwest European margin. Extension led to rift flank uplift and local emergence of footwall highs towards the margins of the rift. Substantial amounts of accommodation space were created in the hangingwalls of normal faults. The fault blocks that were created by rift events exerted a profound control on the distribution of depositional environments, lateral thickness variations and sediment transport paths. An excellent analogue for the region at this time is to be found in NE Greenland (Surlyk 1978; Surlyk 1990; Whitham *et al.* 1999), that was influenced by many of the extensional events documented from the Faroe-Shetland region.

The precise timing of rift events in the Faroe-Shetland region is a matter of debate. Some authors define broad periods of time during which extension occurred (e.g. Carr & Scotchman 2003; Grant *et al.* 1999; Lamers & Carmichael 1999) whereas others are precise to stage level (Dean *et al.* 1999). There is general agreement that there was a major period of extension in the Late Jurassic–Early Cretaceous, which involved the creation of NE–SW oriented faults (Carr & Scotchman 2003; Dean *et al.* 1999; Doré *et al.* 1999; Goodchild *et al.* 1999; Grant *et al.* 1999; Lamers & Carmichael 1999; Roberts *et al.* 1999). This first period of rifting ended at the end of the Valanginian. There is also general agreement on a period of Late Cretaceous–Paleocene rifting (Carr & Scotchman 2003), or a number of extensional events, in this time interval: Campanian (Dean *et al.* 1999; Goodchild *et al.* 1999), Campanian–Maastrichtian (Roberts *et al.* 1999), Paleocene, T10–T38, (Lamers & Carmichael 1999), Mid Paleocene (Dean *et al.* 1999).

There is less agreement about whether there was rifting between the Early and Late Cretaceous. Roberts *et al.* (1999) thought there was no extension in the mid-Cretaceous and that the rift had become inactive at this time. In contrast Goodchild *et al.* (1999) demonstrated Aptian–Albian rifting in the Faroe Shetland Basin based on the existence of the wedge-shaped geometry of Aptian–Albian units. Carr & Scotchman (2003) also indicated a period of mid-Cretaceous rifting. Dean *et al.* (1999) suggested that there was a period of Cenomanian–Santonian rifting.

Cretaceous–Paleocene basin evolution

There are substantial thicknesses of Cretaceous sediments in the Faroe-Shetland region and in some places there may be as much as 7000 m of Cretaceous strata (Stoker *et al.* 1993). It is therefore perhaps surprising that the rift was underfilled with respect to sea-level throughout the Cretaceous with deep marine fine grained sedimentation towards the centre of the rift in the Faroe Shetland Basin. Coarser, more marginal marine conditions were confined to marginal areas such as the West Shetland Basin. Cretaceous sediments are absent on the Orkney-Shetland Platform and adjacent platform areas. However, in view of the presence of Late Cretaceous erosional remnants beneath plateau basalts in western Scotland (Mortinmore *et al.* 2001), it seems likely that Late Cretaceous strata were originally deposited over much of the region and removed by Paleogene and later erosion. The pattern of infill of the basin is reflected in well penetrations of the Cretaceous with older Cretaceous strata penetrated at the basin margins (e.g. 205/25-2) whereas only younger strata are found to the west with the exception of wells drilled on intra-basinal highs (Fig. 27).

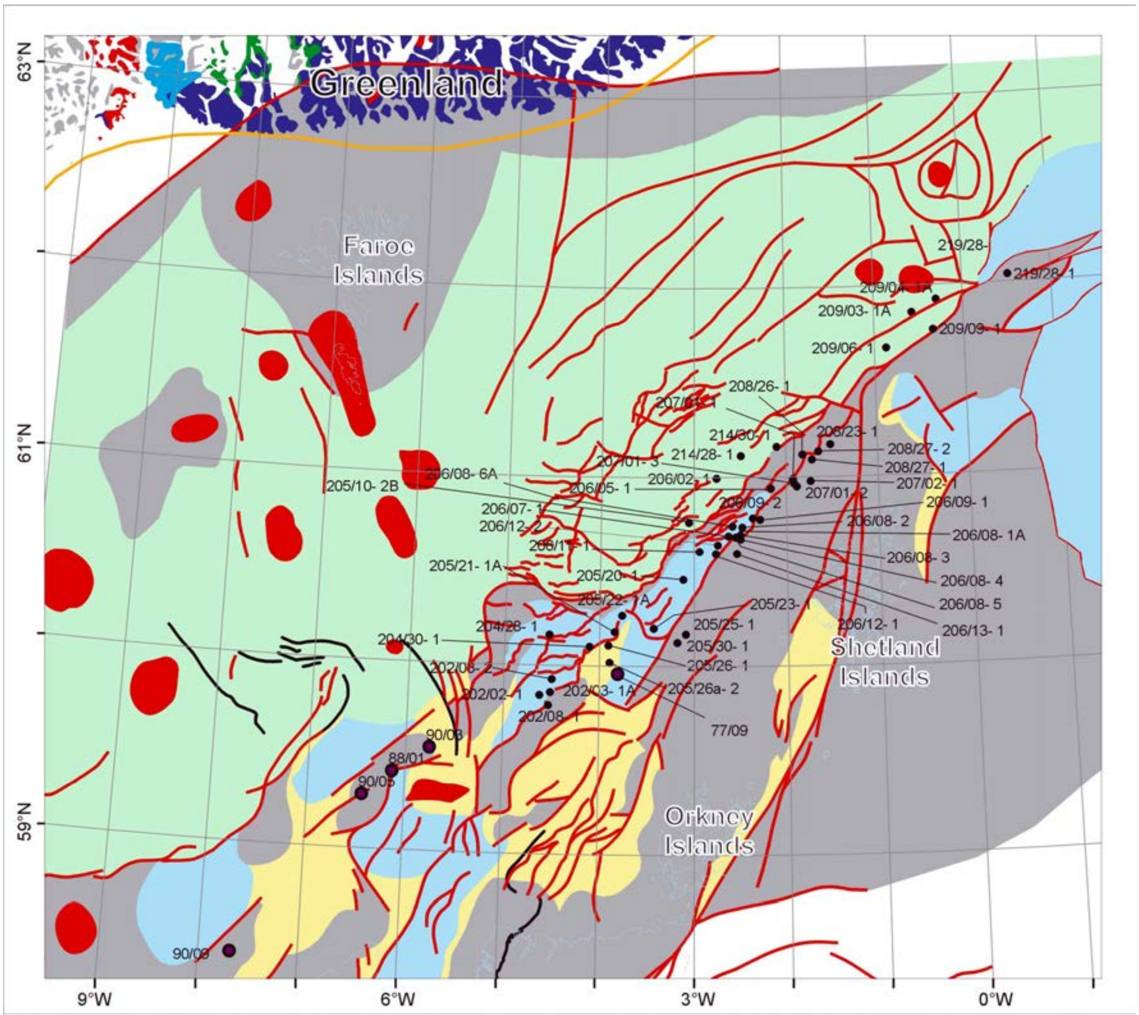

Figure 27a. *Location map of the Faroes-Shetland region showing the wells used in the correlation scheme of Stoker et al. 1993.*

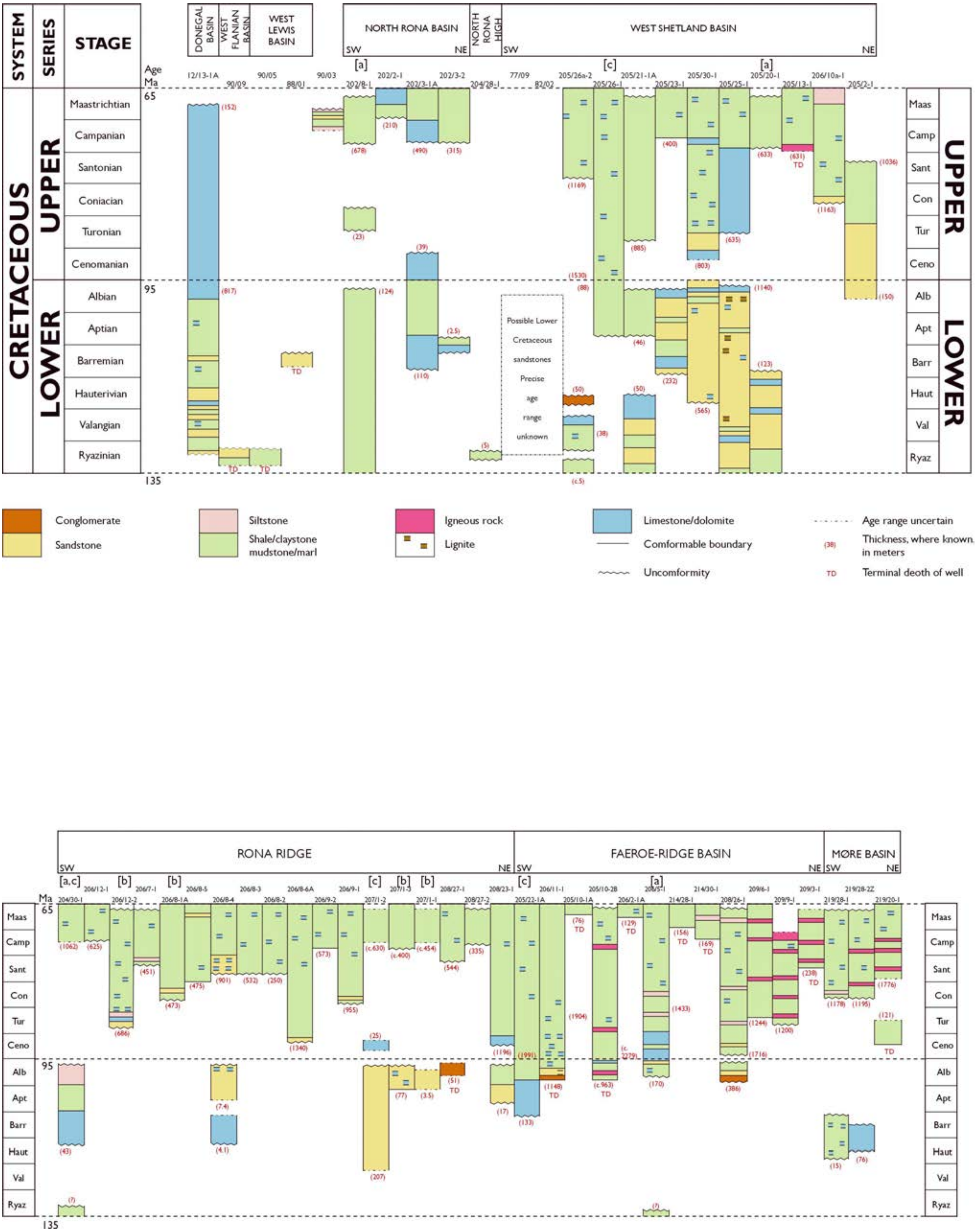

Figure 27b. *Correlation of wells from the Faroe-Shetland region and the Møre Basin. From Stoker et al. 1993.*

Currently there is no formal lithostratigraphic scheme recognised in the region although a set of lithostratigrahic units may be said to be in common use (BGS in Knox *et al.* 1997: Sullivan *et al.* 1999). In addition several stratigraphic schemes developed by the companies are widespread in the literature in spite of the fact that no documentation is presented for the sequence boundaries. Most frequently referred is probably the BP developed scheme of dividing the Tertiary into sequences T10–T50 (Ebdon 1995) (Fig. 28).

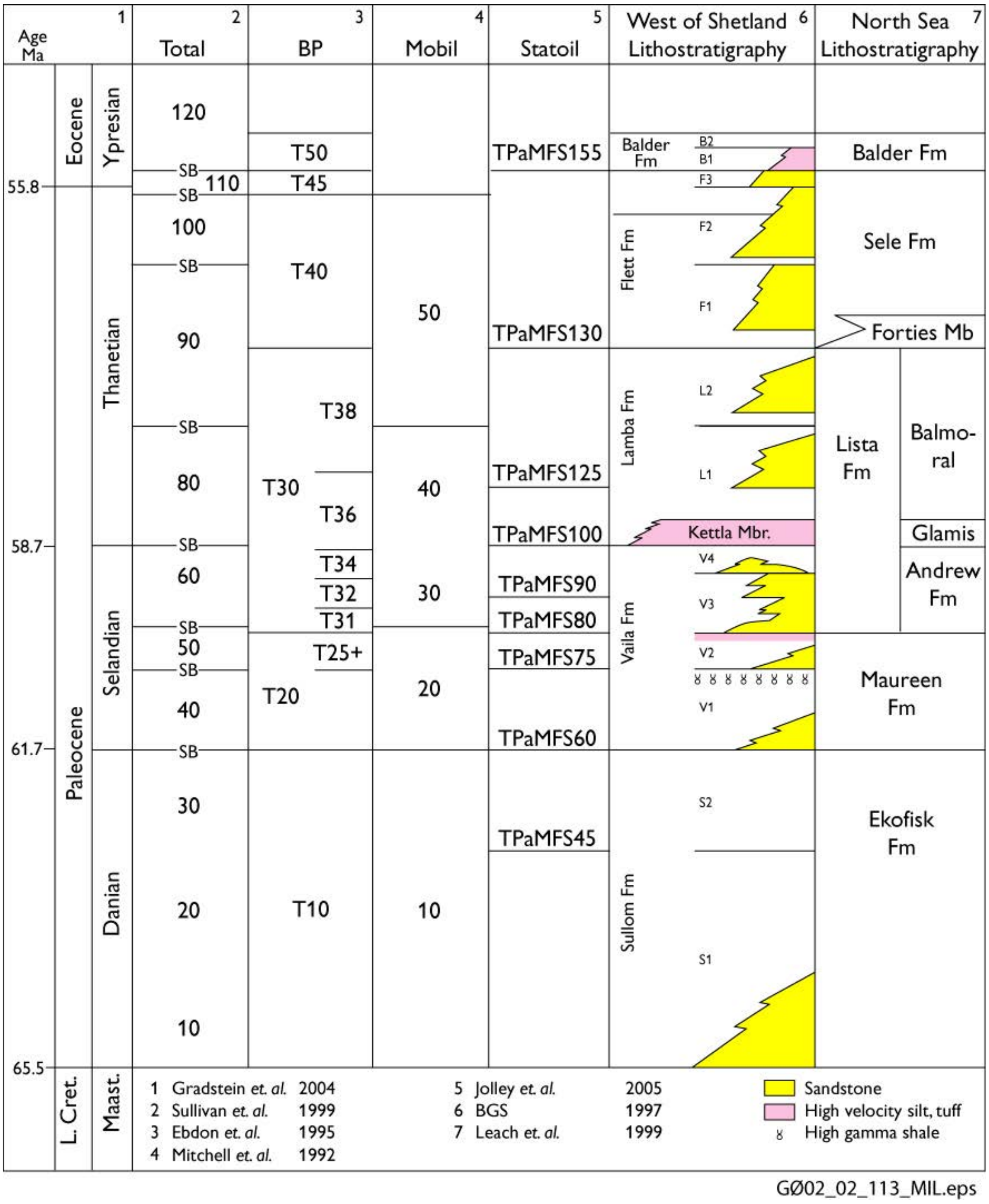

Figure 28. *Compilation of the currently used litho- and sequence stratigraphic schemes of the Early Paleogene successions in the North Sea and West of Shetland region. Figure is compiled from the references (1–7).*

Early Cretaceous

Lower Cretaceous strata reach up to 2000 m in the Faroe–Shetland Basin and more than 1000 m of strata are found in the West Shetland Basin (Stoker *et al.* 1993) (Fig. 27). The succession is composed of a mixture of sandstones, mudstones and conglomerates. Thin coals are present in some wells at the eastern limit of Cretaceous outcrop in the West Shetland Basin e.g. 205/25-1. As a general rule, the farther to the northwest Lower Cretaceous strata are encountered the more mud-prone they become. However, coarse clastic material may be encountered locally on basement highs such as the Rona Ridge (Stoker *et al.* 1993). Lower Cretaceous units are generally wedge-shaped reflecting the influence of rifting (Dean *et al.* 1999). An important reservoir unit is developed in the Aptian–Albian interval on the eastern margin of the rift in the West Shetland Basin and forms the Victory Formation (Goodchild *et al.* 1999) (Fig. 29). These sandstones were deposited in a shallow marine depositional environment and reach 200 m thickness in 207/1-2. Also the Royal Sovereign Formation (206/3-1, 206/4-1) of the Foula Subbasin is characterised by a thick sandstone succession deposited on the hangingwall of the Rona Fault.

