DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2007/17

Developments in the stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussuaq Basin. Volcanic basins of the North Atlantic

Integration of data and conclusions – Phase III report for the Sindri Group March 2007

Henrik Nøhr-Hansen, Simon R.A. Kelly, Andrew G. Whitman, Michael Larsen & David Jolley

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2007/17

Developments in the stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussuaq Basin. Volcanic basins of the North Atlantic

Integration of data and conclusions – Phase III report for the Sindri Group March 2007

Henrik Nøhr-Hansen (GEUS)
Simon R.A. Kelly & Andrew G. Whitham (CASP)
Michael Larsen (DONG Energy) &
David Jolley (University of Aberdeen)

Released 30.04.2009

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

GEUS

Contents

Preface 4

Introduction 6

Lithostratigraphy and sequences 8

- Unconformity-bounded sequences (EG1–EG6) ... 8
- Correlation chart of the Kangerlussuaq Basin ... 8
- Kangerdlugssuaq Group ... 10
  - Watkins Fjord Formation (new unit) ... 10
  - Sorgenfri Formation (revised unit) ... 12
  - Christian IV Formation (new unit) ... 14
  - Sediment Bjerge Formation (new unit) ... 16
- Blosseville Group ... 18
  - Vandfaldsdalen Formation (redefined unit) ... 18
- Sedimentological summary description and interpretation ... 20

Biostratigraphy 22

- Macrobiota ... 22
- Palynological material and preservation ... 22
- Developments in Cretaceous biostratigraphy ... 22
  - Barremian–Maastrichtian macropalaeontology ... 22
  - Albian–Santonian palynology ... 26
- Maastrichtian correlations ... 28
  - Early Maastrichtian ... 28
  - Late Maastrichtian ... 30
  - Maastrichtian ammonite faunas in Greenland. ... 30
  - Maastrichtian palynology ... 33
- Developments in Palaeogene palynostratigraphy ... 36
  - Rybjerg Fjord and 'Sequoia Nunatak' sections (new palynological data) ... 40
- Discussion of the palynological dating of the Vandfaldsdalen Formation ... 42

Basin evolution and tectonic phases 44

Correlation of the Cretaceous–Palaeogene successions West of Shetland, the Faroes and SE Greenland 46

Palaeogeographic maps of the Faroe-Shetland region 48

Phytogeographic evidence for sediment transfer pathways in the Palaeogene 50

Acknowledgements 52

References 52

References 53

Sindri bibliography 57

Preface

This report forms the concluding part of the Kangerlussuaq phase III Sindri Research Project. It summarises the three previous reports:

"Stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussuaq Basin – Volcanic basin of the North Atlantic"

"Phytogeography, provenance and sediment transfer pathways in the Paleocene strata of the Faroe-Shetland region"

"Biostratigraphy zonation (palynology and macrofossil) for the Upper Cretaceous – Lower Palaeogene based on the sedimentary succession in the Kangerlussuaq, southern East Greenland."

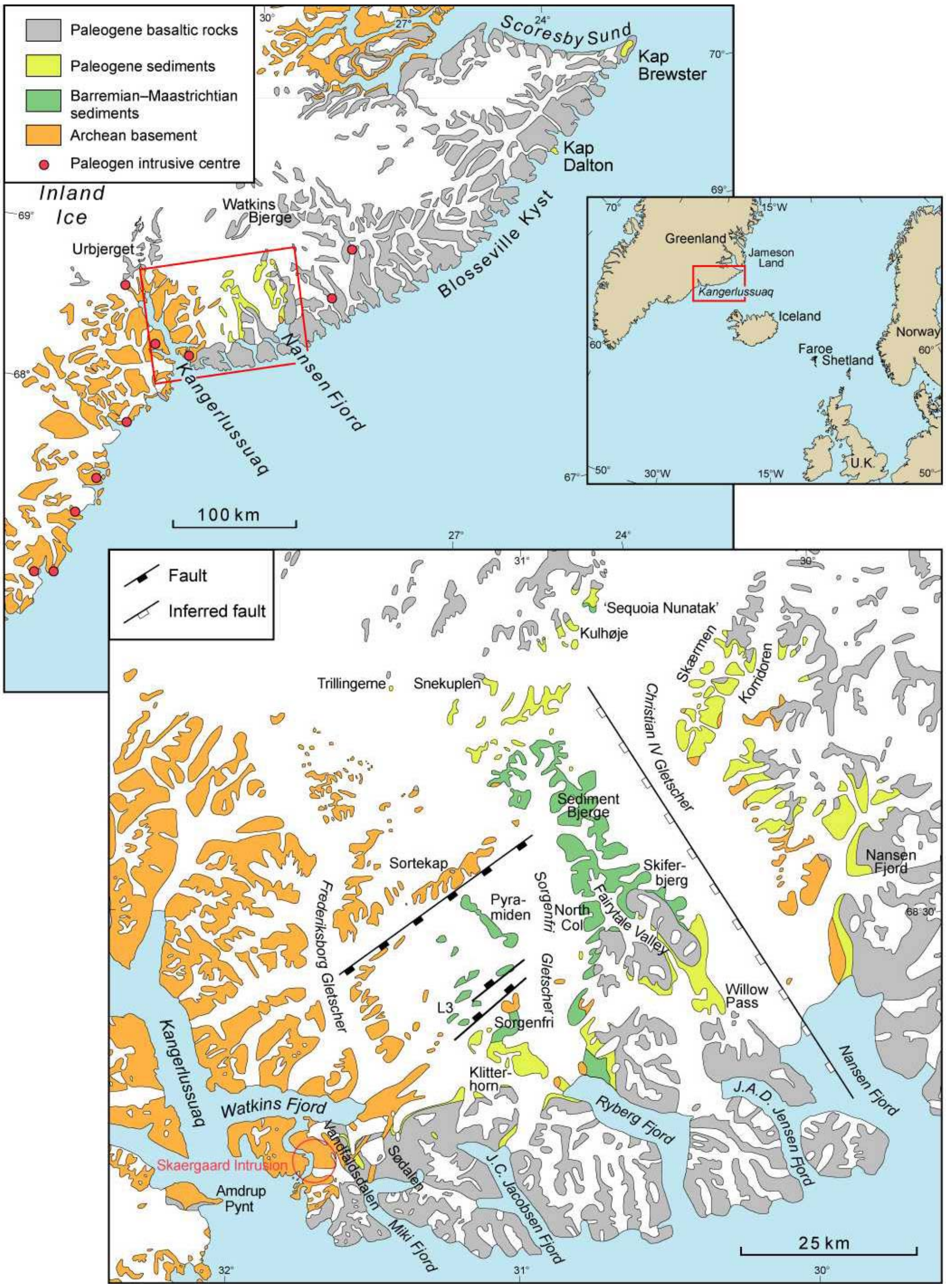
The integration of these studies allows further refinement of the biostratigraphy of the Kangerlussuaq Basin. These new developments affect particularly the biozonal schemes applied in the Maastrichtian and in the Palaeogene parts of the succession.

All figures are enclosed on the CD-ROM as high-resolution PDF or JPG files.

It should be noticed that data from the phase II project (Late Cretaceous sediment provenance and transfer pathways in the Faroe-Shetland region, by Dr. David Jolley (University of Aberdeen) will be reported separately due to delay of dating analyses.

This work has been jointly conducted by the Geological Survey of Denmark and Greenland (GEUS), CASP (formerly Cambridge Arctic Shelf Programme) and University of Aberdeen. The project was funded by the SINDRI programme: "Future Exploration Issues Programme of the Faroese Continental Shelf" (briefly referred to as the SINDRI programme) established by the Faroese Ministry of Petroleum and financed by the partners of the Sindri Group of which the current licensees 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.

Figure 1. *Geological map of the Kangerlusssuaq Basin in southern East Greenland. The pre-basaltic succession consists of Barremian–Paleogene sediments onlapping Archaean crystalline basement. The succession is overlain by 4–6 km of Palaeogene continental flood basalts.*



Paleogene basaltic rocks
Paleogene sediments
Barremian–Maastrichtian sediments
Archean basement
Paleogen intrusive centre
Inland Ice
Scoresby Sund
Kap Brewster
Kap Dalton
Watkins Bjerge
Urbjerget
Blosseville Kyst
Kangerlussuaq
Nansen Fjord
100 km
Greenland
Jameson Land
Kangerlussuaq
Iceland
Faroe
Shetland
Norway
U.K.
Fault
Inferred fault
'Sequoia Nunatak'
Kulhøje
Trillingerne
Snekuplen
Skærmen
Korridoren
Christian IV Gletscher
Sediment Bjerge
Sortekap
Skifer-bjerg
Nansen Fjord
Frederiksborg Gletscher
Pyra-miden
Sorgenfri
North Col
Fairytale Valley
Gletscher
Willow Pass
L3
Sorgenfri
Klitter-horn
Kangerlussuaq
Watkins Fjord
Ryberg Fjord
J.A.D. Jensen Fjord
Nansen Fjord
Skaergaard Intrusion
Amdrup Pynt
Sødalen
J.C. Jacobsen Fjord
Miki Fjord
25 km

Introduction

This is the final report to Sindri concerning the Cretaceous–Palaeogene pre-basaltic sedimentary succession of the Kangerlussuaq Basin in southern East Greenland. It summarises the data presented in the previous reports, but does not entirely replace them. Fuller details of the succession may be found in the appropriate report, but most of which is contained in the principal description by Jolley & Whitham (2004b), Larsen *et al.* (2005a, b) and in the biostratigraphy by Nøhr-Hansen *et al.* (2006). In addition new biostratigraphic data, schemes and discussions are presented. A full list of the Sindri-related reports is contained in a separate bibliography listed after the references.

The most important results from the integration of the stratigraphic studies:

- A revised lithostratigraphy comprising three new formations and six new members is suggested (Fig. 2). The principal sections of the Kangerlussuaq Basin are correlated showing the stratigraphical and spatial relationship between sections (Fig. 3).
- Six unconformity-bounded sequences (EG1–EG6) form a framework for sequence stratigraphic interpretations and is integrated with the interpretation of fauna and provenance shifts (Fig. 2).
- Summary of sedimentological descriptions and interpretation of gross depositional environments for all units is contained in table 1, and correlations chart highlighting the distribution of the formations are illustrated (Figs 4–8).
- The Cretaceous biostratigraphy and macrofaunas were summarised in Nøhr-Hansen *et al.* (2006). A new range chart for the Cretaceous macrofaunas is given showing the distribution of taxa at substage level (Fig. 9). Integrated macropalaeontological and palynological biozonation schemes for the Cretaceous–Palaeogene of the Kangerlussuaq Basin are presented (Fig. 10), and new palynological event and zonation schemes are given for the Cretaceous (Figs 11, 14).
- A new correlation chart for the Maastrichtian of the Kangerlussuaq area with Europe and North America is presented (Fig. 12) together with a palaeogeography map (Fig. 13).
- New palynological event and zonation schemes are given for the Palaeogene (Figs 16, 18). These schemes are updated based on new results from the Vandfaldsdalen Formation obtained from the Rybjerg Fjord section (Fig. 17).
- Brackish-water dinoflagellate cysts from the Kulhøje Member (upper Vandfaldsdalen Formation) suggests an age within the Selandian to latest Thanetian / ?earliest Ypresian range (Fig. 15).
- The onset of volcanism in East Greenland is discussed in detail and two models suggested:
    - A T40 (latest Thanetian / earliest Ypresian) age is suggested based on terrestrial spores and pollen in the Kulhøje Member (Fig. 15), this implies an apparent discrepancy between the absolute ages (geochronology) and the biostratigraphy in East Greenland, but conforms with observations in the Faroes/West Shetland region.
    - A latest Selandian / earliest Thanetian age is suggested based on marine and brackish-water dinoflagellates in the Willow Pass and Kulhøje Members (Fig.15).

- A correlation chart showing the possible correlation of lithostratigraphic units from Kangerlussuaq Basin with units in the Faroe-Shetland Basin illustrate the two models for the onset of volcanism (Fig. 20).
- Four palaeogeographic maps (Albian, Campanian, Late Maastrichtian – Early Paleocene (T10) and Late Paleocene (T30–T40)) showing the evolution of the North Atlantic region and the importance of a western sediment input to the Faroe-Shetland Basin (Fig. 21).
- Palaeogeographic maps showing the sediment transfer pathways for the central part of the North Atlantic region in the Paleocene T22–T36 (Fig. 22).
- A GIS project is established for the Kangerlussuaq Basin with detailed and up-to-date information on geology and localities (see Larsen *et al.* 2005a, b).

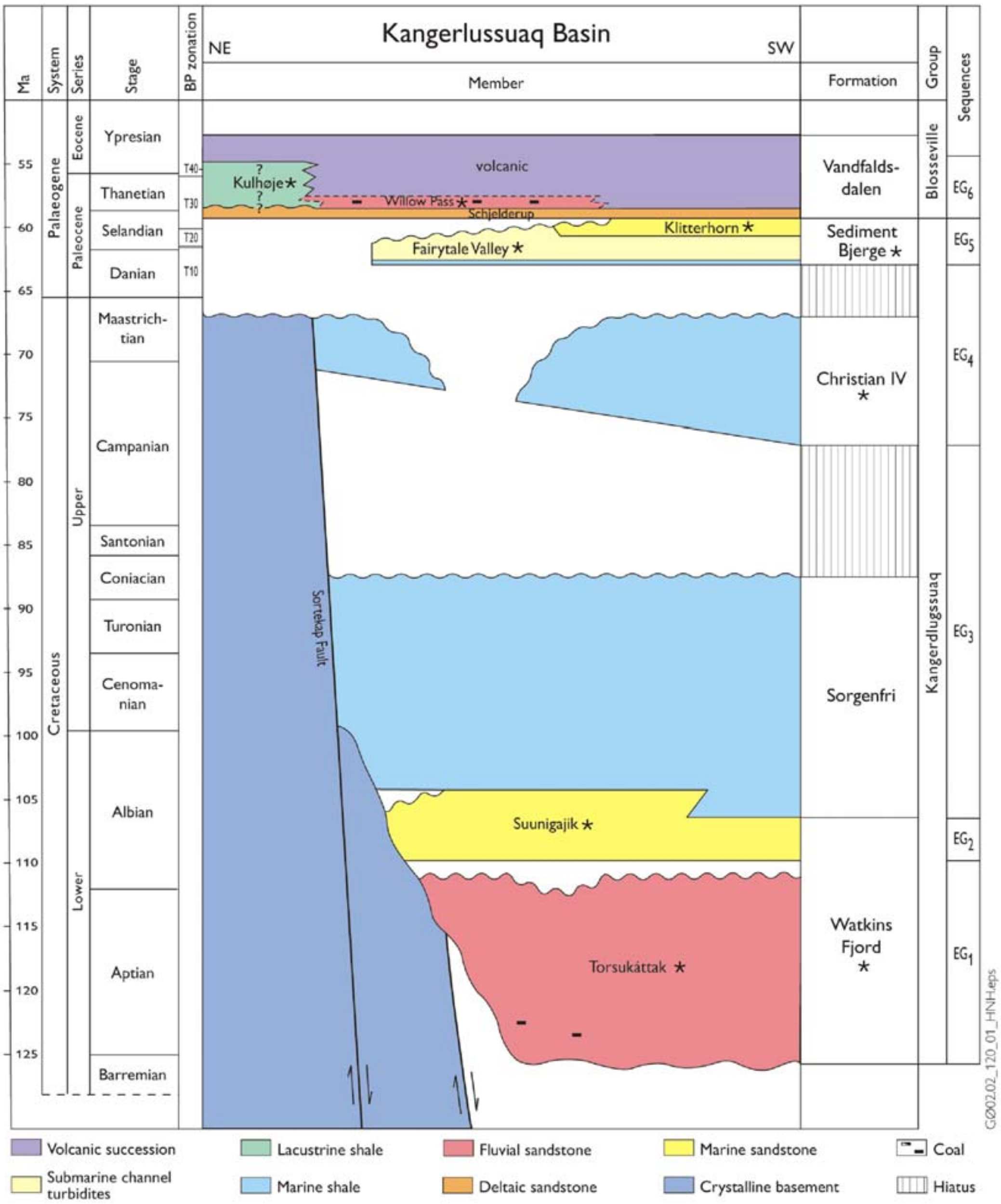


Figure 2. *Simplified stratigraphic scheme for the sedimentary succession in the Kangerlusssuaq with proposed new formations and members (marked with *). Time scale from Gradstein et al. (2004).*

Lithostratigraphy and sequences

The new lithostratigraphic framework proposed for the pre-basaltic sedimentary rocks of the Kangerlussuaq Basin (Fig. 1) builds on the previous lithostratigraphic schemes first established by Wager (1934, 1947) and supplemented by Soper *et al.* (1976). The new framework covers the whole of the Kangerdlugssuaq Group and the lowest part of the Blosseville Group (Larsen *et al.* 2005b, fig. 3).