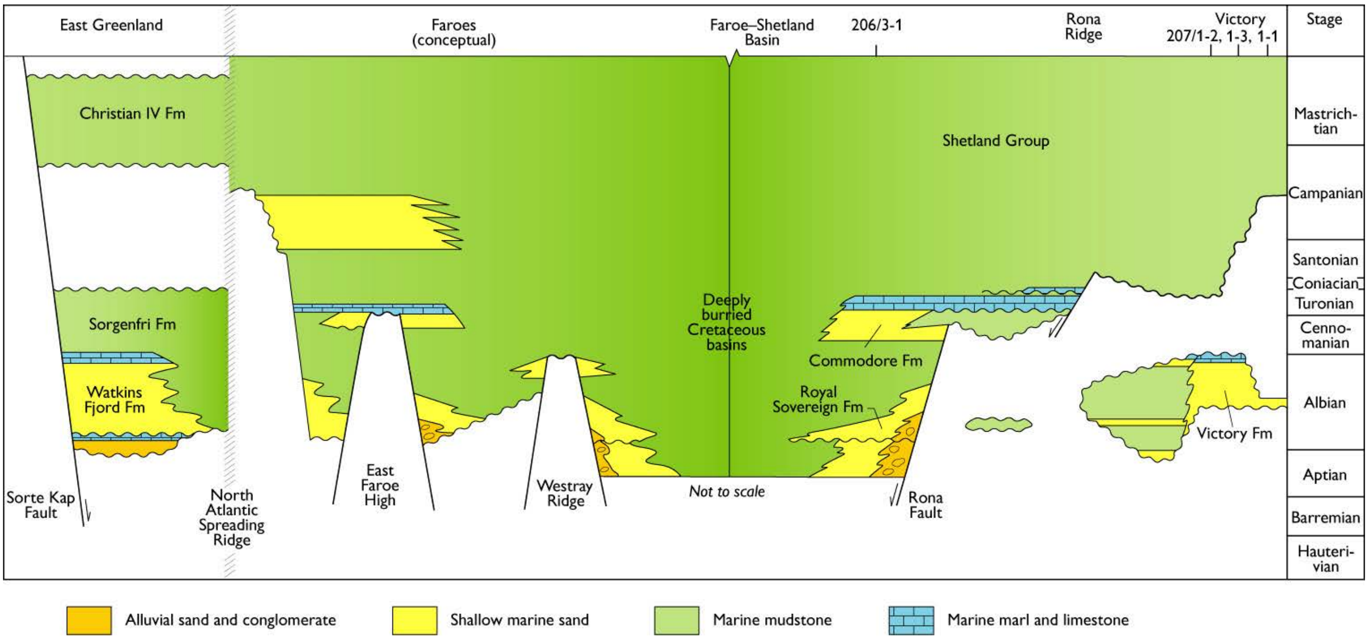

Figure 29. *Correlation of the Cretaceous successions West of Shetland and southern East Greenland. West of Shetland stratigraphy from Grant et al. (1999).*

Late Cretaceous

The are substantial thicknesses of Upper Cretaceous strata in the basins west of Shetland and up to 5000 m of Late Cretaceous sediment is found to the southeast of the Corona Ridge. The succession is dominated by mudstones (Stoker *et al.* 1993) (Fig. 27). Sandstones occur locally in the Cenomanian–Turonian interval and form units up to 300 m thick; the Commodore Formation of Turonian age (wells 206/3-1, 206/4-1) of the Foula Subbasin (Grant *et al.* 1999) (Fig. 29). Sandstones are also reported from this interval offshore Mid-Norway; the Lysing Formation (Dalland *et al.* 1988). With the exception of this interval other sandstone units are not known from the Faroe Shetland region, which may reflect high global sea-levels through the Santonian, Campanian and Maastrichtian. However, in Mid-Norway deep marine gravity deposited sandstones fed from East Greenland are found in the Nise and Springer formations of Santonian–Maastrichtian age e.g. Kittilsen *et al.* (1999).

The depositional environment of the Late Cretaceous succession is thought to be outer-shelf at the basin margins to deep marine in the centre of the basins. The Cenomanian–Turonian sandstones record deposition by sediment gravity flow processes in a deep marine environment, where input is from sources on the Orkney-Shetland platform and thin northwestwards (Grant *et al.* 1999). The sediment source of the thick succession of Campanian–Maastrichtian mudstones is not known although there are indications from studies of pollen floras for sourcing from East Greenland at this time (Jolley & Whitham 2004b). Emergent areas of Scotland are likely to have been limited owing to high global sea-levels and the presence of chalk in sparse exposures on the west side of Scotland (Mortinmore *et al.* 2001) suggests that its potential as a source of fine-grained clastics was limited. This is potentially further an indication that East Greenland was the source of much of the Cretaceous mudstone fill of the basins west of Shetland.

Paleocene

The Paleocene interval is currently the major focus of hydrocarbon exploration in the basin. There are substantial thicknesses of sediment of this age in the basins to the west of Shetland with up to 2000 m in the Flett and Judd sub-basins (Lamers & Carmichael 1999). The initial fill of the basins consists of deep marine clastics. Substantial amounts of coarse clastic material were eroded from the Orkney-Shetland Platform and deposited in the basins west of Shetland by sediment gravity flow processes. The sandstones known as T10 in the Sullom Formation and as T20–T25 in the Vaila Formation are sourced from this region (Fig. 30). Three main sediment input sites have been identified (Lamers & Carmichael 1999): one, supplying sediment to the Judd Sub-basin the other two supplying sediment to the Flett Sub-basin. Sandstones in T20–35 interval form the reservoirs in the West Shetland oilfields e.g. Foinaven, Schiehallion and Loyal. After T35 time, a shelf succession prograded out from the Orkney-Shetland platform over delta slope and deep marine deposits. These shelf sediments are capped by a transgressive succession of fluvio-deltaic sandstones and coals. A sequence boundary is developed beneath this fluvio-deltaic succession and had its maximum basinward extent in T40 time (Roberts *et al.* 1999).

At the same time as sediment was being supplied to the basin from the east, volcanism in the west, in the Faroes region, built up substantial thicknesses of basaltic sediments and lavas (Fig. 30). The onset of volcanism is poorly constrained, but the presence of airfall tuffs in sediments as old as T32 age in well 205/9-1 (Jolley & Whitham 2004b), indicates that the initiation of volcanic activity can be traced at least this far back in time. Evidence for a western source of sediment is found in T36 times in the form of the Kettla Member (Foinaven Subbasin) and Andrew Tuff (Flett Subbasin), which contains volcanic material which can only be derived from the west (Lamers & Carmichael 1999). A western source for some of the T10–T20 sandstones in block 204 has also been suggested by Ebdon *et al.* (1995). Recent studies of well sections has confirmed influxes of a Greenland Flora in sequences T10, T26, T32–35 and T36; Kettla Member (Jolley & Whitham 2004b).

Analysis of palynofloras and microfossils have been interpreted to reflect a change from open marine conditions in the Danian to more restricted marine and non-marine conditions in the Late Thanetian (Mudge & Bujak 2001).

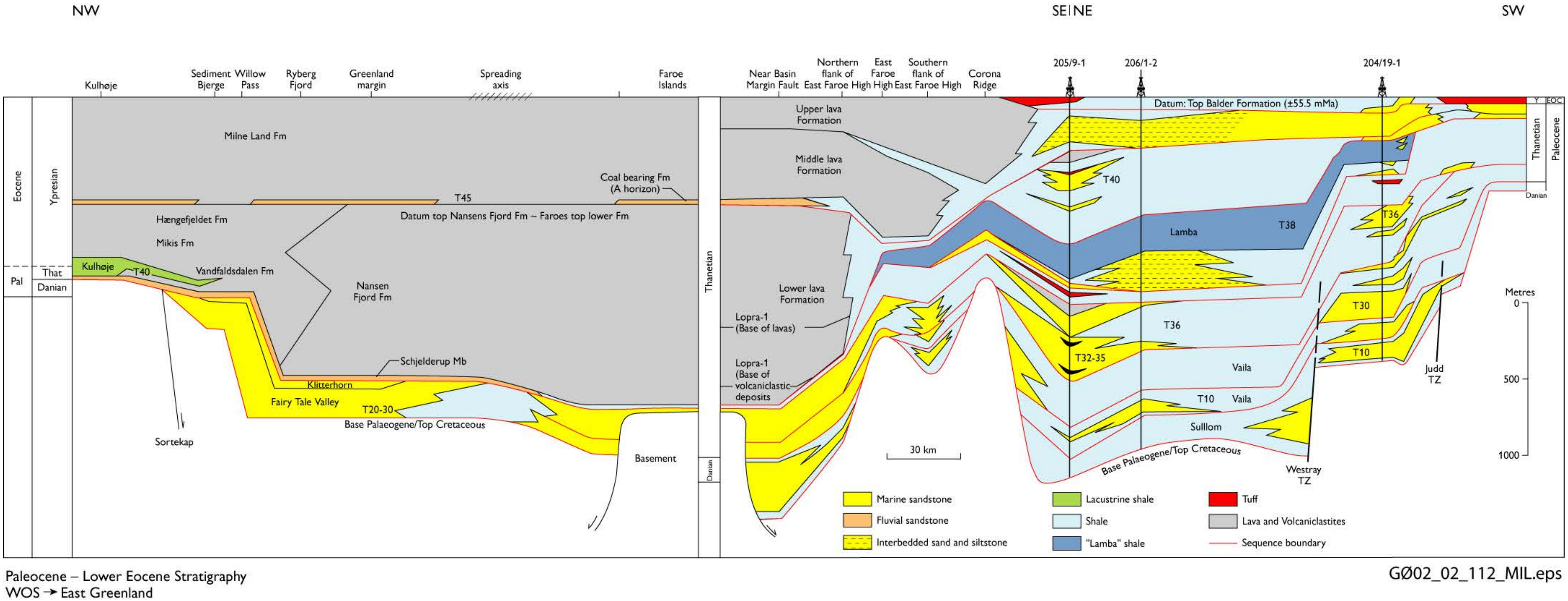

Figure 30. *Correlation of the early Paleogene successions West of Shetland, the Faroes and in southern East Greenland. Right hand side of the diagram from Ellis et al. (2002).*

Correlation between Kangerlussuaq, Faroe Islands and selected UK wells

The established stratigraphic scheme for the Kangerlussuaq Basin, may be related to the Cretaceous Atlantic margin sequences (Fig. 31). However, there is often insufficient stratigraphic information in Faroe–Shetland references to know whether such correlations can be supported by palaeontological data beyond the stage level.

Watkins Fjord Formation

Age: Late Aptian–Late Albian
Lithology: Sandstones
Depositional environment: Fluvial-estuarine-shallow marine
Faroe-Shetland correlation: Victory Fm. (Rona Ridge).
Reference wells: 207/1-2, 207/1-3
Key reference: Goodchild *et al.* (1999)
Remarks: Sandstones of the Royal Sovereign Fm. (Foula Subbasin, well 206/3-1) form a deep basinal counterpart to the shallow marine units. The formation represents basin slope fan deposits and grade into basinal shales of the Cruiser Fm (Grant *et al.* 1999).

Aptian–Albian sandstones belonging to this formation find parallels with units in the Faroe Shetland Basin belonging to the Victory Formation (Goodchild *et al.* 1999) (Figs 29, 31). This formation consists of shallow marine inner shelf to shore face deposits and is encountered in the 207/1 block. It is possible that deposits with similar facies are found locally on the margins on the Faroe Shetland Basin and on intra basinal highs. The Victory sands pass laterally into mudstones, which may be the equivalents of the basal Sorgenfri Formation.

Sorgenfri Formation and Christian IV formations

Age: Late Albian–Late Maastrichtian
Lithology: Sandy mudstones
Depositional environment: Shallow marine to outer shelf
Faroe-Shetland correlation: Cruiser, Mac Beth, Kyrre and Josalfare formations (Shetland Group).
Reference wells: Foinaven and Foula Subbasins e.g. 206/3-1
Key reference: Deegan 1977; Grant *et al.* 1999
Remarks: A prominent unconformity (Santonian–Early Campanian) separates the Sorgenfri and the Christian IV Formation in East Greenland. This has so far not been recognized in the Faroe Shetland Basin, but it may be that the unconformity was only developed in the platform area and has been removed by post Cretaceous erosion.

Like Kangerlussuaq, mudstones are the dominant facies in the Late Cretaceous of the Faroe Shetland Basin (Figs 29, 31). In the Northern North Sea, Late Cretaceous argillaceous strata of Coniacian–Maastrichtian age were first assigned to Shetland Group by Deegan (1977), subsequently this term has been extended by Surlyk (2003) to include mudstones of Cenomanian–Maastrichtian age. This unit name has been informally applied to the sequences West of Shetland as well as formally to mudstone sequences of Coniacian–Maastrichtian age in offshore Mid-Norway (Dalland *et al.* 1988).

Sediments belonging to this group are rarely cored and consist almost entirely of uniform marine grey basinal shales, with rare thin limestone or dolomite stringers (Stoker *et al.* 1993). There is no published information on the depositional environment of the succession. Some must be of deep-marine origin as deep marine high-density turbidites of Turonian age are found in parts of the basin (Grant *et al.* 1999). The mudstones range in age from the Cenomanian–Maastrichtian. There is insufficient published information as yet to recognise equivalents of the Sorgenfri and Christian IV Formation.

Fairytale Valley Member

Age: Selandian
Lithology: Fine to coarse-grained sandstones passing laterally into sandy mudstones with thin sandstone beds. Locally abrupt facies changes across erosional surfaces.
Depositional environment: Slope channel and basin floor fan. Remobilized sandstones are common.
Faroe-Shetland correlation: Vaila Formation
Reference wells: Foinaven and Flett Subbasins 206/1-2, 214/27-1, 205/9-1
Key reference: Knox *et al.* 1997; Lamers & Carmichael 1999; Cooper *et al.* 1999; Leach *et al.* 1999.
Remarks: The presence of Paleocene strata in southern East Greenland has been subject to controversy in the literature; Jolley & Whitham (2004a) and Whitham *et al.* (2004) thus assigned the prevolcanic succession entirely to the Eocene. In contrast, Larsen *et al*. (1999a, b) assigned a Paleocene age to the succession, however, without presenting any biostratigraphic data. The presence of Selandian strata was later documented by Nøhr-Hansen in Larsen *et al*. (2004) and has now been confirmed by Jolley & Whitham (2004b).

The sandstones and mudstones of the Fairytale Valley Member mark a deepening of the depositional basin and are the oldest Paleogene deposits in the Kangerlussuaq Basin. They overlie outer shelf mudstones of the Christian IV Formation with a barely recognisable shale-shale contact. In the West of Shetland region the boundary between Cretaceous and Paleogene sediments is poorly documented and poorly understood. In their paper on palaeoenvironments of the Faroe-Shetland Basin Mudge & Bujak (2001) document the stratigraphy of the Danian in some detail. They define the Maastrichtian–Danian boundary stating by the last occurrence of *P. Grallator* and state that it is a maximum condensation surface. In the adjacent Møre Basin of Mid-Norway, the contact between the Cretaceous and Tertiary is defined by an increase in interval transit time and a decrease in density and resistivity log readings (Dalland *et al.* 1988), there is no distinct lithological change. The boundary is recorded in wells around the Ormen Lange gas discovery (Gjelberg *et al.*

2005). Along the margins of the Faroe-Shetland Basin the Cretaceous–Paleogene boundary is represented by a major unconformity and Danian strata are absent in many wells. The boundary is recognised seismically as a distinct onlap surface.

In Kangerlussuaq, most of the Danian strata are absent corresponding to the development in marginal areas of the Faroes-Shetland Basin. The marginal unconformities corresponds to the time of deposition of thick slope channel and basin floor fans of the Sullom Formation (T10) in the basins (Fig. 31). T10 sands have proven to be present in the most westerly of the Faroe-Shetland wells; 6004/16-1z, recently drilled in the Faroes (Smallwood & Kirk 2005), and these may possibly have a westerly; Greenlandic source area.

Correlation of the deep marine Fairytale Valley Member with the Vaila Formation is based on the consistent occurrence of *Palaeoperidinium pyrophorum* indicating an age no younger than latest Selandian (the *Palaeoperidinium pyrophorum* Zone DP4 of Mudge & Bujak 1996; 2001). In Fairytale Valley, *Areoligera spp.* and *Palaeoperidinium pyrophorum* are common in the lower part of the succession and continue into the upper part, where a distinct dinoflagellate cyst *Spinidinium sp.* and *Suttilisphaera sp.* have their first occurrence. This age determination suggests correlating with NP5 and with the top of sequence T20 or lower part T30 of Ebdon *et al.* (1995). The age is confirmed by Jolley & Whitham (2004b) who suggest correlation of the Fairytale Member with T22 (TPaMFS60–TPaMFS75 interval). The interval is represented by basinal shales in a Corona Basin well illustrated by Jolley & Whitham (2004b).

Recent geochemical studies show that the Vaila Formation in selected UK wells differs in composition from the Fairytale Valley Member of East Greenland and thus have different source areas despite of their common age (Frei *et al.* 2005).

Klitterhorn Member

Age: Thanetian?
Lithology: Fine to medium-grained sandstones
Depositional environment: Shallow marine
Faroe-Shetland correlation: Lamba Formation
Reference wells: Foinaven and Flett Subbasins 206/1-2, 214/27-1, 205/9-1
Key reference: Knox *et al.* 1997
Remarks: Shallow marine facies equivalent to the Klitterhorn Member may possibly be found in the marginal facies of the Lamba Formation of the Faroe-Shetland basin. Highest Paleocene sedimentation rates in the Judd Basin were reached during late T35 earliest T36 times reflected in major fans deposited from the south and west (Kintail Fan of Ebdon *et al.* 1995) (Figs 30, 31). The progradational units show clinoforms up to 500 m high in the Lamba Formation (T38).

Schjelderup Member

Age: Thanetian?/Ypresian
Lithology: Medium to coarse-grained sandstones, carbonaceous mudstones, coals
Depositional environment: Fluvial channel-floodplain
Faroe-Shetland correlation: Flett Formation
Reference wells: Foinaven and Flett Subbasins 206/1-2, 214/27-1, 205/9-1
Key reference: Knox *et al.* 1997
Remarks: The change from marine to terrestrial depositional environments across the Schjelderup Member in Kangerlussuaq and the disappearance of marine dinoflagellates introduces a possible error in the correlation.

The Schjelderup Member marks a prominent change from marine to terrestrial deposition in East Greenland. The change is believed to reflect uplift of the East Greenland margin possibly controlled by the initial effects of the Icelandic mantle plume (Dam *et al.* 1998). In the Faroe-Shetland Basin shelf deposits prograding out from the Orkney Shetland Platform reached their maximum extent at the base of T40 times (Roberts 1999) (Figs 30, 31).