The new lithostratigraphic scheme comprises three new formations and six new members (Fig. 2). 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 used in older literature, have been replaced.

Unconformity-bounded sequences (EG1–EG6)

The sedimentary succession of the Kangerlussuaq Basin is divided into six unconformity-bounded sequences, EG1–EG6 (Fig. 2). Although initially based on the lithostratigraphic subdivision the six sequences can be shown to represent genetic units bounded by sequence stratigraphic key surfaces and thus allow interpretation of tectonic style, basin configuration, drainage patterns or overall depositional patterns. It is anticipated that the sequences have regional significance and that their size and duration may allow identification (seismic) of correlative units in offshore basins.

Correlation chart of the Kangerlussuaq Basin

Twenty-three key sections are shown in Figure 3. They form the basis for our interpretation of lithostratigraphic units, sedimentary environments and reconstruction of the basin evolution. Important observations are thickness variations and identification of hiatuses and angular unconformities.

The thickness variation seen in the Christian IV Formation (Fig. 6) is probably the result of movement on Christian IV fault zone and subsequent erosion.

The basin-wide presence of the sheet-like fluvial sandstones of the Schjelderup Member (Fig. 8) indicates widespread and deep erosion of the East Greenland margin in the Late Paleocene.

Figure 3. *Correlation chart showing the main sections, lithostratigraphic units and facies associations. Note datum for the Cretaceous sections is SB4 (top of Sorgenfri Formation) and SB6 (base of Schjelderup Member) for the Palaeogene sections.*


CASP
GEUS
Kangerlussuaq Basin
Vandfaldsdalen Formation
Klitterhorn Member
Klitterhorn Member
Fairytale Valley Member
Willow Pass Member
Schjelderup Member
Kulhøje Member
A
A'
SB6
SB5
Sediment Bjerge Formation
Christian IV Formation
Fairytale Valley Member
B
B'
SB4
SB3
Sorgenfri Formation
Watkins Fjord Formation
SB2
Suunigajik Member
Torsukáttak Member
SB1
Legend
Sill intrusion
Volcanic
Lacustrine
Fluvio/deltaic
Shallow marine
Outer shelf
Slope/basin floor
Slope channel/submarine fan
Coal
Laminated or massive mudstone
Trough cross-bedded sandstone
Planar bedded sandstone
Hummocky cross-stratified sandstone
Pebbly sandstone
Laminated volcaniclastic sediments
Basaltic lava flov
Current ripple
Wave ripple
Palaeocurrent (current ripple)
Palaeocurrent (current ripple)
Bioturbation
Planolites
Skolithos
Diplocraterion
Ophiomorpha
Thalassinoides
Rhizocorallium
Ammonite
Ammonite (heteromorph)
Belemnite
Gastropod
Bivalve
Coquina
Echinoderms
Fossil wood
Angiosperms
Gymnosperms
Rootlets
Carbonaceous debris
Palaeogene basaltic rocks
Paleocene sediments
Aptian–Maastrichtian sediments
Precambrian basement
Section locations
25 km
Kangerlussuaq Basin

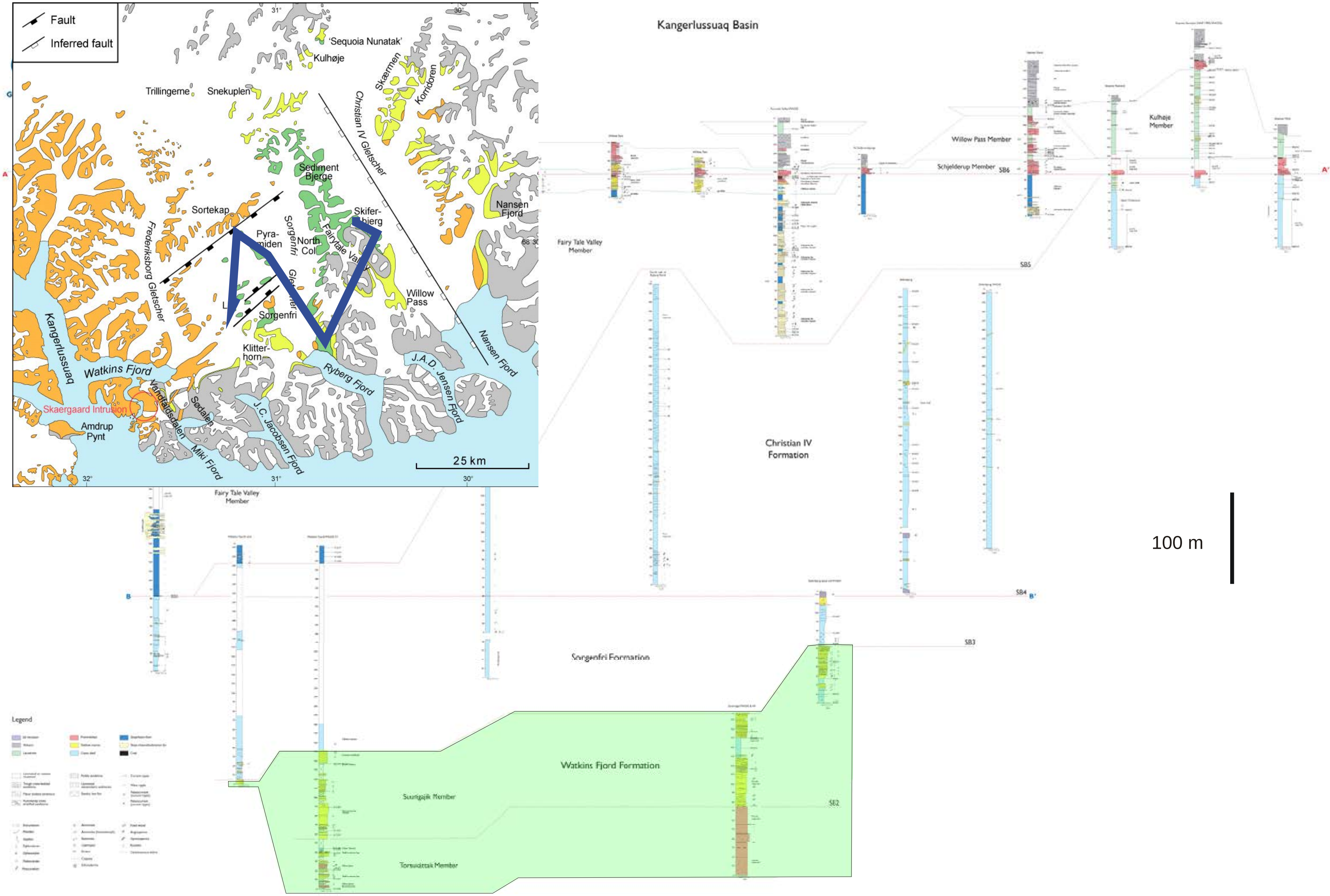
Kangerdlugssuaq Group

For details see Larsen *et al.* (2005b).

Watkins Fjord Formation (new unit)

History. The formation consists of a hitherto un-named sandstone-dominated succession forming the base of the Kangerdlugssuaq Group at the very base of the exposed sedimentary succession. The formation is divided into a lower fluvial dominated unit (Torsukáttak Member, new) and an upper marine unit (Suunigajik Member, new).
Name. After Watkins Fjord into which drains the unnamed glacier passing the type locality.
Type locality. The well-exposed cliff section, 20 km NNE Sødalen, is designated type locality (Larsen *et al.* 2005b, 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 measured because the base and top are not seen in any single section.
Lithology. The formation is sandstone-dominated. The Torsukáttak Member comprises mudstones and fine- to medium-grained sandstones. The sandstones are feldspathic litharenites and locally contain coalified wood fragments and abundant disseminated carbonaceous debris. The Suunigajik Member contains coarse- to very coarse-grained sandstone beds (lithic arkoses) forming lenticular bodies up to 20 m in thickness and several hundred metres in width. To the north and north-east they pass laterally into silty mudstones (for details see Larsen *et al.* 2005b).
Biota. Marine molluscan macrofaunas are locally present in the upper part of the formation in association with dinocyst assemblages. For macrofauna see Figure 9.
Depositional environments. Environments range from fluvio-lacustrine at the base of the formation to marginal and shallow marine at the top.
Boundaries. The formation overlies Archaean gneiss 8 km S of Pyramiden. It is unconformably overlain by the mud-dominated Sorgenfri Formation.
Subdivision. The formation is subdivided into the new Torsukáttak and Suunigajik Members.
Distribution. The formation reaches 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 of Pyramiden and in northernmost Sediment Bjerge and northwards.
Geological age. Molluscan ages from the middle of the formation are Late Barremian–Aptian, and Mid Albian in the upper part.

Figure 4. *Correlation chart of the Kangerlussuaq Basin highlighting the Watkins Fjord Formation composed of the Torsukáttak and Suunigajik Members.*


Fault
Inferred fault
'Sequoia Nunatak'
Kulhøje
Trillingerne
Snekuplen
Skærmen
Korridoren
Christian IV Gletscher
Sediment Bjerge
Sortekap
Skifer-bjerg
Nansen Fjord
Pyra-miden
Sorgenfri
North Col
Fairytale Valley
Fredriksborg Gletscher
Willow Pass
Sorgenfri
Klitter-horn
Kangerlussuaq
Watkins Fjord
Ryberg Fjord
J.A.D. Jensen Fjord
Nansen Fjord
Skaergaard Intrusion
Amdrup Pynt
Vandfaldsdalen
Sødalen
J.C. Jacobsen Fjord
Miki Fjord
25 km
31°
30°
32°
Kangerlussuaq Basin
Willow Pass Member
Schjelderup Member
SB6
Kulhøje Member
A
A'
Fairy Tale Valley Member
SB5
Christian IV Formation
Fairy Tale Valley Member
100 m
B
B'
SB4
SB3
Sorgenfri Formation
Watkins Fjord Formation
Suunigajik Member
SB2
Torsuukittak Member
Legend

Sorgenfri Formation (revised unit)

History. The Sorgenfri Formation was introduced by Soper *et al.* (1976) for the at that time lowermost known unit of the Kangerdlugssuaq Group. Our concept of the formation differs from that in the original description of Soper *et al.* (1976), and includes the lower part of their Ryberg Formation. For details see Larsen *et al.* (2005b).

Name. The formation is named after the Sorgenfri Glacier.

Type section. A new type section replaces the original of Soper *et al.* (1976). An almost complete section through the formation in northern Sediment Bjerge is suggested as type section for the revised formation (see Larsen *et al.* 2005b).

Reference localities. Well-exposed sections also occur at 68°38.3'N 30°55.8'W and at the NW end of Pyramiden at 68°31.5'N 31°11.2'W, but both are incomplete. The base of the formation is exposed at W4259 and at W4247 (Larsen *et al.* 2005b).

Thickness. The formation is 42 m thick at the type locality. At W4225 it is more than 95 m thick and at W4229 it is around 139 m thick (Larsen *et al.* 2005b).

Lithology. The formation is dominated by sandy mudstones with rare, discrete sandstone beds. 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. Bioturbation is common.

Depositional environments. The subordinate sandstones suggest storm-influenced sedimentation in a mid-outer shelf environment.

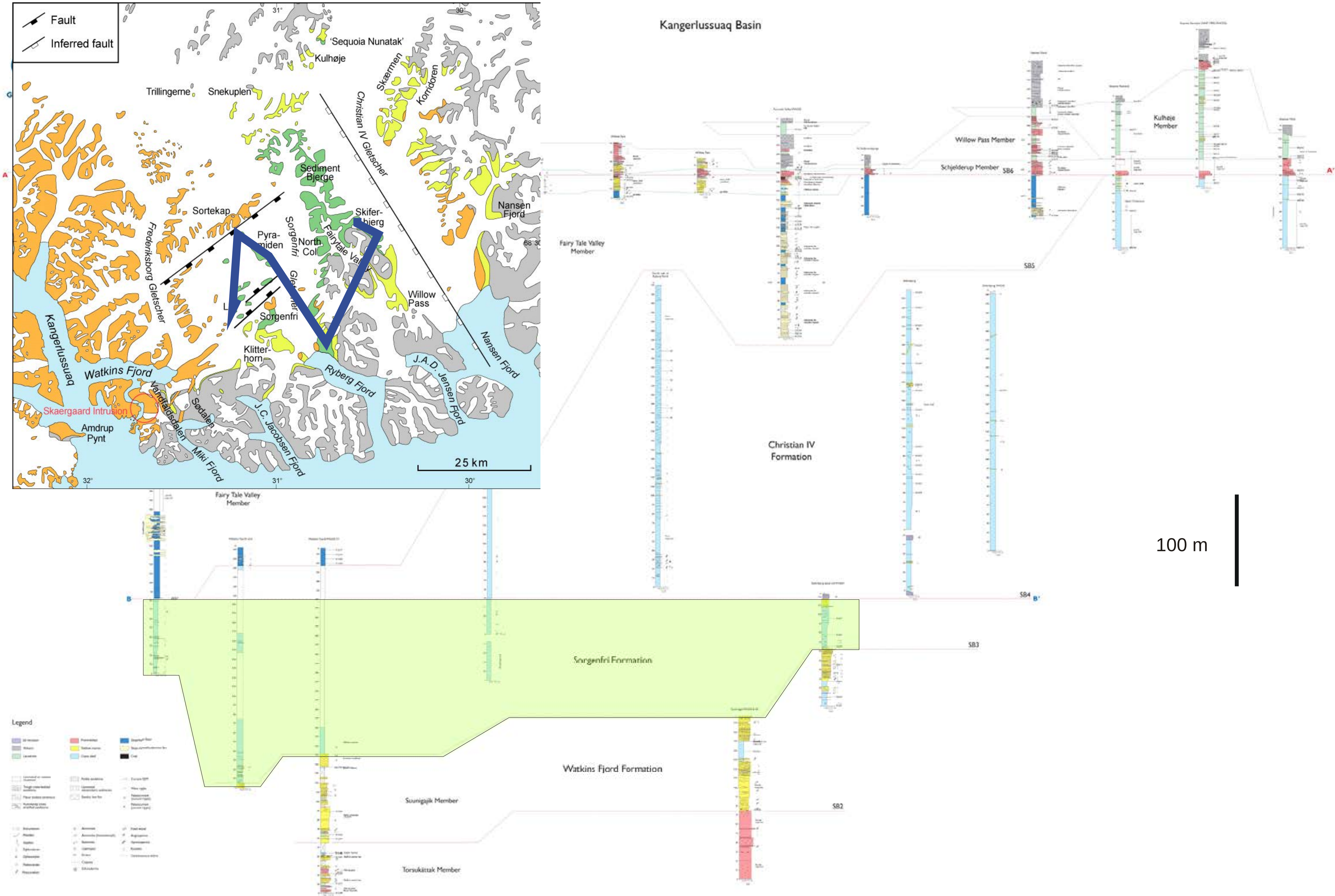
Fossils. Macrofossils are found sporadically throughout the unit but may locally be abundant. Fossils include ammonites, belemnites, bivalves (especially inoceramids), occasionally fish and large reptiles are present. There is good recovery of dinoflagellate cysts (Fig. 11) and microfossils from many of the mudstones. For macrofauna see Figure 9.

Boundaries. The Sorgenfri Formation overlies the Watkins Fjord Formation with an angular unconformity which suggests that a tectonic phase involving block rotation took place between the depositions of the two formations. An oncolitic bed is present at the base of the Sorgenfri Formation in eastern Sediment Bjerge (locality W4247).

Distribution. The formation is exposed widely across the central part of the region.