Willow Pass and Kulhøje members

Age: Thanetian?/Ypresian
Lithology: Medium to coarse-grained sandstones, carbonaceous mudstones, coal, volcanic tuffs
Depositional environment: Floodplain and lake
Faroe-Shetland correlation: Flett Formation
Reference wells: Foinaven and Flett Subbasins 206/1-2, 214/27-1, 205/9-1
Key reference: Knox *et al.* (1997)
Remarks: Studies by Jolley *et al.* (2002); Jolley & Whitham (2004a); Hjortkjær & Jolley (1999) has suggested that the terrestrial spores and pollens show significant assemblage changes that can be correlated across the northern North Atlantic. The flora of the Kulhøje Member may, according to Jolley & Whitham (2004a) be directly correlated with the lower volcaniclastic part of the Lopra 1/1a and further on to the middle part of the Flett Formation (T40) in the 205/9-1 well (Figs 32, 33).

Nansen Fjord Fm, Urbjerget Fm and “Lower lavas”

Age: Ypresian
Lithology: Basaltic lavas, volcanoclastics
Depositional environment: Terrestrial, floodplain and lake, shallow marine
Faroe-Shetland correlation: Lower basalt Formation (Faroes)
Reference wells: Lopra 1a, 205/9-1
Key reference: L.M. Larsen *et al.* (1999); Hansen *et al*. (2002); Waagstein *et al.* (2002); Jolley & Whitham (2004a); Ellis *et al.* (2002)
Remarks: Miscorrelation between radiometric; 61–58 Ma ages (Hansen *et al.* 2002) and palynological; Ypresian (Soper *et al.* 1976a; Jolley & Whitham 2004a) ages for the Lower

Basalts in southern East Greenland may pose a general problem for correlation of Paleogene successions.

The onset of volcanism in East Greenland is constrained by an intrabasaltic mudstone containing the dinoflagellate *Wetzeliella* (now *Apectodinium* sp.) (Soper *et al.* 1976a). The Wetzeliella flora indicates an early Sparnacian age (Soper *et al.* 1976a) corresponding the Ypresian (early Eocene). This early Eocene (T40) age is supported by Jolley & Whitham (2004a) based on correlations with the North-East Greenland flora assemblages. The bloom of *Apectodinium* sp. in the North Atlantic region is attributed to the LPTM which mark the boundary between the Paleocene and the Eocene (Crouch *et al.* 2001; Jolley & Bell 2002; Jolley & Whitham 2004a). Jolley & Whitham therefore concluded that the Vandfaldsdalen Formation (Lower Basalts) of the Kangerlussuaq Basin was extruded entirely within the Eocene.

The volcanic succession of East Greenland can be correlated geochemically with the Faroes volcanic succession (L.M. Larsen *et al.* 1999). This work shows that the Nansen Fjord Formation in Kangerlussuaq and the Lower Lava Formation of the Faroe Island are time equivalents (Figs 30, 31). Likewise the Milne Land Formation of Kangerlussuaq may be correlated to the Upper Lava Formation of the Faroes. The top of the Nansen Fjord Formation is marked by a thin coal-bearing sedimentary unit. This is thought to correlate directly to the coal bearing strata marking the boundary between the Lower and Middle formation in the Faroe Island (L.M. Larsen *et al.* 1999; Ellis *et al.* 2002) (Figs 30, 31). Based on the spores and pollen assemblage of the coal-bearing horizon in the Faroes, Jolley *et al.* 2005 suggested that the boundary is time equivalent with the topmost Flett Formation in the well 205/9-1. From the Lopra 1/1a well *plicapollis pseudoexcelsus* and *Interpollis supplingensis* were recovered from 2550–2900 m indicating ages younger than the uppermost Lamba time (Ellis *et al.* 2002)

In summary, the combined evidence from the geochemical and palynological analyses suggest that volcanism had already started in East Greenland and the Faroes at the time of deposition of the uppermost Lamba and Flett formations in the Faroe-Shetland Basin.

Radiometric controversy

Radiometric datings of the volcanic succession in East Greenland and the North Atlantic indicate that the oldest lavas are of Paleocene age; Ar/Ar dates 61 Ma corresponding to base Selandian of Gradstein (2004) (Sinton & Duncan 1998; Tegner *et al.* 1998; Hansen *et al.* 2002). Slightly younger ages (58.8 Ma) were given by Waagstein *et al.* (2002) for the oldest lavas of the Faroes Lower Basalt Formation. The absolute ages are, however, in conflict with the biostratigraphic evidence which suggests that volcanism was first initiated at the Paleocene–Eocene boundary (55.8 Ma of Gradstein *et al.* 2004). Jolley *et al.* (2002) addressed the problem in the paper “Miscorrelation of the Paleogene timescales”, which was subsequently disputed by several others (Wei 2003; Aubry *et al.* 2003; Thomas 2003; Srivastava 2003). Substantial new evidence is needed to revise the existing time scales and the work is far beyond the scope of this project. In this project the biostratigraphic analyses are used as the prime evidence for correlation.

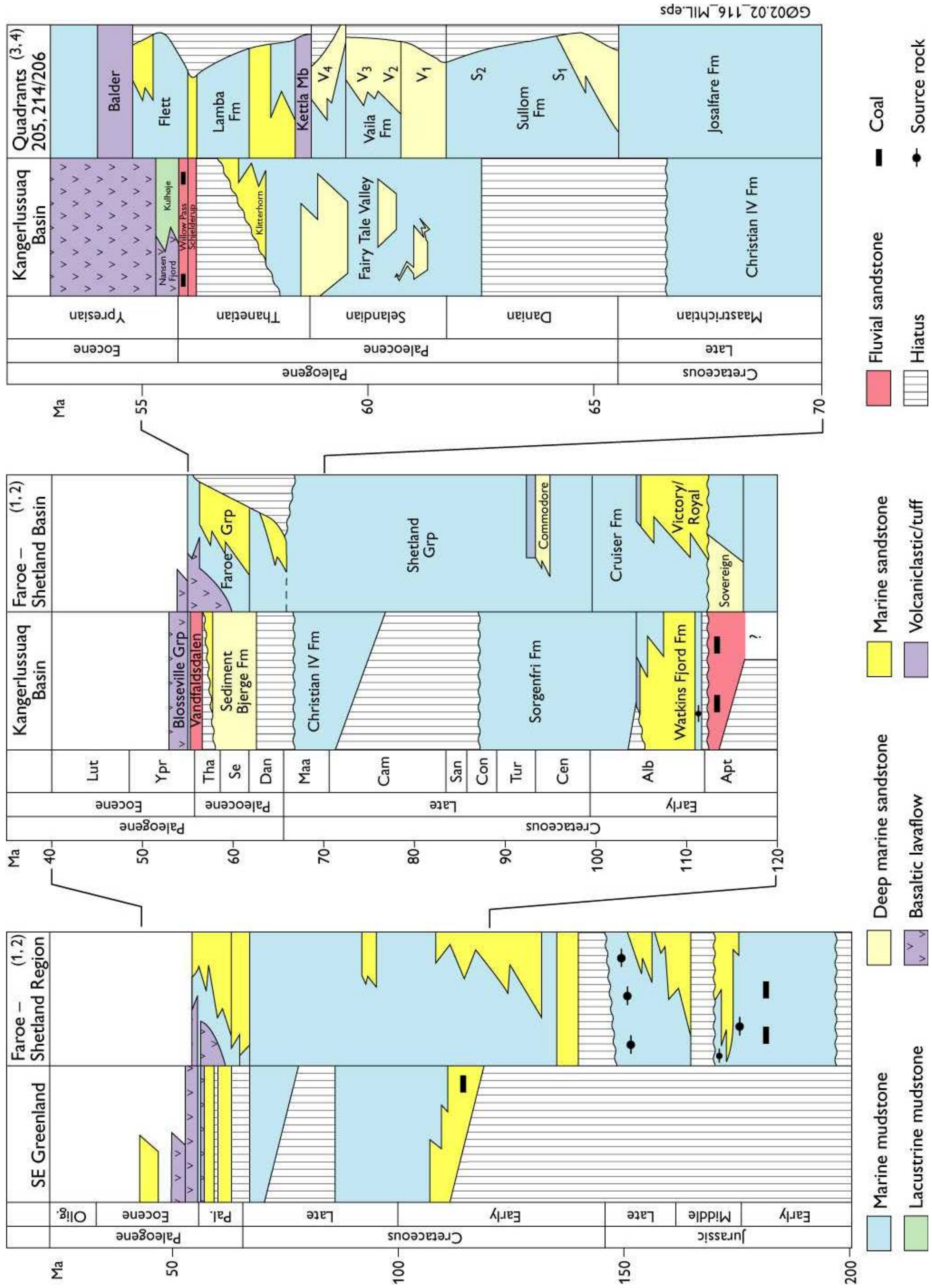

Figure 31. *Correlation of the Jurassic – early Paleogene successions West of Shetland, the Faroes and in southern East Greenland. Stratigraphic information from 1) Grant et al. (1999); 2) Ellis et al. (2002); 3) Knox et al. (1997); 4) Mudge & Bujak (2001).*

Comparison of the Faroe-Shetland region and Kangerlussuaq

Comparison of the Cretaceous–Paleogene basins in the Faroe-Shetland region with Kangerlussuaq reveals many differences and similarities. Observations in Kangerlussuaq indicate periods of extension in the Mid-Albian and in the Late Cretaceous–Paleocene interval. The mid-Albian rift event has been noted by Goodchild *et al.* (1999) and Carr & Scotchman (2003) in the Faroe-Shetland region. The Late Cretaceous–Paleocene period of rifting has been widely recognised in the Faroe Shetland region. The precise timing of the event in Kangerlussuaq is poorly constrained. However, the onset of sedimentation in the Late Campanian, accompanied by the creation of large amounts of accommodation space for Late Campanian–Maastrichtian strata, may be evidence for thermal subsidence following a period of regional Campanian rifting. The presence of active, northwest-oriented faults that were active during the Late Maastrichtian–Paleocene interval may be linked to the NW oriented transfer zones in the Faroe-Shetland region.

Dean *et al.* (1999) suggested that rifting occurred during the Cenomanian–Santonian and the presence of Turonian deep marine sandstones in the Faroe Shetland Basin possibly relates to formation of a sequence boundary of this age. No evidence, however, exists to suggest neither rifting nor the development of a sequence boundary in the Kangerlussuaq succession.

As has been noted by Larsen *et al.* (1999a, 1999b) the sedimentological evolution of the Cretaceous–Early Paleogene succession in Kangerlussuaq finds strong parallels with successions of equivalent age on the eastern margins of the Faroe-Shetland rift. In both areas shallow marine sandstones of mid-Cretaceous (Aptian?–Albian) age are overlain by a by Late Cretaceous mudstones (Fig. 31). In both areas there is an influx of deep marine sandstones in the Paleocene. Deep marine sediments are succeeded by a prograding package of pro-delta, fluvio-deltaic and finally fluvial sediments. An important sequence boundary, occurs at the base of the fluvial sediments (EG SB_6) and probably corresponds to a major sequence boundary of T40 age in the Faroe Shetland region (Roberts *et al.* 1999). Although there are these similarities, there are also some important differences between the two regions.

In the Kangerlussuaq succession, two major unconformities occur, which have not been recognised in the Faroe-Shetland region (Fig. 31). These unconformities coincide with major changes in the heavy mineral composition of sandstones (Whitham *et al.* 2004). The lower unconformity is between the Sorgenfri and Christian IV formations and spans the Coniacian–Late Campanian interval (EG SB_4). The unconformity is thought to be related to a period of relative sea level fall and may have been accompanied by the deposition of lowstand fan deposits in adjacent basins. It is possible that the development of this sequence boundary may have been accompanied by deposition of deep marine reservoir quality sands in the adjacent basins. Although outside the Faroe–Shetland region prominent, reservoir sands that may be an analogues are seen in contemporaneous successions on the Nyk High in Mid-Norway (Kittilsen *et al.* 1999). These Upper Cretaceous deep marine sands appear to have been derived from formerly adjacent areas of East Greenland (Morton *et al.* in press).

The other unconformity occurs between the Christian IV and Sediment Bjerge formations and spans the Late Maastrichtian–Danian interval (EG SB_5). In contrast to the lower unconformity the development of this unconformity is thought to have been related to Late Cretaceous–Paleocene rifting. Sandstone provenance studies provide a possible means of testing the hypothesis that Kangerlussuaq provided sediment to the southwestern end of the Faroe–Shetland Basin (see the following pages). The only Paleocene sands in the basin so far recognised as having a western source are in well 205/9-1 (Lamers & Carmichael 1999) and these sands do not have heavy mineral characteristics compatible with an origin from Kangerlussuaq region (Whitham *et al.* 2004). Recent studies by Jolley *et al.* (2005) based on pollen frequency data, however, suggest that sediment derived from Greenland is present in several wells of the Faroe–Shetland Basin. The high abundance of “Greenland flora” was coupled with periods of low relative sea level in the Paleogene and appears to be focussed along sediment transfer zones e.g. the Westray and Judd transfer zones (Larsen & Whitham 2005) (Fig. 1).

Petroleum assessment

The following section reviews aspects of the depositional system of the Faroe-Shetland Basin and surrounding regions with relevance to the petroleum system. These aspects are: evidence for sediment sourcing from East Greenland to the Faroe-Shetland Basin and evidence for Cretaceous and Paleogene source rocks. Palaeogeographies for the Cretaceous and Paleogene of the Faroe-Shetland Basin and adjacent regions are also presented to illustrate the potential distribution of sandstone reservoirs and source rocks.

Ziska & Andersen (2005) in a review of the exploration possibilities of the Faroes stress the apparent symmetrical development of the Faroes-Shetland rift and thus the possibility for finding similar reservoir sections below the basalts on the Faroes side of the basin, as have already been identified on the UK side.

Based on comparison with the UK sector a number of possible play types can be foreseen around the Faroe Islands. Of relevance to the present study is the Lower Cretaceous shallow-marine sandstones which are proven as reservoir unit in the Victory Field, West of the Shetland Islands (Goodchild *et al.* 1999). These reservoir units are sealed by a thick, Upper Cretaceous shale succession.

In the UK sector Upper Cretaceous plays are poorly known, but have Upper Cretaceous sandstones as reservoir and Middle and Upper Jurassic coal and mudstone as source. The trap is stratigraphic and sealed by Upper Cretaceous mudstones. The play is a high risk play and is only poorly known in the area West of Shetland (Grant *et al.* 1999). However, Santonian – Lower Campanian turbidite sandstones form the main reservoir unit in plays currently tested in the Vøring basin (Kittilsen *et al.* 1999).

The main exploration target tested in the Faroes area during the first licensing round was the Paleocene deep-water play (Lamers & Carmichael 1999). The Paleocene play is the most recently described play in the area west of the Shetland Islands and the Paleocene succession can be divided into a series of sandpulses related to uplift episodes of the UK mainland. Sandstones of this age form the main reservoirs of the Foinaven and Schiehallion fields. Further into the Judd Basin sandstones derived from a western source area is thought to become important. In order to test this hypotheses a number of sediment provenance studies have been performed:

Sediment provenance studies

Plate reconstructions of the North Atlantic region indicate the former proximity of Greenland to the Faroe Islands region. Consequently, as hydrocarbon exploration pushes further westward in the Faroe-Shetland Basin, there are increasing questions as to the role that Greenland has played as a source of sediment to the basin. Potential clues to the evolution of the region may be provided by basins farther north in the North Atlantic rift where exploration of areas towards the continent–ocean boundary is further advanced. The discovery of a thick sequence of sands of Santonian–Maastrichtian age in a well drilled on the Nyk High, in the western part of the Vøring Basin (Kittilsen *et al.* 1999), suggested that East Greenland was capable of supplying considerable quantities of sand to basins on the basins on the NW European margin. Since the publication of this work, heavy mineral analysis of sands from this well and material from East Greenland (Morton *et al.* in press) has further emphasised the link between the two regions. Sandstone provenance studies in the Vøring Basin thus have shown that there is a group of sands of Late Cretaceous age that may have been sourced from NE Greenland (Morton & Grant 1998). These sandstones thicken westward to form excellent reservoirs (Kittilsen *et al*., 1999). This model of sediment sourcing from East Greenland to Mid-Norway is relevant to the Faroe-Shetland Basin region since like the Vøring Basin separation of Europe from Greenland was achieved along the western edge of the basin, consequently both eastern and western margins of the basin are now part of the NW European plate (Fig. 1). A major problem with the Faroe-Shetland Basin, however, is that the location of the western margin of the basin is hidden on seismic section by considerable thicknesses of Paleogene basalts. Knowing the evolution of East Greenland thus becomes essential to an understanding of the supply of sediment to the Faroe-Shetland Basin from Greenland.

The first study to suggest that the Cretaceous–Paleogene sediment forming the fill of the Faroe-Shetland Basin came from anywhere other than the Orkney Shetland Platform were Lamers & Carmichael (1999). In their paper they show influx of volcaniclastic sediment from an area to the west of the basin in T36 time. More recently, Jolley & Whitham (2004b) used pollen floras to demonstrate that sediment containing a distinctive Greenland' flora was transported to the Faroe-Shetland Basin from the west. Whitham *et al.* (2004) undertook a study of sandstones from the Kangerlussuaq succession to characterise an area that may have potentially provided sands to the Faroe-Shetland Basin. Their study demonstrates that sandstones show stratigraphic variations that are related to major sequence boundaries in the succession. Furthermore, the sands show distinctive characteristics particularly in the age distribution of detrital zircons that would seem to allow them to be differentiated from sands derived from the NW European margin (Whitham & Morton 2004; Frei et al. 2005). As yet there is little evidence to suggest that any sand in the Faroe-Shetland Basin was supplied from East Greenland in the Paleogene interval that contains sandstone reservoirs and there are no sands of Late Cretaceous age recorded in the basin. The only public indication for a Greenlandic source of Early Paleocene sands in the Faroes wells are presented by Poulsen *et al.* (2004). It should be emphasised, however that no heavy mineral analyses of sands from wells drilled in Faroes waters have been released into the public domain.