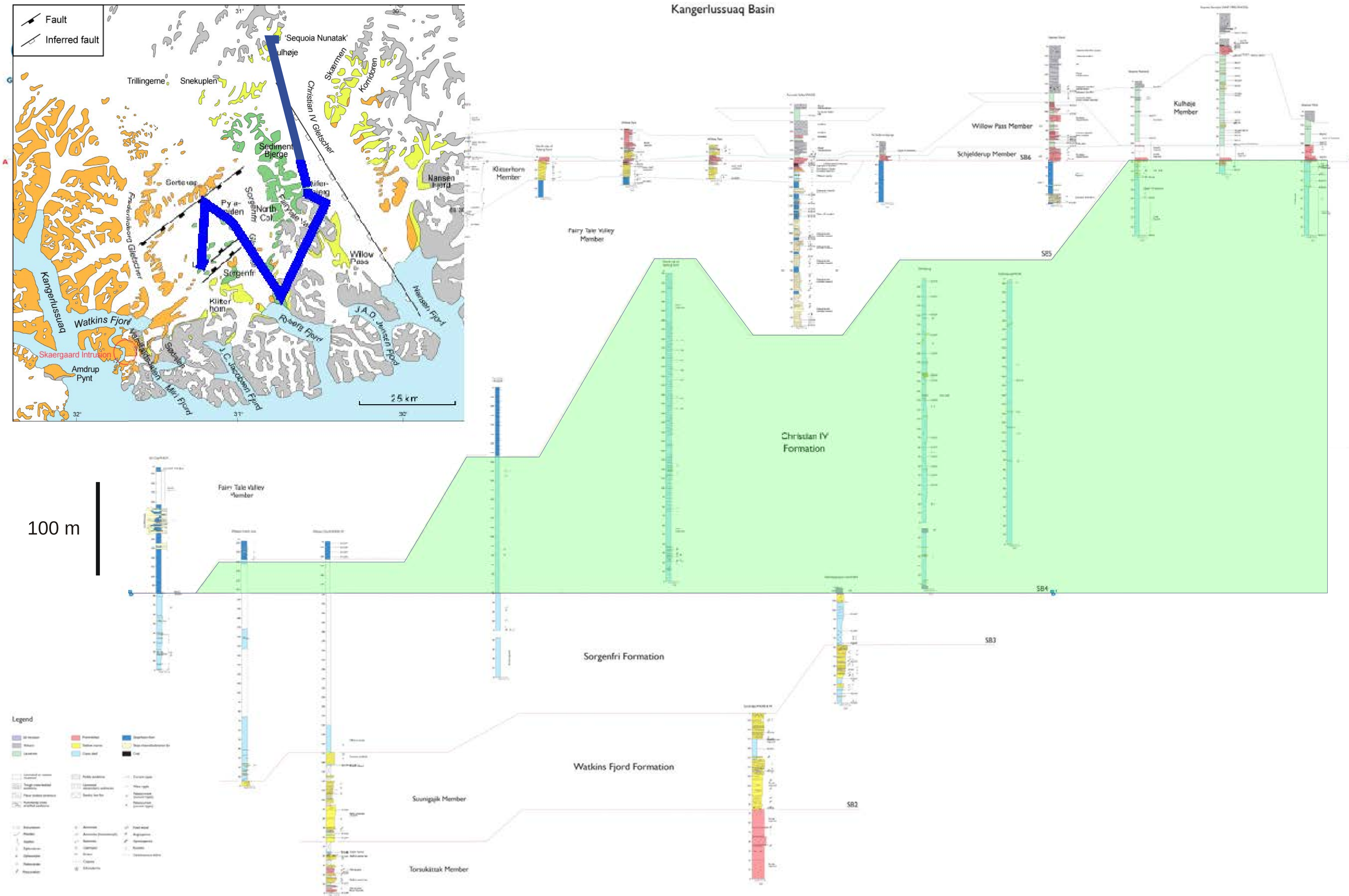
Geological age. The biota indicates the presence of the Mid Albian, Upper Albian, Lower or Mid Cenomanian, Turonian and Coniacian Stages. Representatives of the *Hoplites loricatus* and *Mortoniceras inflatum* ammonite zones occur and *Rhombodella paucispina* and *Subtilisphaera kalaalliti* dinocyst Zones are represented. Miospores are prominent in the Turonian part of the formation. Thus the formation is of Mid-Albian to Mid-Coniacian age. Ammonites indicate that the base of the unit may be diachronous ranging from the Mid to Late Albian.

Figure 5. *Correlation chart of the Kangerlussuaq Basin highlighting the Sorgenfri Formation.*


Fault
Inferred fault
'Sequoia Nunatak'
Kulhøje
Trillingerne
Snekuplen
Skærmen
Korridoren
Christian IV Gletscher
Sediment Bjerge
Sortekap
Skifer-bjerg
Pyra-miden
Sorgenfri Gletscher
North Col
Fairytale Valley
Frederiksborg Gletscher
Sorgenfri
Willow Pass
Nansen Fjord
Kangerlussuaq
Watkins Fjord
Klitter-horn
Ryberg Fjord
J.A.D. Jensen Fjord
Skaergaard Intrusion
Amdrup Pynt
Vandfaldsdalen
Sødalen
Miki Fjord
J.C. Jacobsen Fjord
25 km
32°
31°
30°
Kangerlussuaq Basin
Willow Pass Member
Schjelderup Member
SB6
Kulhøje Member
A
A'
Fairy Tale Valley Member
SB5
Christian IV Formation
100 m
B
B'
SB4
SB3
Sorgenfri Formation
Watkins Fjord Formation
Suunigajik Member
SB2
Torsukáttak Member
Legend

Christian IV Formation (new unit)

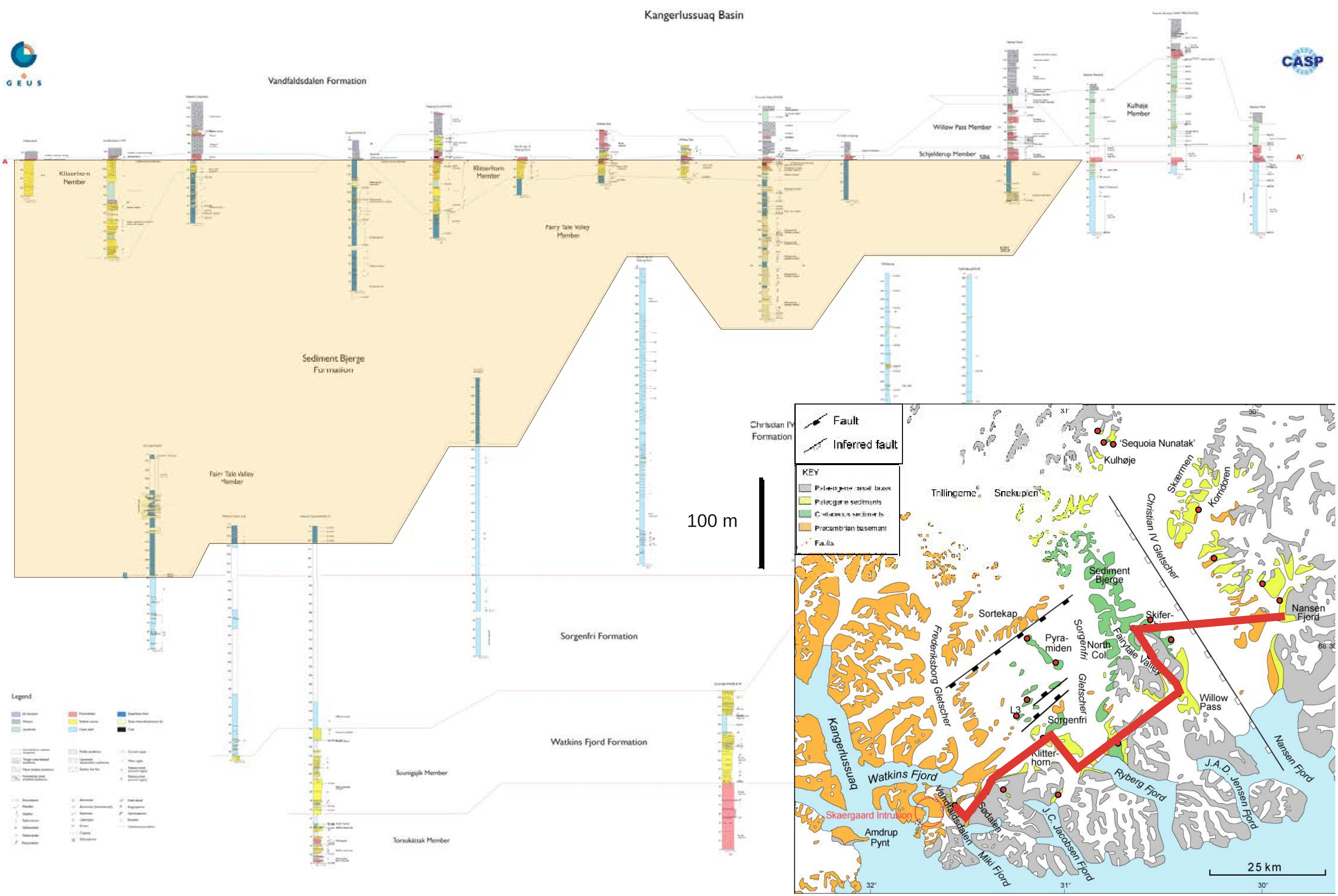
History. We subdivide the original Ryberg Formation of Soper *et al.* (1976) into three units. The lower part we transfer into the upper part of the Sorgenfri Formation (see above); the middle part is defined as a new formation; the Christian IV Formation; the upper part is referred to the new Sediment Bjerge Formation. For more data see Larsen *et al*. (2005b).
Name. After 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 (type section: Skiferbjerg W4245 Larsen *et al.* 2005b, fig. 13). However, the upper and lower contacts are not exposed in the type section.
Reference localities. The base of the section is well exposed at W4282, to the NW of Pyramiden, and also at P2383 and W4293 in the northern Sediment Bjerge (Larsen *et al.* 2005b).
Thickness. The maximum measured thickness is 250 m at the type locality. However, the formation could be in excess of 500 m thick around W4293, northern Sediment Bjerge, but this is uncertain due to faulting and intrusions.
Lithology. Bioturbated sandy mudstones dominate the formation, usually parallel bedded on a 10 cm to m scale. Locally bedding is lenticular and hummocky cross stratification, parallel lamination and ripple cross lamination may be arranged sequentially. Calcareous concretions are less abundant than in the underlying Sorgenfri Formation and often show a characteristic ferruginous red colour. Substantial penecontemporaneous slumping is present in some areas.
Depositional environments. The succession reflects deposition in a shallow marine shelf to outer shelf environment. Chaotic bedded units and units with matrix-supported clasts were produced by gravity induced sliding and debris flows, respectively, probably indicating slope and base of slope environments.
Biota. The macrofauna is characterised by scaphitid and heteromorph ammonites, nautiloids, belemnites, bivalves (including the inoceramid *Tenuiptera fibrosus*), gastropods, brachiopods echinoids, crustaceans and occasional drifted plant leaves. Microbiota includes a wide range of dinoflagellate cysts (Fig. 14) and foraminifera. In the bioturbated units a variety of trace fossils are preserved. For macrofauna see Figure 9.
Boundaries. The base is marked by an unconformity, which is planar at the scale of 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. The formation is unconformably overlain by the Sediment Bjerge and Vandfaldsdalen Formations.
Distribution. There are extensive areas of exposure in northern Sediment Bjerge. The northernmost exposures are found at Sequoia Nunatak and the southernmost exposures in the Sediment Bjerge are found at W4213. West of Sorgenfri Gletscher exposures are not extensive or common, but include Pyramiden (W4282) and ‘Watkins Fjord’ (L3). It is cut out at ‘Sill City’.
Geological age. Late Campanian – Late Maastrichtian; including equivalents of the ammonite zone of *Pachydiscus neubergensis*, bivalve zone of *Tenuipteria fibrosa* and the dinoflagellate cyst zones *Isabelidinium cooksoniae*, *Cerodinium diebellii* and *Wodehouseia spinata.*
Figure 6. *Correlation chart of the Kangerlussuaq Basin highlighting the Christian IV Formation.*


Fault
Inferred fault
'Sequoia Nunatak'
Kulhøje
Trillingerne
Snekuplen
Skærmen
Komdoren
Christian IV Gletscher
Sediment Bjerge
Nansen Fjord
Sorgenfri
Willow Pass
Klitter horn
Kangerlussuaq
Watkins Fjord
Skaergaard Intrusion
Amdrup Pynt
Frederiksborg Gletscher
Ryberg Fjord
J.A.D. Jensen Fjord
J. C. Jacobsen Fjord
Miki Fjord
Nansen Fjord
25 km
32°
31°
30°
A
A'
Kangerlussuaq Basin
Willow Pass Member
Schjelderup Member
SB6
Kulhøje Member
Klitterhorn Member
Fairy Tale Valley Member
SB5
Christian IV Formation
SB4
Fairy Tale Valley Member
100 m
Sorgenfri Formation
SB3
Watkins Fjord Formation
Suunigajik Member
SB2
Torsukåttak Member
Legend

Sediment Bjerge Formation (new unit)

History. The Sediment Bjerge Formation represents the upper part of the original Ryberg Formation of Soper *et al.* (1976).
Name. The formation is named after Sediment Bjerge (formerly 'Sedimentary Mountains' of e.g. Higgins & Soper 1981, p. 339), lying between the Sorgenfri Gletscher and Christian IV Gletscher.
Type locality. East side of Fairytale Valley (Larsen *et al*. 1999, loc. 8), eastern central Sediment Bjerge. 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. The greatest thickness observed is 174 m at the type section where the base is not exposed (Larsen *et al.* 2005 a, fig. 15; Larsen *et al.* 1999, 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 10 cm to metre scale and defined by variation in the sandstone mudstone ratio and by calcareous concretions that typically occur in the more sandy 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.
Fossils and trace fossils. The macrofauna is generally scarce, with occasional poorly preserved molluscs. Trace fossils are widespread; *Zoophycos, Chondrites, Phycosiphon, Planolites, Teichichnus* and *Rhizocorallium* occur. Reworked concretionary clasts from the Christian IV Formation have yielded a rich Cretaceous macrofauna. Large sandstone clasts within a mass flow deposit at localities W4215–4216 also a distinctive reworked oyster-dominated assemblage. Dinoflagellate cysts are rare in the upper part.
Depositional environment. The lower part of the formation reflects deposition in marine submarine fan environment (Larsen *et al*. 2005b). The upper part is shallow marine and estuarine with distributary mouthbars, crevasse channels, distal crevasse levees and interdistributary lagoons.
Boundaries. Exposure of the base was seen at 'Watkins Fjord' and appears unconformable. The top is unconformably overlain by the coarse-grained cross-bedded arkosic sandstone of the Schjelderup Member (Vandfaldsdalen Formation).
Subdivision. The formation is subdivided into the lower Fairytale Valley Member and the upper Klitterhorn Member.
Distribution. The formation is exposed in Vandfaldsdalen, Sødalen, Ryberg Fjord, Sediment Bjerge and Nansen Fjord, showing increasing thickness towards towards the south-east.
Geological age. Danian–Selandian based on dinoflagellate cysts (Figs 15, 16).

Figure 7. *Correlation chart of the Kangerlussuaq Basin highlighting the Sediment Bjerge Formation, including the Fairytale Valley and Klitterhorn Members.*