A major study was funded by the SINDRI consortium investigating the provenance of sediment in the Faroe-Shetland Basin and on the Orkney-Shetland Platform and in East Greenland (Frei *et al.* 2005). The study provides unique geochemical signatures for the units of the Kangerlussuaq succession and may form the basis for future detailed provenace studies in the region.

Evidence for Cretaceous and Paleogene source rocks

There are two main source rocks in the Faroe-Shetland Basin. The richest of these is the Kimmeridge Clay Formation (Cawley *et al.* 2005; Stoker *et al.* 1993) with drilled thicknesses of > 250m thick, TOC contents >5% and petroleum potentials of 50 kg/t. Source rocks are also encountered in the Mid Jurassic (Cawley *et al.* 2005; Stoker *et al.* 1993). In this case, intervals are typically quite thin, but TOC contents are > 4% with petroleum potentials of 15–20 kg/t. Lower in the section there are also suggestions of source rocks in the Devonian and Carboniferous at least in adjacent regions (Christiansen *et al.* 1990; Marshall *et al.* 1985).

Evidence for younger source rocks is scant, but the presence or absence of source rocks of Cretaceous or younger age is important because of the large thicknesses of Cretaceous sediment in the NW European margin basins which mean that Jurassic and older source rocks are deeply buried. Extension during rifting also means that the coverage of these source rocks is increasingly patchy with increasing age. There are two main candidates regionally in the Cretaceous–Paleocene interval, in the Aptian and the Cenomanian–Turonian. Aptian source rocks are known from the North Sea (Copestake *et al.* 2003). In this case, the source rock interval is 3–15 m thick and has TOC contents of up to 12.7%. Organic rich sediments were also deposited in many parts of the globe during the Cenomanian–Turonian anoxic event. However, these appear to be only poorly developed in the region. A thin source rock unit (the Plenus marl) is developed in parts of the northern North Sea with local TOC contents of up to 10.2% and HI values of 222 mg/g. This unit has therefore limited source rock potential. Possible Cretaceous source rocks are also reported from the deep water basins west of Norway although a good quality source rock is still to be confirmed (Kristensen *et al.* 2004)

Hydrocarbon bearing fluid inclusions in sandstones from Kangerlussuaq was studied by CASP and reported in Jonk *et al.* (2005). These are significant because they indicate the existence of a viable hydrocarbon system in an area where there are no pre-Aptian strata. John Parnell and co-workers have further investigated these fluid inclusions, and their origins, in two SINDRI funded studies (Baron *et al.* 2004, 2005). These studies show that source-rocks capable of generating hydrocarbons are widespread, since hydrocarbon bearing fluid inclusions are found in sandstones at five exposures spread over an area of around 2500 km^2 The studies also show that the source of the hydrocarbons are probably marine mudstones in the Mid-Albian succession; Watkins Fjord Formation (Baron *et al.* 2005).

Palaeogeographies

Four palaeogeographies have been constructed for the Faroe-Shetland-Greenland region. These are designed to illustrate the implications of this study for sediment transport from East Greenland to the Faroes region from the Early Cretaceous to the Late Paleocene. The palaeogeographies show the distribution of depositional environments, potential sediment transport paths and the distribution of reservoir sands.

The Cretaceous basins of the north Atlantic rift have their origins in a major period of rifting that occurred in the Late Jurassic–Early Cretaceous (Doré *et al.* 1999). A major uncertainty for hydrocarbon exploration in the region is the westward extent of the Cretaceous basin beneath the flood basalt cover. At present the location of the western basin margin is not known because of problems in seismic imaging through the basalts. Furthermore, it is not known whether a single, wide basin was formed between Greenland and NW Europe in this region, which is the situation for the Vøring and Møre basins, or whether there was an intervening high similar to the Rockall Hatton Bank. We prefer the simple single basin for two main reasons. Firstly, the Cretaceous structural development between East Greenland and the NW European margin to the north and south of the Faroe-Shetland region point towards a single basin model. This is elegantly shown by the 3D gravity modelling of Kimbell *et al.* (2005) who show two individual sedimentary basins, the North Rockall Basin and the Møre Basin, between the UK and the NW European margin COB immediately to the south and the north. In both cases, on the conjugate Greenland margin, there is insufficient space between the East Greenland coastlines and the Greenland COB to accommodate another sedimentary basin. Secondly a simple scenario is always to be preferred over a more complex one in the absence of any evidence.

The volume of sediment in a rift will to a large extent be controlled by the presence of non-extended continental crust beyond the rift flanks, particularly during times of post-rift thermal subsidence when the flanks become submerged by rising sea level, covered by sediment (White & McKenzie 1988), and large river systems may be captured. In the case of the Faroe-Shetland Basin, the southeast flank of the basin is a relatively narrow high delimited to the east by the rift basins of the North Sea. In contrast, the northwestern flanks of the basin are wide stretching to the to the Davis strait. Consequently Greenland has always had the potential to supply a far larger proportion of sediment into the rift than the Orkney-Shetland Platform and the northern Scottish mainland on the other flank of the rift. It is thought this had a major influence on the origin of sediment in the rift particularly in the Late Cretaceous.

Albian

The Albian was a time of coarse clastic sedimentation on the margins of the rift accumulating in high-energy shallow marine depositional environments (Fig. 32). Local highs in the rift may also have accumulated fringes of sandy shallow marine strata (e.g. Victory Field (Goodchild *et al.* 1999)), but it is thought that these would have been of limited thickness and aerial extent. Mudstones would have been the dominant deposit in more basinal areas away from coarse grained deep marine fans supplied by sediment from areas of high energy, shallow marine sedimentation through relay ramps and during periods of lowstand. Deposition of mudstones with oil-source rock potential occurred in low energy shallow marine environments between areas of shallower high-energy sedimentation. Following faulting in the Mid to Late Albian, mudstone deposition became more widespread as coarse clastic sedimentation stepped back on to the basin margins during post-rift thermal subsidence. A similar picture to that found in the Faroe-Shetland Basin is recorded in NE Greenland (Whitham *et al.* 1999).

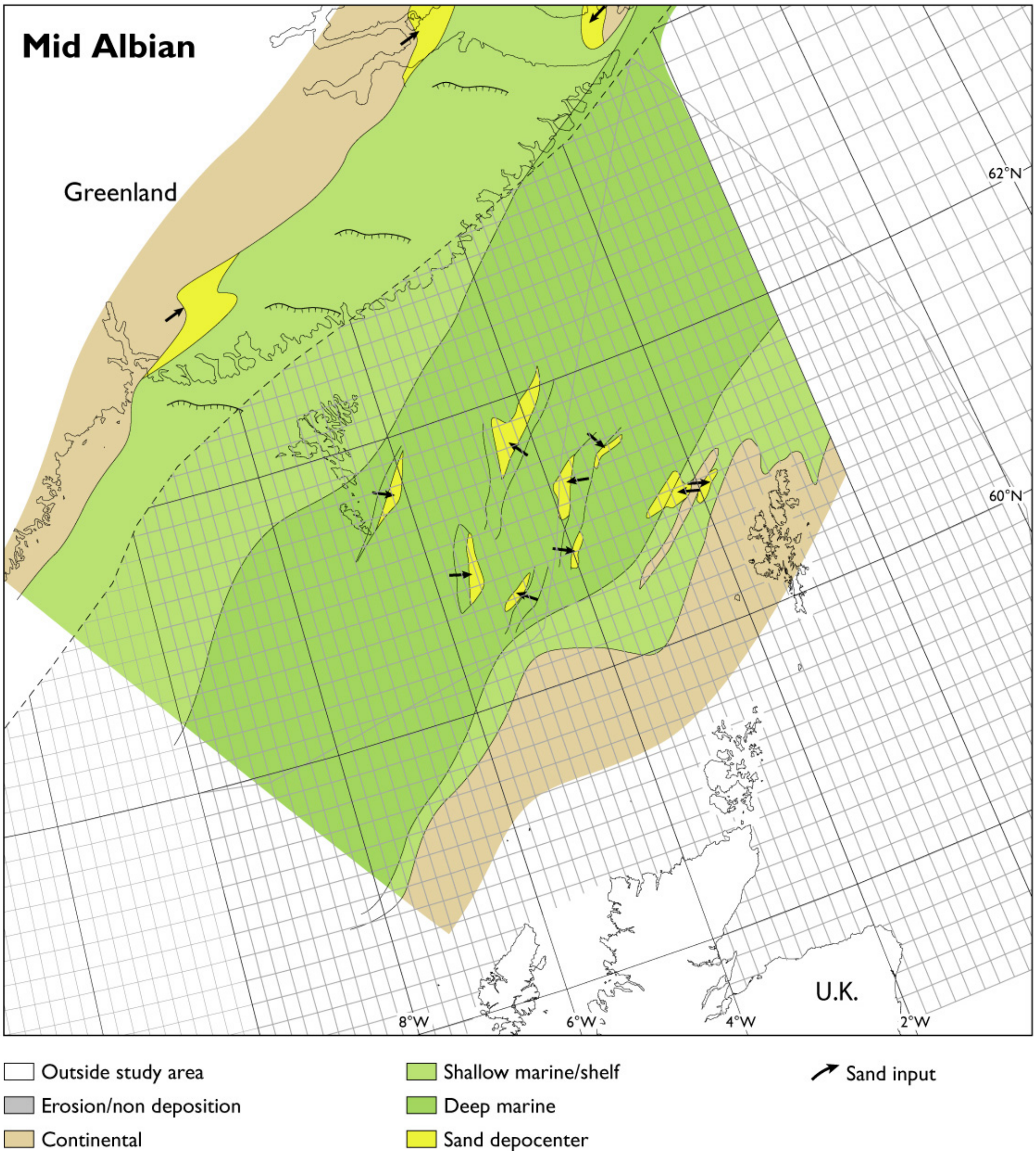

Figure 32. *Palaeogeographic reconstruction of the Kangerlussuaq–Faroes–Shetland region in Albian times.*

Campanian

Rising sea levels and limited extension in basins meant that areas of coarse clastic sedimentation stepped backwards from the rift onto the basin flanks (Fig. 33). At times the Orkney Shetland Platform probably was totally submerged. A little way to the south around the latitude of Skye chalk sedimentation occurred possibly extending across the entire Scottish mainland at times (Cope *et al.* 1992; Mortinmore *et al.* 2001). Given the limited source areas for sediment on the southwest side of the Faroe-Shetland Basin, the large thicknesses of Campanian mudstone found in the Faroe-Shetland Basin must have been derived from Greenland. During the Early Campanian there was a major fall in sea level leading to the formation of a sequence boundary in East Greenland. The reasons for this sea level fall are uncertain, but may have their origins in the rifting and plume impact on the western side of Greenland (Dam *et al.* 2000; Lawver & Müller 1994). Sands associated with the formation of this sequence boundary in East Greenland would have been deposited in basinal areas to the east.

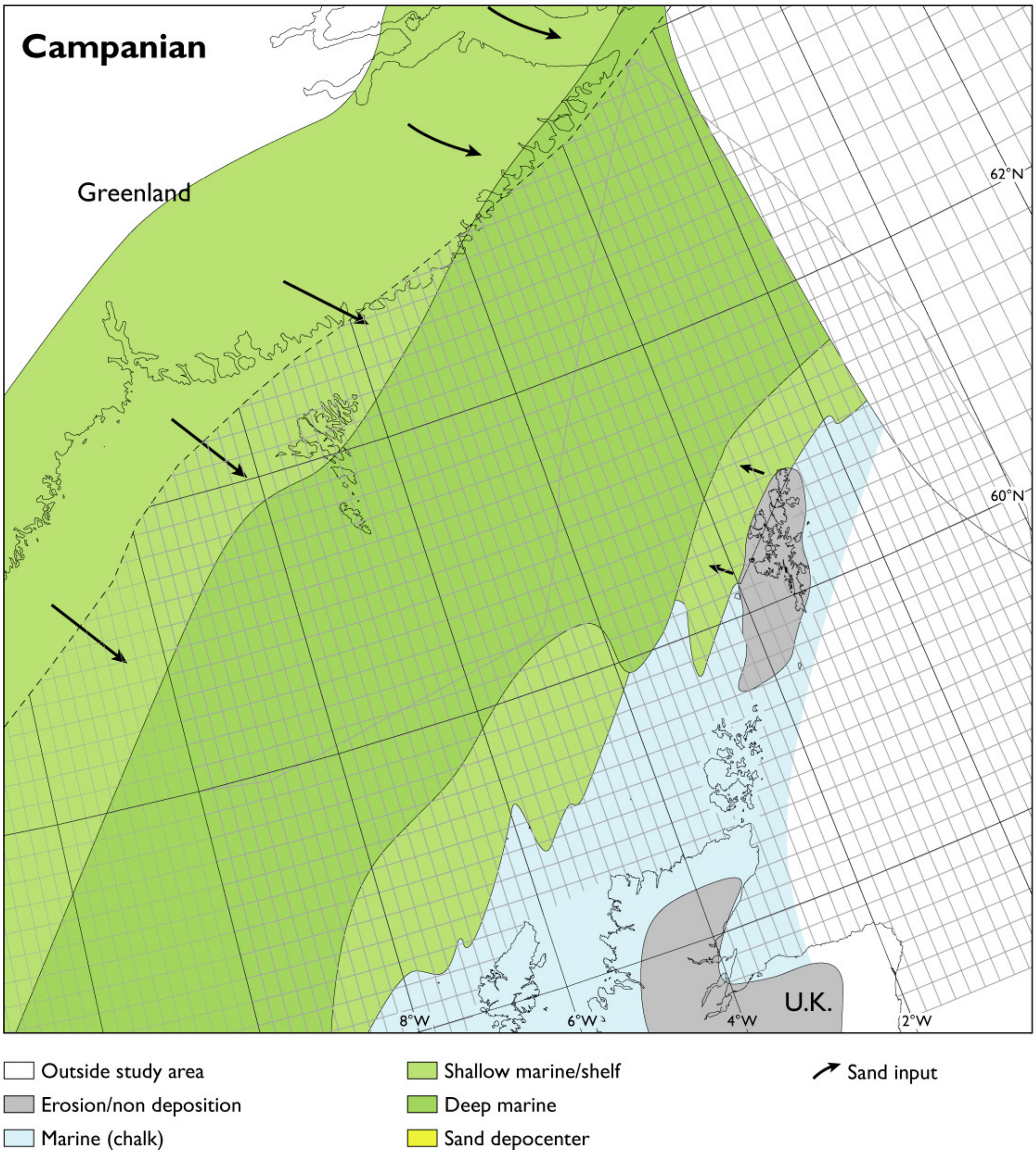

Figure 33. *Palaeogeographic reconstruction of the Kangerlussuaq–Faroes–Shetland region in Campanian times.*

Late Maastrichtian – Early Paleocene

During the Latest Maastrichtian to Early Paleocene the Faroe-Shetland Basin came under the influence of rifting and the direct influence of the Iceland hotspot. As a result the basin margins were rapidly uplifted and denuded and large quantities of sediment were eroded transported to the Faroe-Shetland Basin (Fig. 34). This process led to the large thicknesses of Paleocene sediments recorded in the basin today (Stoker *et al.* 1993). With the uplift of the rift flanks, sands were supplied from the Orkney Shetland Platform to deep marine fans in the Faroe-Shetland Basin (Lamers & Carmichael, 1999). A study of tectonic lineaments that may have had fundamental control on sediment dispersal patterns concluded that a major sediment input point may also have existed in the Kangerlussuaq Basin in the earliest Paleocene (Larsen & Whitham 2005).

The presence of a volcanic centre or centres in the western Faroe-Shetland Basin is uncertain, but is suggested by the presence of tuffs in sediments as old as T10 age in wells from the region (David Jolley pers. comm. 2005). Sediment derived from the Greenland side of the rift reached as far east as wells 204/20-3 and 205/9-1 as indicated by the presence of a distinctive Greenland flora (Jolley & Whitham 2004b). In the light of active rifting at the time, sediment transport across the structural grain of the rift from East Greenland seems unlikely. Although transfer zones, that transect the rift (Naylor *et al.* 1999), may have allowed southeasterly sediment transport. In the light of the orientation of the faults in the rift, relative to the trend of the Blosseville Kyst on reconstructions, the most likely sediment transport path from Greenland to the Faroe-Shetland Basin would appear to be from the Blosseville Kyst region down the axes of the graben.