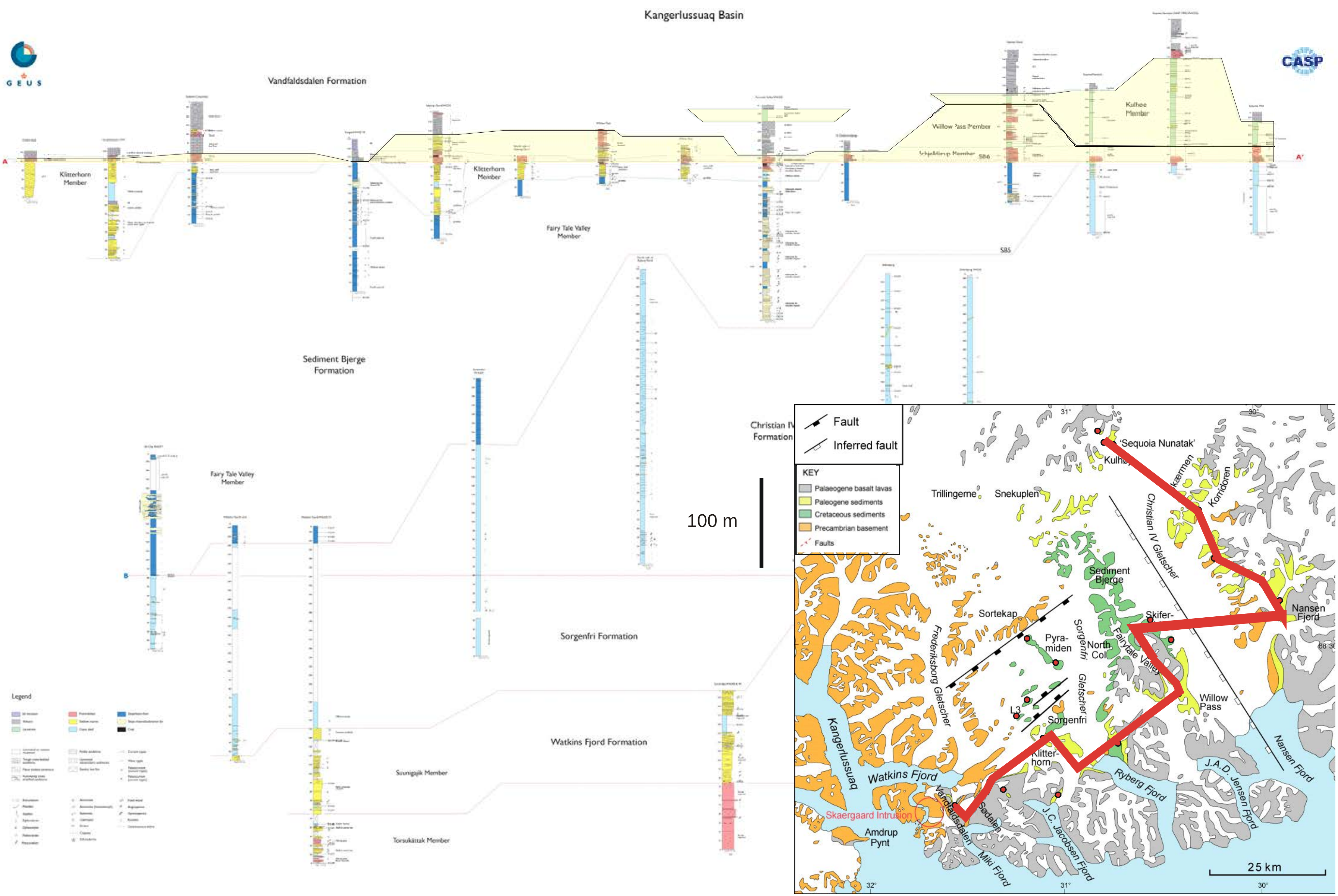
Kangerlussuaq Basin
Vandfaldsdalen Formation
Klitterhorn Member
Klitterhorn Member
Fairy Tale Valley Member
Willow Pass Member
Schjelderup Member
SB6
Kulhøje Member
SB5
Sediment Bjerge Formation
Fairy Tale Valley Member
Christian IV Formation
100 m
Sorgenfri Formation
Watkins Fjord Formation
Suunigajik Member
Torsukáttak Member
Legend
Fault
Inferred fault
KEY
Palaeogene sediments
Precambrian basement
'Sequoia Nunatak'
Kulhøje
Trillingerne
Snekupien
Skærmen
Korridoren
Christian IV Gletscher
Sediment Bjerge
Nansen Fjord
Sortekap
Pyramiden
North Col
Sorgenfri Gletscher
Fairytale Valley
Frederiksborg Gletscher
L3
Sorgenfri
Willow Pass
Kangerlussuaq
Watkins Fjord
Klitterhorn
Ryberg Fjord
J.A.D. Jensen Fjord
Nansen Fjord
Skaergaard Intrusion
Vandfaldsdalen
Sodalen
Amdrup Pynt
J.C. Jacobsen Fjord
Miki Fjord
25 km
32°
31°
30°

Blosseville Group

Vandfaldsdalen Formation (redefined unit)

History. The Vandfaldsdalen Formation was originally named by Soper *et al.* (1976). Since that time it has been placed in the Blosseville Group by most 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 north side of Miki Fjord.
Type locality. Vandfaldsdalen on the north side of Miki Fjord (Soper *et al.* 1976).
Reference locality. Ryberg Fjord, Kulhøje.
Thickness. Soper *et al.* (1976) gave the thickness as up to *c.* 925 m at Ryberg Fjord, but this included *c.* 500 m of volcanoclastic rocks.
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 (Larsen *et al.* 2005a, figs 17, 18). The Vandfaldsdalen Formation lies unconformably on Archaean basement and sediments of Early Cretaceous to Early Paleocene age (Sediment Bjerge and Christian IV Formations).
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 syn- and pre-basaltic sediments according to Kelly *et al*. (2000) and Jolley & Whitham (2004a). Nøhr-Hansen recorded few Selandian indicators from the Schjelderup Member and perhaps also from the Willow Pass Member (Fig. 17). The earliest date of the basaltic volcanism in southern East Greenland is 61 Ma according to Hansen *et al.* (2002).

Figure 8. *Correlation chart of the Kangerlussuaq Basin highlighting the Vandfaldsdalen Formation, including the Schjelderup, Willow Pass and Kulhøje Members.*



Kangerlussuaq Basin
Vandfaldsdalen Formation
CASP
Klitterhorn Member
Klitterhorn Member
Fairy Tale Valley Member
Willow Pass Member
Kulhøe Member
Schjelderups Member
SB6
SB5
A
A'
Sediment Bjerge Formation
Christian IV Formation
Fairy Tale Valley Member
100 m
B
Sorgenfri Formation
Watkins Fjord Formation
Suunigajik Member
Torsukáttak Member
Legend
Fault
Inferred fault
KEY
Palaeogene basalt lavas
Paleogene sediments
Cretaceous sediments
Precambrian basement
Faults
'Sequoia Nunatak'
Kulhøe
Trillingerne
Snekuplen
Komdoren
Christian IV Gletscher
Sediment Bjerge
Nansen Fjord
Sortekap
Pyramiden
North Col
Skifer-
Fairytale Valley
Sorgenfri Gletscher
Frederiksborg Gletscher
Willow Pass
L3
Sorgenfri
Klitterhorn
Kangerlussuaq
Watkins Fjord
Vandfaldsdalen
Skaergaard Intrusion
Sødalen
Amdrup Pynt
Miki Fjord
J.C. Jacobsen Fjord
Ryberg Fjord
J.A.D. Jensen Fjord
Nansen Fjord
25 km
31°
30°
32°
31°
30°
68°30'

Sedimentological summary description and interpretation

Formation/ Member Age	**Estimated thickness**	**Lithology**	**Sedimentary structures**	**Fossils/ trace fossils**	**Depositional environment**
Vandfaldsdalen Fm./Kulhøje Mb. Late Paleocene	100 m	Mudstones and fine-grained sandstones, tuffaceous.	Horizontal lamination Graded airfall tuffs.	Leaf imprints.	Volcanic dammed lakes.
Vandfaldsdalen Fm./Willow Pass Mb. Late Paleocene	50 m	Fine- to coarse-grained tuffs, basaltic lavas and hyaloclastites.	Massive, trough cross-bedding, Gilbert-type delta foresets Variable towards north-west, east and south-east.	Carbonaceous wood fragments Leaf imprints Locally *Planolites* isp.	Continental volcanic terrain associated with fluvial, lacustrine and shallow marine environments.
Vandfaldsdalen Fm./Schjelderup Mb. Selandian/ ? Thanetian	20 m	Coarse-grained to pebbly sandstones.	Large-scale trough cross-bedding Unidirectional towards east-south-east.	Carbonaceous wood fragments and tree trunks.	Proximal braided river channels.
Sediment Bjerge Fm./Klitterhorn Mb. Selandian	20–110 m	Well sorted fine- and medium-grained sandstones.	HCS Low angle trough cross-bedding. Large scale planar sets.	Bivalves *Planolites* isp. *Skolithos* isp. *Ophiomorpha* isp.	Inner shelf sandsheet, shoreface, delta.
Sediment Bjerge Fm./Fairytale Valley Mb. Danian-–Selandian	160 m	Fine- to medium-grained sandstones. Mudstones with thin-bedded sandstones.	Structureless, parallel lamination and cross-lamination (Ta-e). Locally contorted Unidirectional towards south-south-east.	Leaf imprints *Teichichnus* isp. *Planolites* isp. *Skolithos* isp. Bivalves, gastropods.	Submarine fan and channel-levee, slope. Post-depositional deformation (slump and sandstone injection).
Christian IV Fm. Mid-Campanian–Maastrichtian	250–500? m	Silty mudstones and fine-grained sandstones.	Horizontal lamination. Sandstones parallel lamination, cross-lamination and HCS.	Ammonites Dinoflagellate cysts Inoceramid bivalves; *Planolites* isp.	Storm influenced shelf. Moderate to high sedimentation rates.
Sorgenfri Fm. Mid-Albian–Coniacian	200 m	Mudstones and fine-grained sandstones. Abundant phosphatic concretions.	Horizontal lamination. Sandstones structureless, parallel lamination and cross-lamination (Ta-e). Unidirectional towards south-east.	Belemnites Ammonites Dinoflagellate cysts Inoceramid bivalves; *Planolites* isp.	Shelf to offshore transition. Low sedimentation rates.
Watkins Fjord Fm./ Suunigajik Mb. Late Aptian – Mid Albian	100 m	Coarse- to medium-grained sandstones.	Massive, trough and large-scale planar cross-bedding. Bimodal towards north-east and south-east.	Ammonites *Skolithos* isp. *Ophiomorpha* isp. *Arenicolites* isp.	Channel-fill and sandbars in fluvio-estuarine environment.
Watkins Fjord Fm./ Torsukáttak Mb. ?Barremian – Late Aptian	75 m	Fine- to coarse-grained sandstones and gravel interbedded with mudstones.	Trough cross- bedding, ε-cross-stratification, HCS unidirectional towards east.	Rootlets Bivalves Ammonites *Ophiomorpha* isp.	Fluvial channels, deltaic mouthbars overlain by shallow marine deposits.