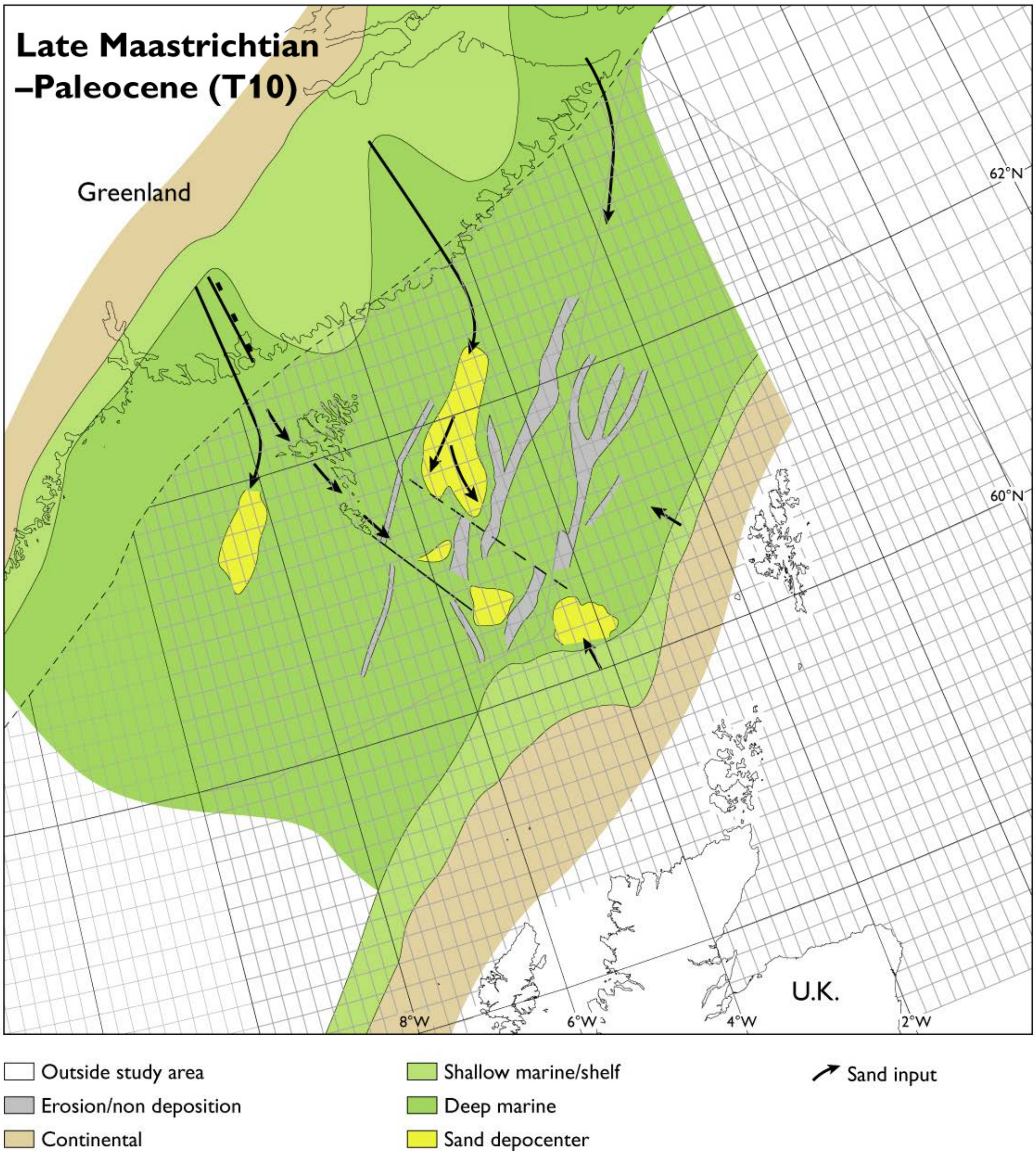

Figure 34. *Palaeogeographic reconstruction of the Kangerlussuaq–Faroes–Shetland region in Late Maastrichtian – Early Paleocene(T10) times.*

Late Paleocene

The presence of basaltic material in the Kettla Member of T36 age, which is derived from the west (Lamers & Carmichael 1999), is evidence for volcanic activity in the Faroe-Shetland Basin by the end of the Paleocene (Fig. 35). Sediment from the Orkney-Shetland Platform prograded out into the basin, with sands deposited at the toesets of clinoforms forming important reservoir targets. These clinoforms reached their maximum extent basinward extent in T40 time (Roberts *et al.* 1999). Similar clinoforms may well have been developed at the western margin of the basin. A major source of sediment to the west is indicated by the presence of a distinctive Greenland flora in strata as young as T36 age (Jolley & Whitham 2004b) and substantial thicknesses of sand found in well 6004/16-1z (Smallwood & Kirk 2005). As Paleocene–Eocene sands in Kangerlussuaq do not contain any evidence for basaltic volcanism basaltic centres may have been a barrier to the eastward transport of sand from Greenland to the Faroe-Shetland Basin at this time, deflecting sediment to the north or the south. Any Greenland sourced sediment is likely to have come down the axis of the rift from the Blosseville Kyst region in a scenario similar to that described in the Early Paleocene.

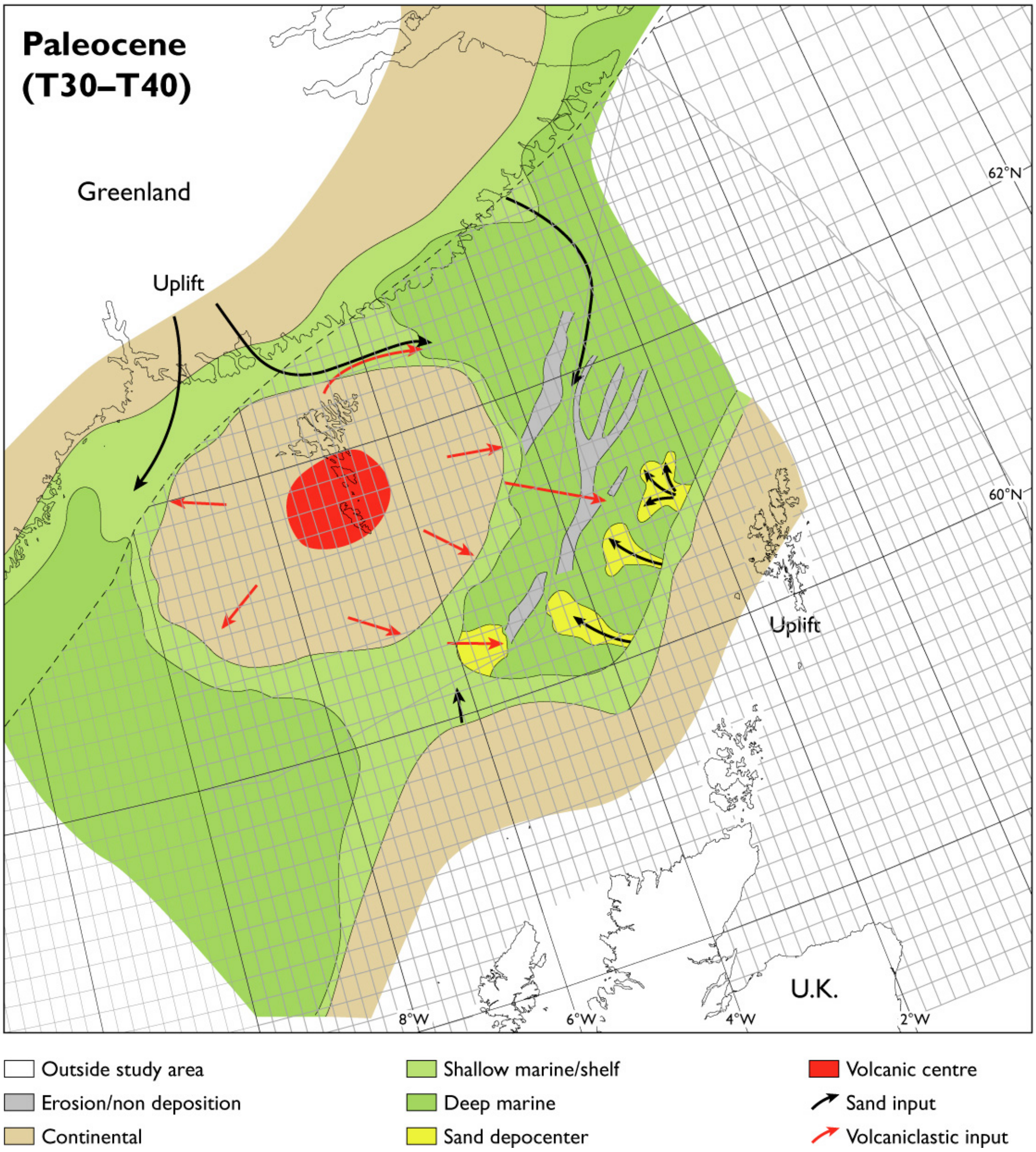

Figure 35. *Palaeogeographic reconstruction of the Kangerlussuaq–Faroes–Shetland region in Late Paleocene (T30–T40) times.*

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Appendix 1

Palynostratigraphy of the Kangerlussuaq area, East Greenland

Henrik Nøhr-Hansen

Methods

Palynological preparation and studies of the samples were carried out at the Geological Survey of Denmark and Greenland (GEUS). Palynomorphs were extracted from 20 g of sediment from each sample by modified standard preparation techniques including treatment with hydrochloric (HCl) and hydrofluoric (HF) acids, sieving using a 20 μ nylon mesh and oxidation (3–10 minutes) with concentrated nitric acid (HNO_3). Finally, palynomorphs were separated from coal particles and woody material in most samples, using the separation method described by Hansen & Gudmondsson (1978) or by swirling. After each of the steps mentioned above the organic residues were mounted in a solid medium (Eukitt ®) or in glycerine gel. The palynological slides were studied with transmitted light using a Leitz Dialux 22 microscope (No. 512 742/057691). Dinoflagellate cysts, acritarchs and selected stratigraphically important spores and pollen species were recorded from the sieved, oxidised or gravity-separated slides. Approximately 100 specimens were counted whenever possible.
The sample depths and relative abundance of species referred to in the biostratigraphic section (below) are illustrated on range-charts of nine selected sections (Enclosures 1–9).
Material
The present stratigraphic study is based on the study of 107 GEUS samples representing 18 sections from the Kangerlussuaq area collected between 1995 and 2000.

1) Sequoia west section, Enclosure 4, 8 samples. Marine deposits of late Early Maastrichtian to early Late Maastrichtian age. Preservation fair.

2) Sequoia Nunatak section McIntyre (NNP 1990, Kulhøje) (CASP W4232b), 17 samples. Nonmarine deposits of Late Paleocene age. Preservation fair to poor.

3) Sequoia Nunatak section, Enclosure 3 (CASP W4235 & 4236), 5 samples. Marine deposits of early Late Maastrichtian age. Preservation fair.

4) Korridoren section 2 samples (413216, 413217). Nonmarine deposits, spores, pollen and degraded plant fragments constitute all the organic material.

5) Nansen Fjord section, 7 samples. Nonmarine deposits, spores, pollen, degraded plant fragments and few fungal spores constitute all the organic material.

6) Skiferbjerg section, Enclosure 5, (CASP N4245, N4246), 20 samples. Marine deposits of Early Maastrichtian to Late Maastrichtian age. Preservation fair.

7) East Skiferbjerg basal section, 2 samples (455692, 455694). Organic material thermal overmature.

8) Skiferbjerg basal section, Enclosure 1 (CASP W4244), 3 samples. Marine deposits of middle Albian to Campanian/Maastrichtian age. Organic material thermal mature to overmature.

9) Pyramiden (E. Hoch) section, 1 Enclosure 2, 10 samples. Marine deposits of Cenomanian to Santonian age.

10) Pyramiden section, 6 samples most charcoal, very few poorly preserved dinoflagellate cyst fragments in 412717 (*Chatangiella* spp. rew? *Palaeoperidinium pyrophorum*, *Spiniferites* spp. *Phelodinium* spp.? *Thrithyrodinium evitti*?).

11) Fairytale Valley section, Enclosure 7, (CASP W4220), 5 samples. Marine deposits of middle to Late Selandian age with reworked Late Cretaceous palynomorphs. Preservation poor.

12) Willow Pass section, 2 samples. Marine deposits of Selandian age with reworked Upper Cretaceous palynomorphs. Preservation poor.

13) Rybjerg Fjord section MIL, Enclosure 8, (CASP W4276), 4 samples. Marine deposits of middle to Late Selandian age, with common *Areoligera* spp. and *Palaeoperidinium pyrophorum* species. Preservation poor.

14) Rybjerg Fjord North section, 2 samples. Marine deposits of middle to Late Selandian age, with few *Areoligera* spp. and *Palaeoperidinium pyrophorum* and reworked Cretaceous palynomorphs. Preservation poor.

15) Sorgenfri section (CASP W4218), 4 samples. Marine deposits of middle to Late Selandian? age, one sample (GEUS 412780) contain very few, poorly preserved dinoflagellate cyst fragments.

16) Jacobsen Fjord section, 2 samples, no palynological age indicators. Organic material thermal overmature.

17) Sødalen/Canyondal section, Enclosure 9 (CASP K7371-3), 5 samples. Marine deposits of middle to Late Selandian age with common *Areoligera* spp. and *Palaeoperidinium pyrophorum* and few reworked Late Cretaceous *Chatangiella* spp.

18) Watkins Fjord section, Enclosure 6 (CASP W4259, W4260, W4291), 2 samples. Marine deposits of latest Danian age.

Palynostratigraphy

Early to Late Cretaceous

The oldest marine deposits are recorded at the Skiferbjerg Basal locality (Enclosure 1). The dinoflagellate cyst assemblage indicates a middle Albian to Late Campanian/early Late Maastrichtian age. A middle Albian age (*Rhombodella paucispina* Zone (IV) Nøhr-Hansen, 1993) is suggested for the basal part of the section (GEUS 455680). The age is indicated by poorly preserved specimens of *Chichaouadinium vestitum*, *Hapsocysta benteae* and *Leptodinium cancellatum*. The middle part of the section (GEUS 455685) is probably also middle Albian, indicated by common *Oligosphaeridium complex* together with a few specimens of *Apteodinium* cf. *grande*, *Hapsocysta benteae*, *Litosphaeridium arundum*, *Oligosphaeridiuim* sp. 1 Nøhr-Hansen 1993 and *Pseudoceratium polymorphum*. Apart from one questionable specimen of *Circulodiniun* sp. 1 Nøhr-Hansen 1993, has no Late Albian marker species been recorded. The uppermost sample from the Skiferbjerg Basal section (GEUS 455687) only contain a few fragment of poorly preserved dinoflagellate cysts, one possible specimen of *Laciniadinium arcticum* suggests an age not younger than early Late Maastrichtian, and a possible *Phelodinium kozlowski/tricuspis* specimen suggests an age not older than Late Campanian.

Ten samples of unknown exact stratigraphic position where collected from the Pyramiden area (Enclosure 2) by E. Hoch. The marine palynomorphs from the samples indicated ages from Cenomanian to Santonian.

Two samples (GEUS 255096 & 255101) contain Litosphaeridium siphoniphorum and common Ovoidinium sp. 1 and represent the Ovoidinium sp. 1 Subzone (V3) of Nøhr-Hansen 1993, which Kelly et al. (1999 a & b) modified and correlated to latest Early to mid Middle Cenomanian.

Two samples (GEUS 255090 & 255099) contain *Stephodinium coronatum*, which according to Costa & Davey (1992) has its last occurrence in the latest Turonian, suggesting a Late Cenomanian to Late Turonian age for the two samples due to they don't contain the lower Cenomanian marker species mentioned above. One sample (GEUS 255100) contains common *Cyclonephelium membraniphorum*. The species has its last common occurrence in the latest Turonian onshore UK according to Pearce et al. (2003).

Five samples (GEUS 255088, 255089, 255091, 255102 & 255103) all contain common *Heterospharidium difficile* which according to Costa & Davey (1992) range from the base of Turonian to the latest Santonian. However since Turonian marker species are absent, the samples are suggested to be of Coniacian or early Santonian ages.

Early to Late Maastrichtian

The 160 m thick succession from the Sequoia Nunatak locality (Enclosure 3) yields ammonite fragment in the lower part. The palynomorph assemblage from the lower part is dominated by late Cretaceous, early Late Maastrichtian marker species (e.g. *Alterbidinium acutulum, Cerodinium diebelii, Cerodinium pannuceum, Diphyes colligerum, Hystrichostro-*

gylon coninckii, Isabelidinium cooksoniae, Laciniadinium arcticum, Triblastula utiensis together with a few pollen specimens, e.g. *Aquillapollenites* spp. and *Wodehouseia spinata*). Reworked material is represented by specimens of Albian–Cenomanian age (*Rhombodella paucispinosa* & *Chlamydophorella nyei*) and of Campanian age (*Isabelidinium microamum*).
Discussion: According to Nichols & Sweet (1993) *Wodehouseia spinata* has its first occurrence in the lower part of the Late Maastrichtian. Schøiler & Wilson (1993) recorded the range of *Triblastula utinensis* from their middle Early to early Late Maastrichtian *Triblastula utinensis* Range Zone. May (1980), Brinkhuis & Zachariasse (1988) and Kirsch (1991) recorded the first occurrence of *Diphyes colligerum* in the Late Maastrichtian. Aurisano (1989) reported the first occurrence of *Cerodinium pannuceum* from the Early Maastrichtian in U.S.A. Schøiler & Wilson (1993) recorded the last occurrence of *Alterbidinium acutulum* from their late Early Maastrichtian *Alterbidinium acutulum* Interval Subzone. However later Schøiler *et al.* (1997) recorded a few *Alterbidinium acutulum* together with *Isabelidinium cooksoniae* from their early Late Maastrichtian *Isabelidinium cooksoniae* Interval Zone from the Maastrichtian type section in the Netherlands.
The presence of a few *Trithyrodinium evittii* specimens in the Sequoia Nunatak section could indicate a Danian age, however the species occur in the latest Cretaceous in lower latitudes (Nøhr-Hansen & Dam, 1999).
The presence of the species discussed above and the absence of latest Maastrichtian markers (e.g. *Palynodinium grallator*) suggest an early Late Maastrichtian age for the lower part of the Sequoia Nunatak section. The lowermost sample (GEUS 406765) may be correlated to the upper part of the *Triblastula utinensis* Range Zone, earliest Late Maastrichtian (Schøiler & Wilson, 1993). Whereas the three middle samples (GEUS 406767, 406769 & 406772) may be correlated to the middle part of the Late Maastrichtian *Isabelidinium cooksoniae* Interval Zone (Schøiler & Wilson, 1993). The uppermost sample from the Sequoia Nunatak locality (GEUS 406773) yields very few and very thermally mature dinoflagellate cysts upon which dating is questionable.

The lower part of the Sequoia West section (GEUS samples 406737, 406738 & 406747; Enclosure 4) has been dated as late Early Maastrichtian probably the *Alterbidinium acutulum* Interval Subzone of Schøiler & Wilson (1993). The dating is based on the absence of the Late Maastrichtian pollen marker *Wodehouseia spinata* and the absence of *Odontochitina* species, which in northern latitudes have their last occurrence in the earliest Maastrichtian according to Williams *et al.* (2004). The presence of *Aquillapollenites* spp. indicates a Campanian to Maastrichtian age and the presence of *Cerodinium diebelii* indicates a post middle Campanian age.
The upper part of the section contains almost the same palynoassemblage as the Sequoia Nunatak section. *Alterbidinium acutulum, Cerodinium diebelii, C. pannuceum, Isabelidinium* spp. *Laciniadinium arcticum, Aquillapollenites* spp. and *Wodehouseia spinata* occur through most of the upper part. *Triblastula utiensis* has been recorded from the middle part (GEUS samples 406748 & 406750). *Allisocysta circumtabulata Cerodinium pannuceum,* and *Diphyes colligerum* has been recorded from the upper part (GEUS samples 406751 to 406753). Reworked material is represented by specimens of Albian–Cenomanian age (*Chlamydophorella nyei*) and Santonian age (*Raphidodinium fucatum* and *Surculodinium longifurcatum*).

Discussion: *Allisocysta circumtabulata* first occur in the lowermost upper Maastrichtian in the Maastrichtian type section in the Netherlands (Schøiler *et al.* 1997). Marheineche (1992) recorded the first occurrence of *Allisocysta circumtabulata* from the uppermost lower Maastrichtian in Germany.
The presence of the species discussed above and the absence of markers of latest Maastrichtian age (e.g. *Palynodinium grallator*) also date the upper part of the Sequoia West section as early Late Maastrichtian. The samples (GEUS 406748 & 406750) may be correlated to the upper part of the *Triblastula utinensis* Range Zone, earliest Late Maastrichtian (Schøiler & Wilson, 1993). Whereas the samples (GEUS 406751–406753) may be correlated to the middle part of the Late Maastrichtian *Isabelidinium cooksoniae* Interval Zone (Schøiler & Wilson, 1993).

The 250m thick succession from the Skiferbjerg 2003 locality (Enclosure 5) yields ammonite fragment throughout and an echinoderm specimen from the base. Three of the studied samples (GEUS 455641, 1260 m; 455646, 1280 m and 455649 1290 m) also contain ammonites. The preservation of palynomorphs is poor to very poor, especially in the upper part.
The presence of *Cerodinium diebelii,* a few *Odontochitina operculata* and consistent *Alterbidinium acutulum* in the lowermost part (1135–1215 m) suggests an age not older than Early Maastrichtian probably the correlating with the *Alterbidinium acutulum* Interval Subzone of Schøiler & Wilson (1993).
The next sample at 1225 m is characterised by abundant *Spiniferites* spp. and by the incoming of *Cerodinium pannuceum, Cerodinium speciosum, Diphyes colligerum, Hystrichosphaeropsis quasicribrata, Hystrichostrogylon coninckii* and a questionable *Triblastula utiensis* specimen, suggesting a Late Maastrichtian age. However the absence of Wodehouseia *spp.* may indicate that the sample is of latest Early Maastrichtian age. The sample may correlate with the latest Early Maastrichtian part of the *Triblastula utinensis* Range Zone (Schøiler & Wilson, 1993). Like in the Sequoia Nunatak section is reworked material of Albian–Cenomanian age present.
The sample at 1235 m is characterised by the first common occurrence of *Areoligera* spp. Firth (1993) recognised high abundance of *Areoligera* cysts from the Lower to Upper Maastrichtian boundary in Maryland, U.S.A. He suggested that the abundance might reflect a level of maximum transgression in the middle of the Maastrichtian. Schøiler & Wilson (1993) also recorded common *Areoligera* sp. from the Early Maastrichtian in the North Sea.
The upper part of the section (1245–1315 m) is characterised by abundant *Isabelidinium* spp. and *Spiniferites* spp., common *Cerodinium diebelii,* and *Trithyrodinium evitttii* together with *Isabelidinium cooksoniae, Cerodinium striatum* and the pollen *Aquilapollenites* spp. and *Wodehouseia spinata*. The presence of ammonites at 1280 m and 1290 m and the presence of *Wodehouseia spinata* at 1265–1295 m, strongly suggest a Late Maastrichtian age. The presence of a few poor *Cerodinium striatum* specimens and the increase in numbers of *Trithyrodinium evittii* was first interpreted to indicate an early Danian, earliest Palaeocene age. However, Aurisano (1989) has reported *Cerodinium striatum* from Early to middle Maastrichtian in U.S.A. and *Trithyrodinium evittii* do occur in the latest Cretaceous in lower latitudes (Nøhr-Hansen & Dam, 1999).
Like in the two Sequoia sections, described above, the marker species for the upper part of the Skiferbjerg 2003 section, suggests an early Late Maastrichtian age, correlating with the *Isabelidinium cooksoniae* Interval Zone of Schøiler & Wilson (1993).

The uppermost studied sample (1340 m) yields few poorly preserved palynomorphs, upon which dating is questionable.
The first occurrence of *Triblastula utinensis*, *Wodehouseia spinata* together with the first common occurrence of *Areoligera* spp. at a rather narrow interval is useful for correlation of the studied sections, and may be important in tracing the Lower/Upper Maastrichtian boundary outside the studied area. The co-occurrence with reworked material of Albian–Cenomanian age may be of local importance.

Paleocene (Danian–?Selandian)
Paleocene marine deposits have been documented in two samples (GEUS 413269 & 413271) from the shale succession at Watkins Fjord 2003 (Enclosure 6). The deposits rest unconformably on the middle Cretaceous Watkins Fjord Formation and indicate the presence of a hiatus spanning the Late Cretaceous and the Early Danian (earliest Paleocene).
The lower sample (GEUS 413269) dates the lower deposits latest Danian (dinoflagellate cyst *Spiniferites magnificus* Zone DP2 of Mudge and Bujak, 1996) based on the presence of *Cerodinium striatum, Palaeocystodinium bulliforme, Spiniferites magnificus.* The top of the latest Danian *Spiniferites magnificus* Zone was defined by the last occurrence of the *Spiniferites magnificus* in the lower part of the Maureen Formation by Mudge and Bujak (1996), who mentioned that *Spiniferites magnificus* not has been recorded outside the North Sea. Mangerud *et al.* (1999) defined the top of their Early Palaeocene (Danian) Grane A Biozone by the last occurrence of the *Spiniferites magnificus* and *Alisocysta reticulata* in the middle of the Våle Formation offshore Norway.
The upper sample (GEUS 413271) are dated a possible earliest Selandian age (lower part of dinoflagellate cyst *Thalassiphora* cf. *delicata* Subzone DP3a of Mudge and Bujak, 1996) based on the presence of *Cerodinium striatum, Palaeocystodinium bulliforme*, common *Areoligera* spp. and common *Palaeoperidinium pyrophorum*. Mangerud *et al.* (1999) divided their early Late Palaeocene Grane B Biozone into four subzones, the top of the oldest was defined by the by the last occurrence of common *Palaeocystodinium bulliforme* in the upper half of the Våle Formation offshore Norway. The subzone correlate with the lower part of the *Thalassiphora* cf. *delicata* Subzone DP3a of Mudge and Bujak (1996). Mudge and Bujak (1996) mentioned in their description of subzone DP3a, that *Palaeoperidinium pyrophorum* dominate in the subzone.
This last common occurrence of *Palaeocystodinium bulliforme* is according to Mangerud *et al.* (1999) a useful regional North Sea event. *Palaeocystodinium bulliforme* is quite common onshore Nuussuaq, West Greenland where it range from the mid to Late Danian *Palaeocystodinium bulliforme* Zone and into the Late Danian/Early Selandian *Alisocysta margarita* Zone (Nøhr-Hansen *et al.*, 2002). *Palaeocystodinium bulliforme* has also recently been recorded onshore Kap Brewster, East Greenland where it co-occur together with *Thalassiphora delicata* and *Alisocysta margarita* suggesting deposits of Late Danian/Early Selandian age (Nøhr-Hansen and Piasecki, 2002). Few, possible reworked specimen of upper Cretaceous and lowermost Danian ages are also recorded from the Watkins Fjord section.
The latest Danian to earliest Selandian ages suggested here for the Watkins Fjord section correlate with the top of sequence T10 or lowermost T20 of Ebdon *et al*. (1995), according to Mudge and Bujak (2001).

Paleocene, Selandian

The upper prebasaltic successions at Fairytale Valley (Enclosure 7), Willow Pass, Rybjerg Fjord MIL (Enclosure 8), Rybjerg Fjord North section and Sødalen/Canyondal (Enclosure 9) all contain very poor preserved thermally altered low diverse and low density palynoassemblages. However, the consistent occurrence of *Palaeoperidinium pyrophorum* in all five sections indicate an age no younger than latest Selandian (the *Palaeoperidinium pyrophorum* Zone DP4 of Mudge and Bujak 1996; 2001). *Areoligera* spp. and *Palaeoperidinium pyrophorum* are common in the lower successions at Fairytale Valley (GEUS sample 413108, 94m) and present in the upper succession, where a distinct *Spinidinium* sp. and a distinct *Suttilisphaera* sp. have their first occurrence (GEUS sample 413144, 141m). *Palaeoperidinium pyrophorum* and *Areoligera* spp. are also present to common in the Sødalen/Canyondal section.

The dating of the five sections suggest correlating with NP5 and with the top of sequence T20 or lower part T30 of Ebdon *et al*. (1995).

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Section : Skiferbjerg Basal

Operator :

Code : SKIFERBJERGBASAL

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Interval : 100m - 60m

Scale : 1:500

Chart date : 06 September 2005

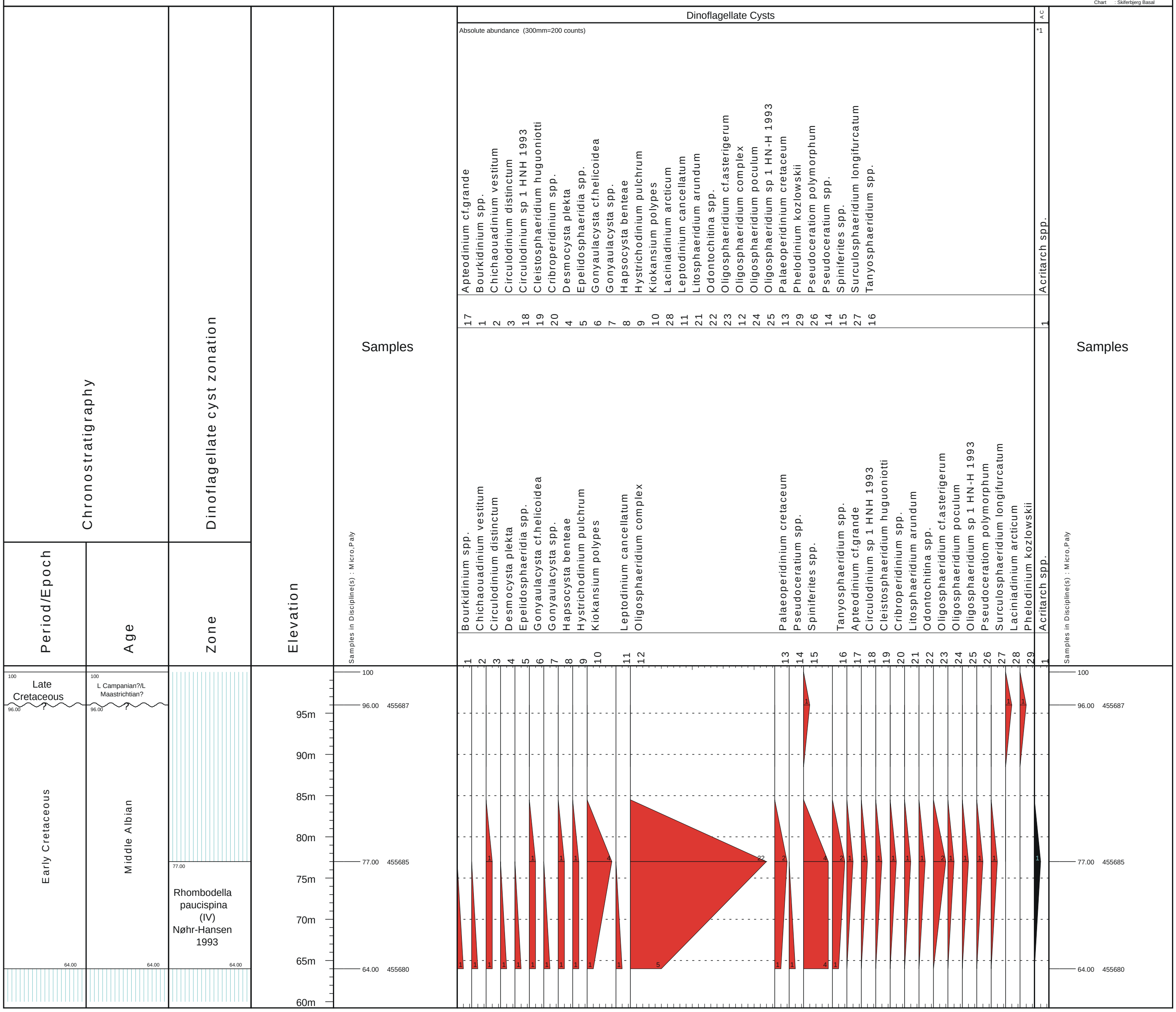
Skiferbjerg Basal

GEUS

Copenhagen

Project : EAST GREENLAND

Chart : Skiferbjerg Basal



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Operator :

Code : PYRAMIDEN

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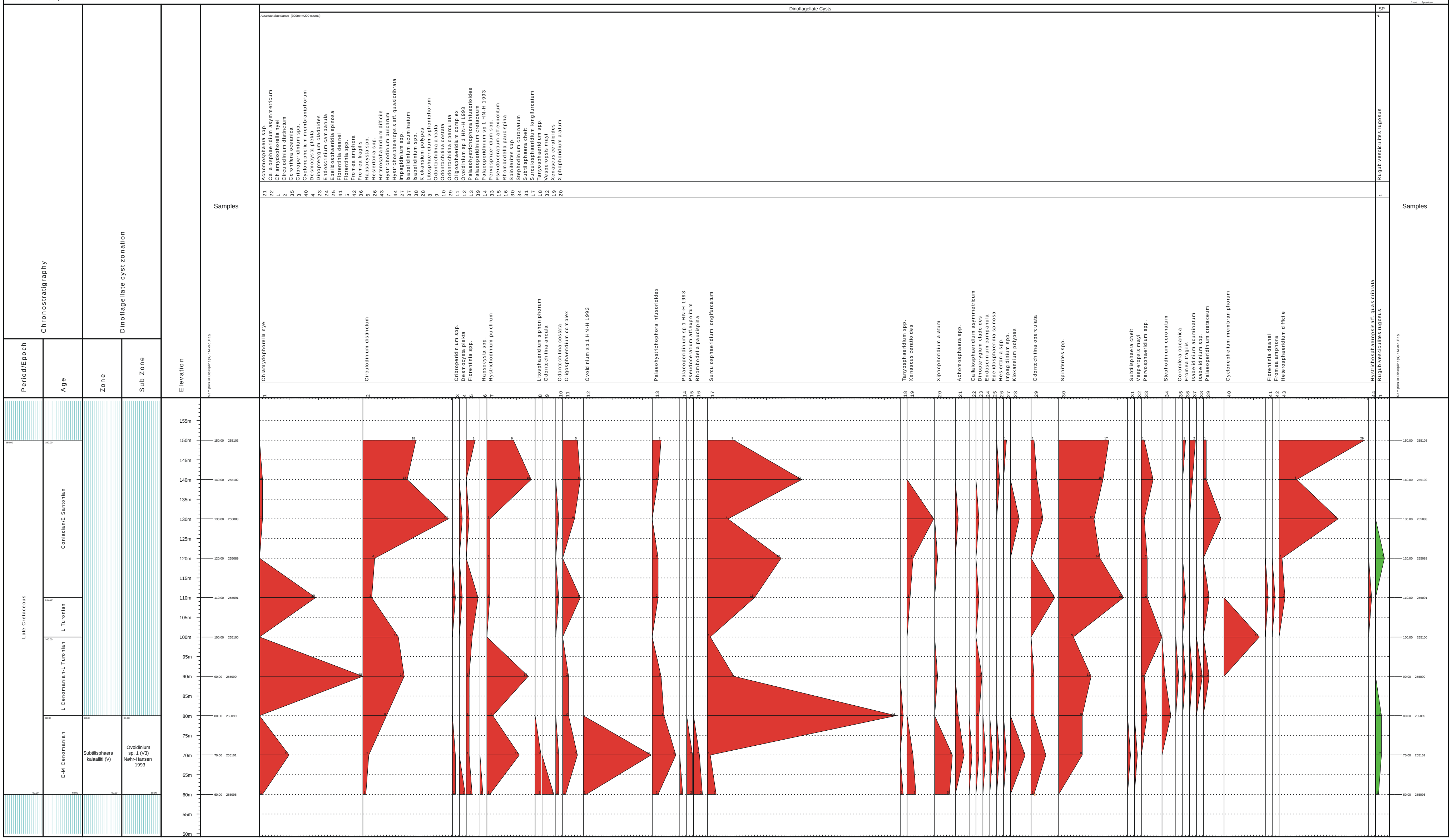
Interval : 160m - 50m

Scale : 1:500

Chart date : 06 September 2005

Pyramiden

GEUS
Copenhagen



Sequoia Nunatak

Section : Sequoia Nunatak

Operator :
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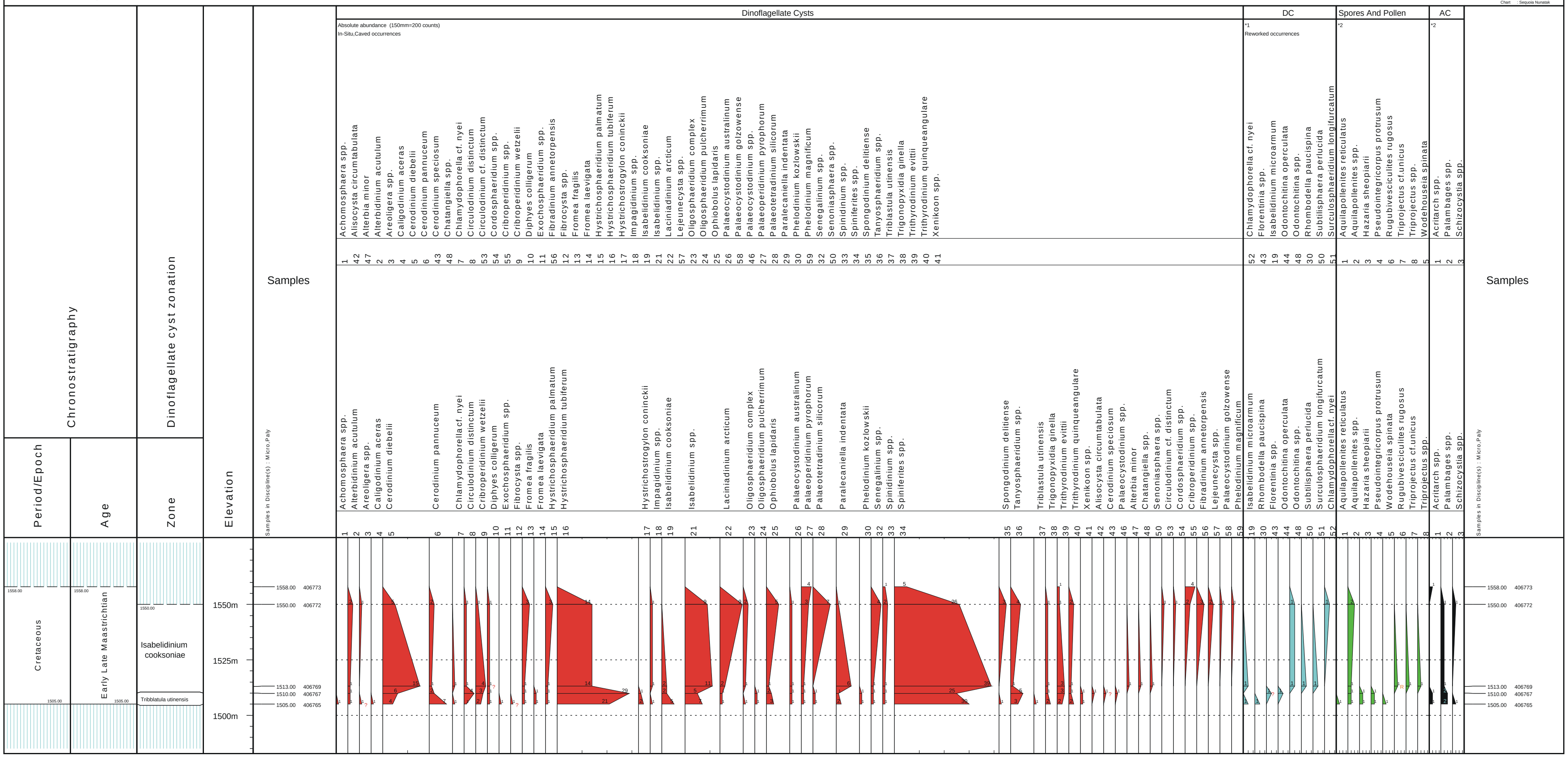
Chart date : 06 September 2005

GEUS
Copenhagen

Project : EAST GREENLAND
Chart : Sequoia Nunatak



Section : Sequoia West

Operator :

Code : SEQUOIAWEST

Lat/Long : 0° 0' 0.00"N 0° 0' 0.00"E

Interval : 1526m - 1408m

Scale : 1:1000

Chart date : 06 September 2005

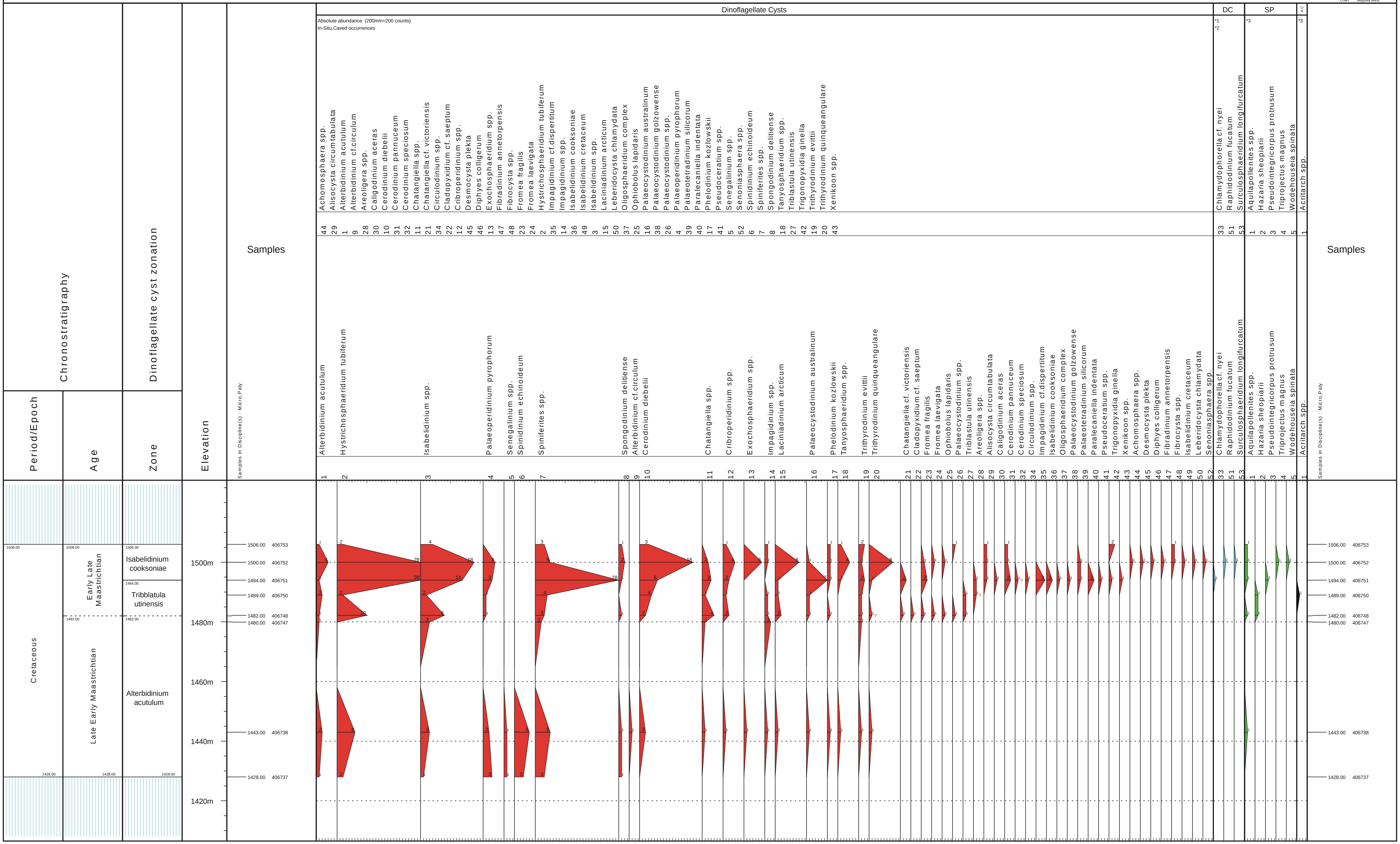
Sequoia West

GEUS

Copenhagen

Project : EAST GREENLAND

Chart : Sequoia West



Section : Skiferbjerg 2003

Operator :

Code : SKIFERBJERG2003

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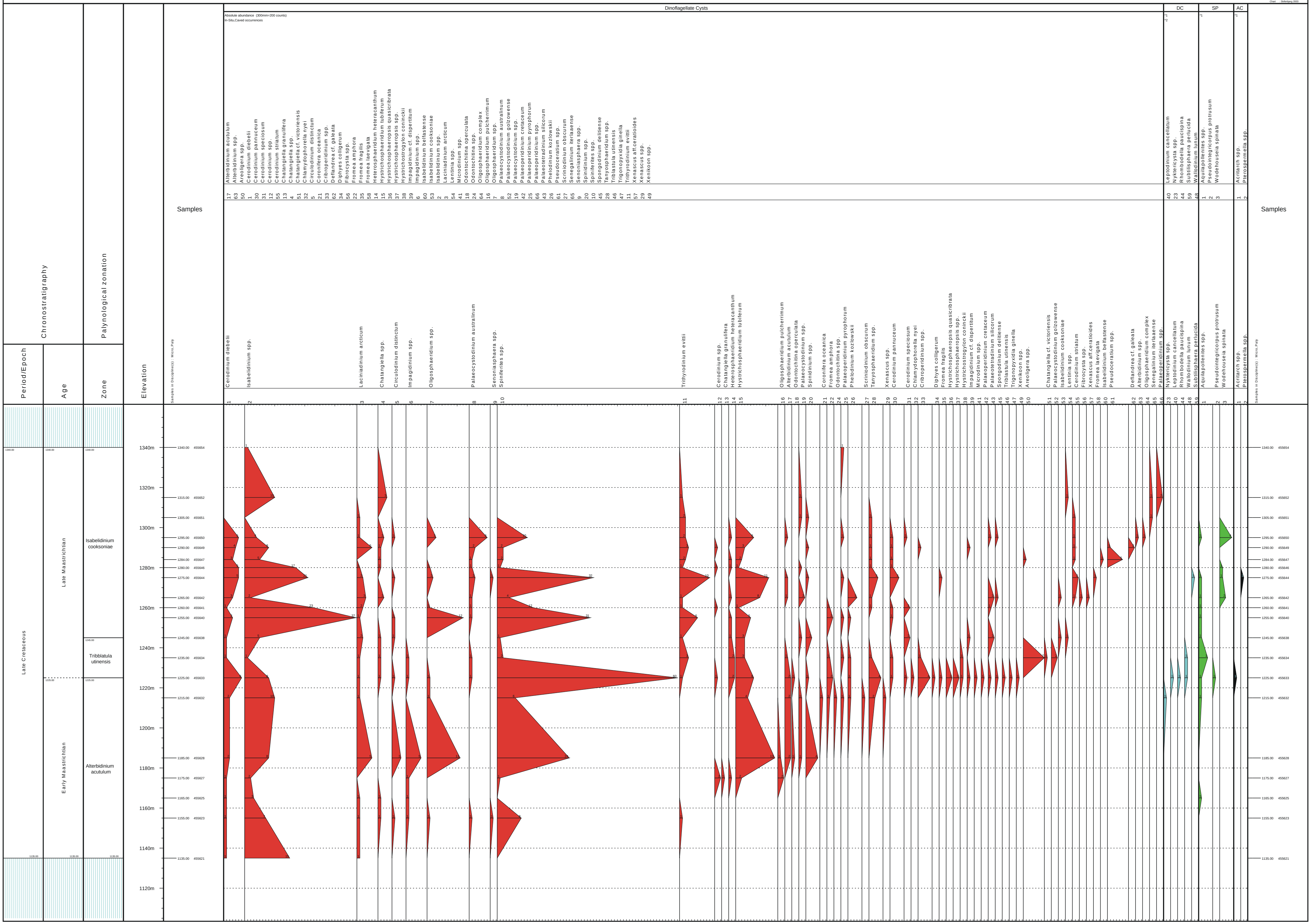
Interval : 1360m - 1105m

Scale : 1:1000

Chart date : 06 September 2005

Skiferbjerg 2003

GEUS
Copenhagen



Section : Watkins Fjord 2003

Operator :

Code : WATKINSFJORD2003

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Interval : 200m - 170m

Scale : 1:500

Chart date : 06 September 2005

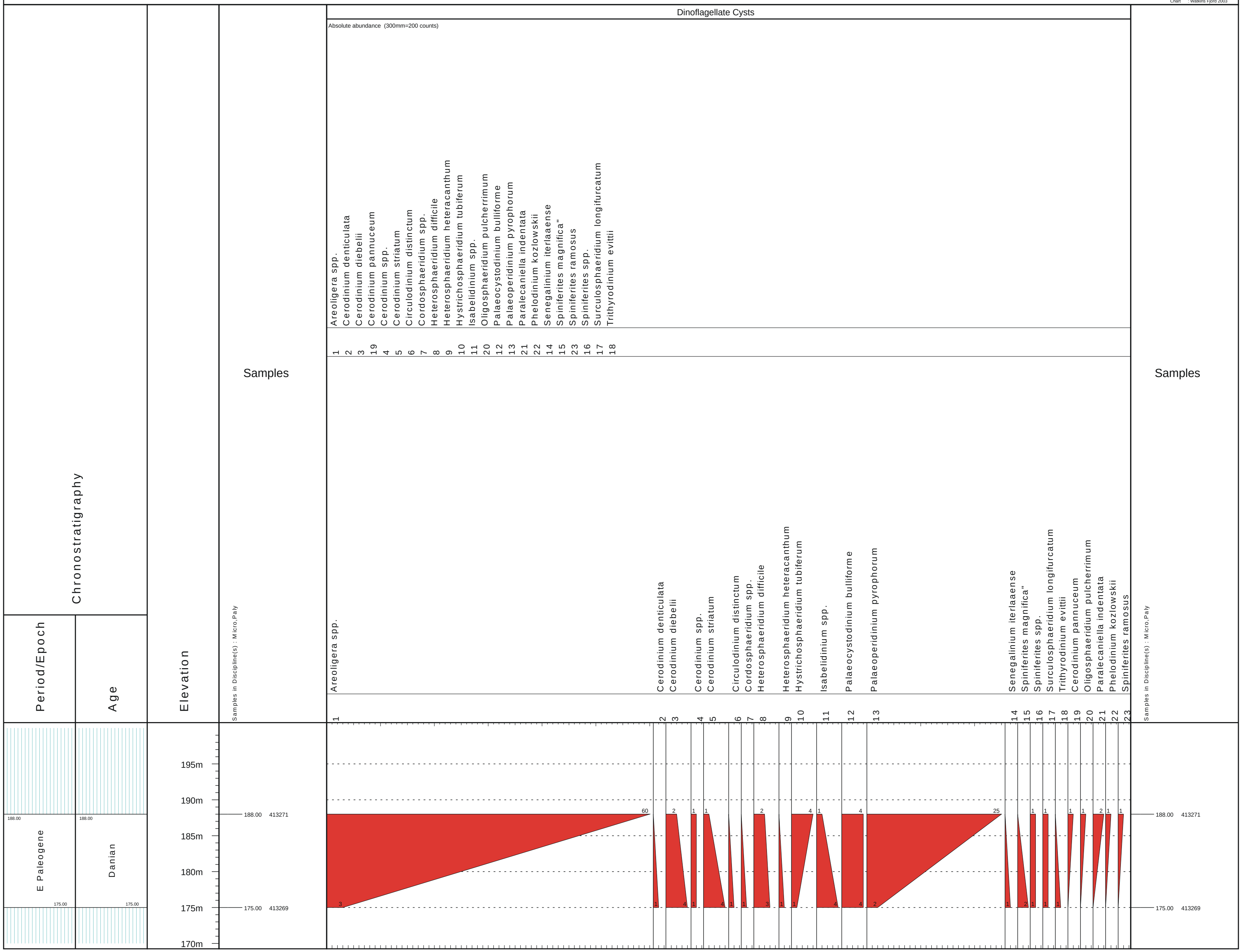
Watkins Fjord 2003

GEUS

Copenhagen

Project : EAST GREENLAND

Chart : Watkins Fjord 2003



Section : Fairytale Valley

Operator :

Code : FAIRYTALEVALLEY

Lat/Long : 0° 0' 0.00"N 0° 0' 0.00"E

Interval : 150m - 90m

Scale : 1:500

Chart date : 06 September 2005

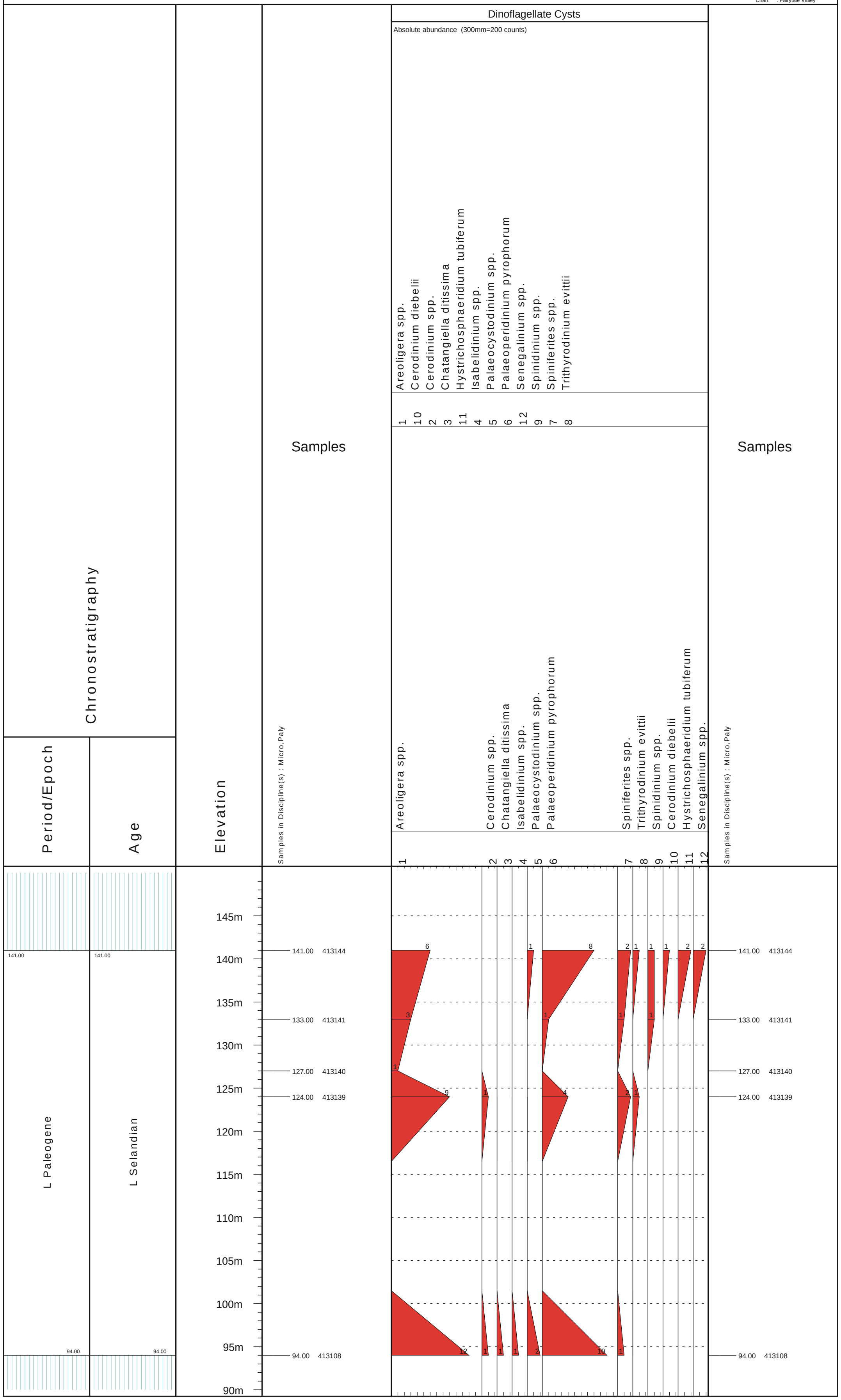
Fairytale Valley

GEUS

Copenhagen

Project : EAST GREENLAND

Chart : Fairytale Valley



Section : Willow Pass Rybjerg Fjord

GEUS
Copenhagen

Operator :
Code : WILLOWPASSRYBJERGFJORD
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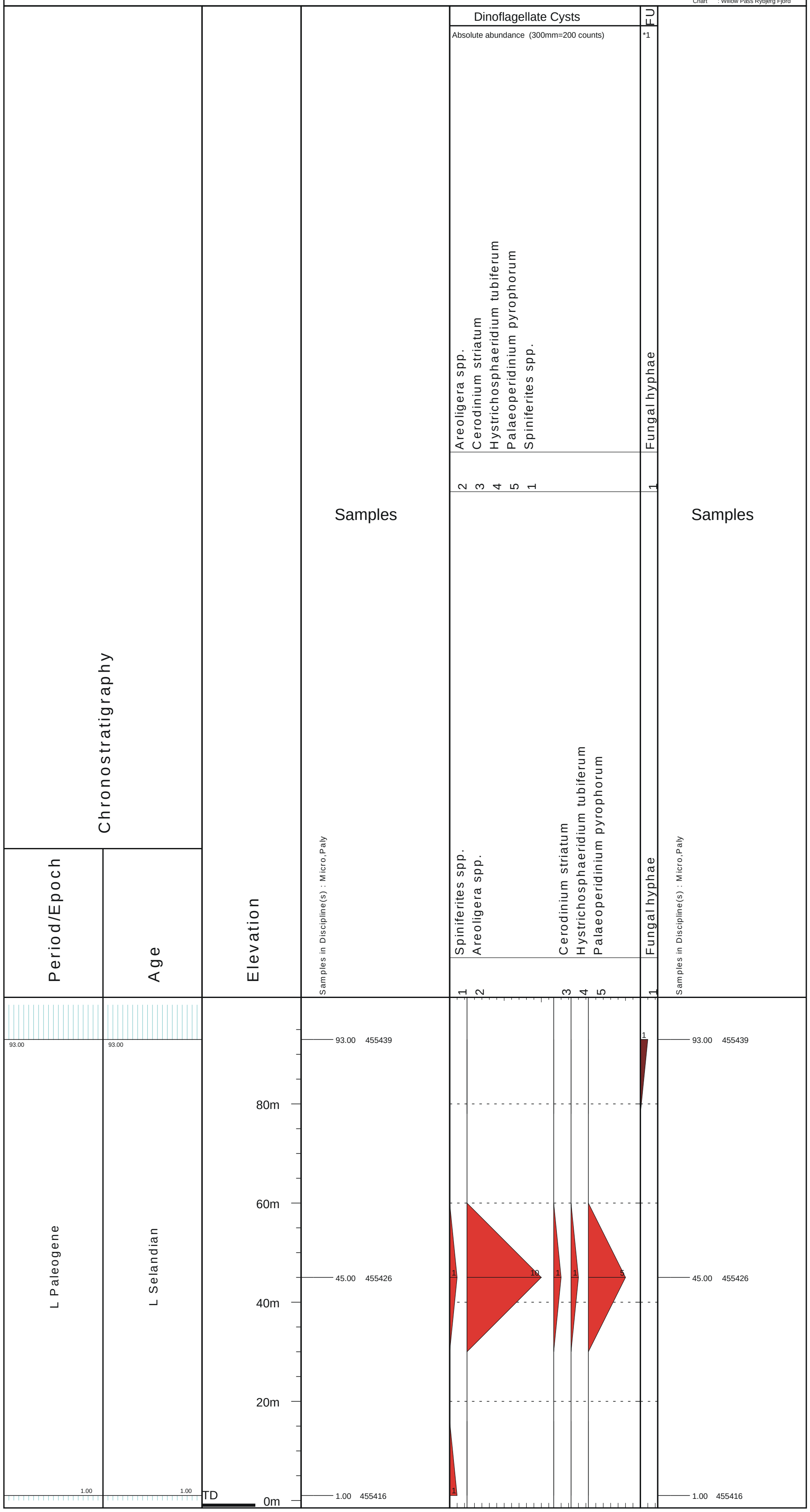
Interval : 100m - 0m
Scale : 1:1000
Chart date : 06 September 2005

Project : EAST GREENLAND
Chart : Willow Pass Rybjerg Fjord



Section : Sødalen

GEUS
Copenhagen

Operator :
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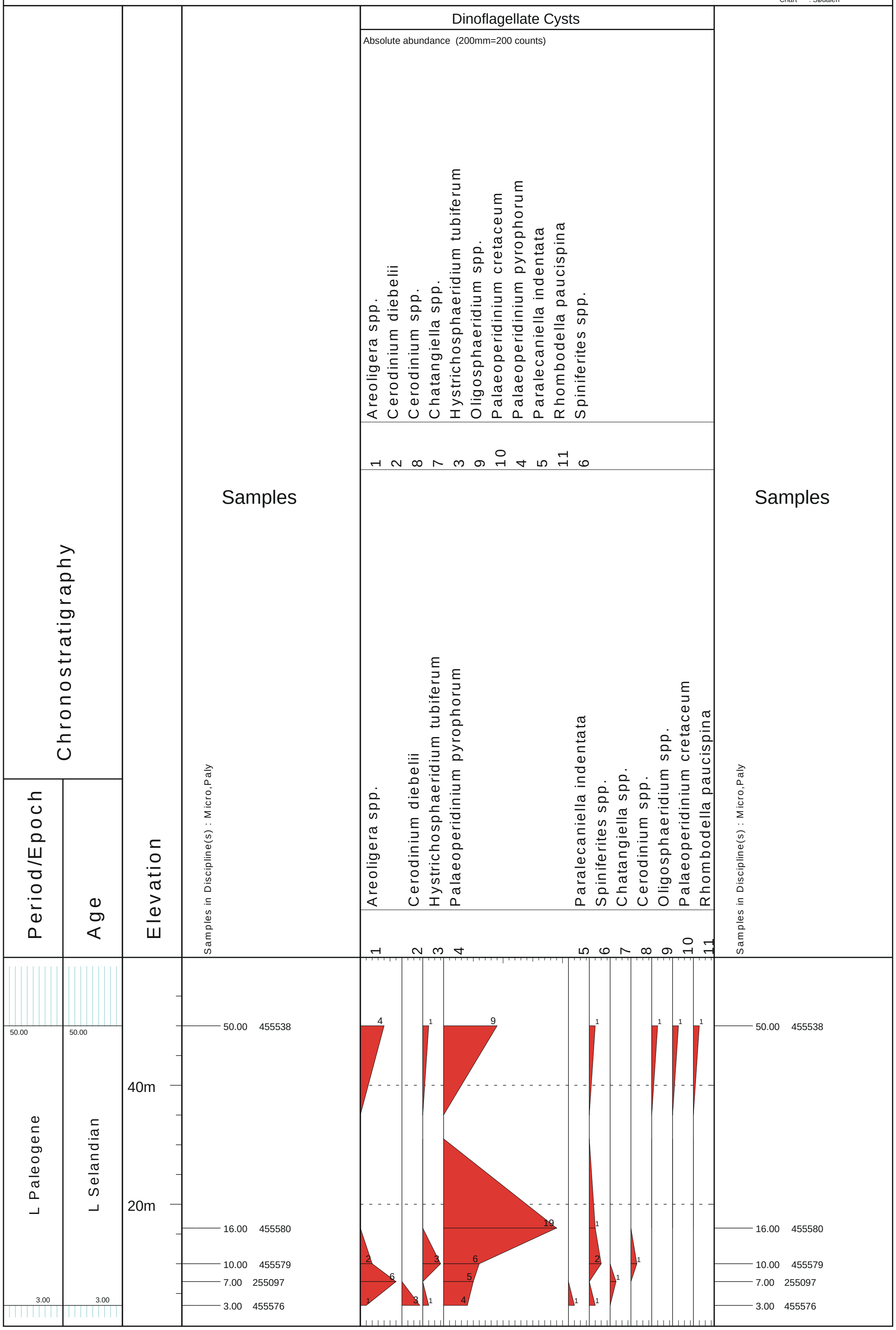
Interval : 60m - 1m
Scale : 1:1000
Chart date : 06 September 2005

Project : EAST GREENLAND
Chart : Sødalen



Appendix 2

Palynology of the “Sequoia Nunatak” section (Kulhøje area)

David J. McIntyre

Introduction

Pollen and spores from seventeen samples from the “Sequoia Nunatak” section at Kulhøje, East Greenland were recorded. Where possible 200 specimens were counted and species identified were recorded. The results are presented on the Excel spreadsheet attached to this report.

Pollen and spores from the section

Pollen and other plant material in the samples at the base of the section are brown and significantly corroded and pyrite pitting is commonly present. Although counts were made for all samples except the basal sample the counts for the samples up to 84-135, because of the poor material, and difficulty of identification of grains, should be regarded as no more than approximate. In the section above 84-135 preservation is considerably better and identification of pollen and spores is more certain.

The basal sample, 84-266, has almost no identifiable palynomorphs, and the species of pollen recorded higher in the section were not seen in this sample. A specimen of the acritarch *Fromea chytra*, recorded in the basal sample, indicates that the sample is likely Upper Cretaceous, as noted on the section log.

Samples in the rest of the section have abundant bisaccate pollen, mainly of *Picea* and *Pinus* type, but also some probable *Abies* type. Pollen of *Sequoia* type and probable *Metasequoia* and possible *Taxodium* are abundant to dominant through the section. Pollen of *Momipites* is common in many samples; most of this pollen cannot be assigned to species but *M. anellus* and *M. ventifluminis* were identified in a few samples. These are widespread in North America in the Paleocene and some occur rarely in the early Eocene. Many were described by Nichols and Ott (1978) and Pocknall and Nichols (1996) also refer to them. I noted some species in my Somerset Island paper (McIntyre, 1989) including *M. anellus* and *M. ventifluminis*. They are also common in the Mackenzie Delta.

Caryapollenites occurs rarely in only a few samples. The few *Caryapollenites* pollen are types described from the Paleocene and differ from grains in the Eocene which are very much like modern *Carya*. Nichols & Ott (1978) have some discussion of this.

Tricolporopollenites mullensis is present in most samples, and *Paraalnipollenites alterniporus* occurs rarely. Pollen of *Alnus* is present in many samples and *Ulmus* type (*Ulmipollenites tricostatus* and *U. undulosus*) occurs in most samples. Other pollen present in a few samples include *Cercidiphyllum* sp., *Platanus* sp., *Simplicepollis rallus.* The pollen assemblages in the section indicate a Late Paleocene age. The absence of *Tilia* is another indication of Paleocene. There are some simple pollen types in the Paleocene and the advanced types similar to modern *Tilia* are absent. These do not become common until the Eocene and are abundant in some Kap Dalton samples.

The presence of the fungal type *Pesavis parva* also indicates a Paleocene age. *Pesavis parva* occurs in the Paleocene and rarely in the late Maastrichtian. It is a form, which is smaller and more simple, than the Eocene *Pesavis tagluensis* (Kalgutkar & Sweet 1988). Some other fungal species were also noted but do not provide significant information about age other than Paleocene – Eocene.

The rare, very poor specimens referred to *Diervilla* are similar to specimens recorded in Alaska and northern Canada from the Paleocene and differ from later Eocene types. They differ from the *Diervilla* I recorded in the Eocene of the Fossil Forest. It is similar to what Wiggins (Wiggins pers. com.) called *Protodiervilla* from the Paleocene of Alaska and I recall seeing it rarely in the Mackenzie Delta.

The presence of a single *Aquilapollenites spinulosus* could also indicate a Paleocene age. *Aquilapollenites spinulosus* occurs in the Paleocene but is not generally common (Pocknall and Nichols, 1996). This is one of a few *Aquilapollenites*, which are Early Tertiary species. The pollen types recorded in the Sequoia Nunatak section clearly indicate a Late Paleocene age, except for the basal sample. The freshwater colonial alga *Pediastrum* occurs in most samples. There is no evidence of any marine algal types (including dinoflagellates) in the Paleocene part of the section.

Discussion

I have no doubt that this section is Paleocene. Lots of "*Inaperturopollenites hiatus*". This name is used mainly in the Cretaceous for spherical split pollen with no other useful features. These pollens are also called TCT in the Tertiary; mainly they are Taxodiaceae pollen with some possible Cupressaceae and perhaps some Taxaceae. What we see in the Tertiary, especially the lower part, and often in great numbers, are pollens, which I believe, are mainly Taxodiaceae. The larger specimens can be referred to Sequoia and the smaller grains, and generally the most abundant, are mostly *Metasequoia* and some possible *Taxodium*. The *Metasequoia* determination is confirmed by abundant leaves, twigs and cones in some places. This is very evident in the fossil forest on Axel Heiberg Island. All these types had disappeared from the Arctic by the mid-Tertiary as the climate became much colder.

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PALYNOLOGY, "SEQUOIA NUNATAK" SECTION - KULHOJE

Sample	Monolete spores	Trilete spores	Sphagnum	Osmunda	Pediastrum	Pesavis parva	Picea and Pinus	Sequoiapollenites	Metasequoia/Taxodium	Sciadopitys	Cycadopites	Triporate (indeterminate)	Momipites sp.	Momipites anellus	Momipites ventifluminis	Caryapollenites	Paraalnipollenites alterniporu	Triporopollenites mullensis	Ulmipollenites undulosus	Ulmipollenites tricostatus	Alnus	Tricolpate spp.	Betula	Acer	Cercidiphyllum	Platanus	Simplicepollis rallus	Liliacidites	Pterocarya	Fraxinoipollenites variabilis	Diervilla	Ericaceae	Aquilapollenites spinulosus
84-276	3	1					48	12	61	4	1	25	20	2		3	4	11				6											
84-147						x	2	5	1			4	1						5														
84-255	6				x	x	24	20	103			12	2					5	2	3		4		1	4	6	5	3					
84-251	7	1			x	x	53	66	33			16	1	1			1	8	3	5	5	7	1		1	8	3	1	1	1			
84-143	3	1			x		37	74	38			14	1		1			8	4	5	1	3	2			4	6		1		1		
84-142	1				x	x	41	90	46			5						2	2	1	2	1	1		1	12							
84-141	4		1	1	x		29	85	51			6						4	2	5	1	6	1		3	7							
84-140	3			1	x		36	92	45			3	1					7				2	1			8	1	1					
84-138	1		1				39	70	74			7	2	1				1		1	1	5			1	2	1	1					
84-137	5				x	x	59	30	32			17	18	2	4			4	15	5	2	6			1		3			2		1	
84-136	3	1			x	x	46	60	18			25	20	15	5	4	1	3		11	1	4			1						1		1
84-135		1	1				27	95	54			10	1					1		1	2	10											
84-186		1		1		x	60	60	48			9	1				1	3			1	6			1	1				1			
84-134	1	1			x	x	116	40	29			4	2				1	1		2	2	6			1	1				2			
84-133	2					x	53	68	40			19	8	2			1	3		2	1	3				1							
84-132							88	66	38			7		1				1				2											
84-266		x		x			x																										

Appendix 3

Correlation chart showing the main sedimentary sections