Table 1. *Sedimentology and gross depositional environments.*

Biostratigraphy

Macrobiota

The Cretaceous macrobiota of the Kangerlussuaq Basin are dominated by marine molluscan faunas, particularly ammonites, belemnites and bivalves. These groups provide important biostratigraphic indicators and in particular the ammonites and the inoceramid bivalves. The best preserved material is three-dimensional and comes from calcareous, sideritic and phosphatised concretionary horizons in the mudstones. Plant macrofossils are commonly present as driftwood, and occasional foliage fragments. However, within the Palaeogene, plant macrofossils become much more abundant and marine molluscan horizons become few and far between and of less biostratigraphic significance. Branches of trees are even locally present in the volcanic blocky lava flows within the lower part of the Blosseville Group.

Palynological material and preservation

The organic material is dominated by coal fragments and amorphous material of unknown origin, whereas dinoflagellate cysts, spores and pollen often are rare. The preservation of the palynomorphs is poor to bad and their colour varies from brown to black due to intense thermal heating by Palaeogene intrusions.

More than 200 samples representing 23 outcrop sections (Fig. 3) have been studied and up to 100 specimens have been counted from each sample when possible. However, many samples are almost barren of dinoflagellate cysts. The poor preservation and few stratigraphic marker species together with common reworking of Late Cretaceous palynomorphs has made this study very difficult and time consuming. Nevertheless, dinoflagellate cysts are probably the best biostratigraphic tool for dating the sediments from the Kangerlussuaq area.

Developments in Cretaceous biostratigraphy

Barremian–Maastrichtian macropalaeontology

The rich macrofauna present in the Cretaceous succession of the Kangerlussuaq Basin (Figs 9, 10) was described in Nøhr-Hansen *et al.* (2006). A summary biostratigraphic zonal scheme for in the Kangerlussuaq Basin is show in Figure 10.

Figure 9. *Biostratigraphic distribution of the Cretaceous macrofauna in the Kangerlussuaq Basin.*

Group	Taxon	Reworked (Vandfaldsdalen, Paleocene)	Maastrichtian L	Maastrichtian L–E	Maastrichtian E	Campanian (L, M, E)	Santonian (L, M, E)	Coniacian (L, M, E)	Turonian L	Turonian M	Turonian E	Cenomanian L	Cenomanian M	Cenomanian E	Albian L	Albian M (upper)	Albian M (lower)	Albian E	Aptian L	Aptian M	Aptian E	Barremian L	Barremian E
Molluscs – Ammonites	*Parancyloceras bidentatum* (von Koenen)																					●	
Molluscs – Ammonites	*Tetragonites* sp. 1																					●	
Molluscs – Ammonites	*Tropaeum subarcticum* Casey																		●				
Molluscs – Ammonites	*Anahoplites planus* xx gp.																●						
Molluscs – Ammonites	*?Gastroplites* sp.																●						
Molluscs – Ammonites	*Euhoplites loricatus* xx																●						
Molluscs – Ammonites	*Euhoplites ?aspasia*															●							
Molluscs – Ammonites	*Hamites* sp.														●								
Molluscs – Ammonites	*Mortoniceras (Deiradoceras)* sp.														●								
Molluscs – Ammonites	*Euhoplites boloniensis* Spath														●								
Molluscs – Ammonites	*Phylloceras (Hypophylloceras) lombardiensis* (Joly)													●									
Molluscs – Ammonites	*Parapuzosia (Austiniceras) austeni* (Sharpe)													●									
Molluscs – Ammonites	*Gaudryceras (Mesogaudryceras) leptonema* (Sharpe)													●									
Molluscs – Ammonites	Tetragonitid gen et sp. nov.													●									
Molluscs – Ammonites	*Schloenbachia varians* (Sharpe)													●									
Molluscs – Ammonites	*Gaudryceras (Gaudryceras) cassisianum* (d'Orbigny)												●										
Molluscs – Ammonites	*Baculites* spp.		●		●				●														
Molluscs – Ammonites	*Pachydiscus (Pachydiscus)* sp.			●	●																		
Molluscs – Ammonites	*Acanthoscaphites tridens* (Kner)			●	●																		
Molluscs – Ammonites	*Diplomoceras cylindraceum* (Defrance)	Ma	●	●	●																		
Molluscs – Ammonites	*Anagaudryceras politissimum* (Kossmat)		●	●																			
Molluscs – Ammonites	*Neophylloceras groenlandicum* Birkelund		●																				
Molluscs – Ammonites	*Anagaudryceras* cf. *lueneburgense* (Schluter)		●																				
Molluscs – Ammonites	*Discoscaphites angmartussutensis* Birkelund		●																				
Molluscs – Ammonites	*Saghalinites wrighti* Birkelund		●																				
Molluscs – Ammonites	*Discoscaphites* sp. nov		●																				
Molluscs – Ammonites	*Jeletzkytes* sp.		●																				
Molluscs – Nautiloid	*Eutrephoceras* sp.	Ma		●																			
Molluscs – Belemnites	*Neohibolites minimus* Miller gp.														○	●	●						
Molluscs – Belemnites	*Actinocamax* cf. *manitobensis* (Whiteaves)								○														
Molluscs – Belemnites	*Belemnitella* sp.			●																			
Molluscs – Bivalves	*Entolium (Entolium) orbiculare* (J Sowerby).																		○			●	
Molluscs – Bivalves	*Arctica* sp.																○		○			●	
Molluscs – Bivalves	*Actinoceramus concentricus* (Parkinson)																●						
Molluscs – Bivalves	*Actinoceramus?* sp.														●								
Molluscs – Bivalves	*?Pinna* sp.														●								
Molluscs – Bivalves	*Inoceramus crippsi* Mantell													●									
Molluscs – Bivalves	Nuculoid			●										●									
Molluscs – Bivalves	*Inoceramus lamarcki* Parkinson gp.								●														
Molluscs – Bivalves	*Mimachlamys cretosus* subsp. *denticulata* (Von Hagenow)			●																			
Molluscs – Bivalves	*Spyridoceramus tegulatus* (Von Hagenow)		●	●	●																		
Molluscs – Bivalves	Carditid			●																			
Molluscs – Bivalves	Ostreid			●																			
Molluscs – Bivalves	Lucinid sp.	Ma	●																				
Molluscs – Bivalves	*Protocardium* sp.	Ma	●																				
Molluscs – Bivalves	Astartid sp.	Ma	●																				
Molluscs – Gastropods	*?Avellana* sp.		●																				
Molluscs – Gastropods	*?Cerithium* sp.			●																			
Molluscs – Gastropods	*?Margarita steenstrupi* Ravn			●																			
Molluscs – Gastropods	*?Perialax* sp.		●																				
Molluscs – Gastropods	*?Perissoptera* sp.	Ma	●																				
Molluscs – Scaphopod	*Dentalium* sp.	Ma	●	●																			
Echinoderms – Regular echinoids	Cidarid (spines)			●																			
Echinoderms – Regular echinoids	aff. *Gauthiera pseudomagnifica* (Cotteau)			●																			
Echinoderms – Irregular echinoids	Spatangoid																●						
Echinoderms – Irregular echinoids	Conulid			●																			
Echinoderms – Irregular echinoids	aff. *Cyclaster* spp.			●																			
Echinoderms – Irregular echinoids	*Diplodetus* spp.			●																			
Echinoderms – Irregular echinoids	*Echinocorys* spp.			●																			
Echinoderms – Irregular echinoids	*Hemiaster aequigranis*			●																			
Echinoderms – Irregular echinoids	Holasterid (large)			●																			
Echinoderms – Irregular echinoids	aff. *Homoaster evaristei*			●																			
Echinoderms – Crinoid	*Isselicrinus* or *Buchicrinus* sp.		●																				
Annelids	*Serpula* spp.		●	●	●										●								
Brachiopods	Terebratulid spp.		●	●												●							
Crustacean	Decapod spp.		●	○												●							
Vertebrates – Reptile	Pliosaur jaw & teeth															●							
Vertebrates – Fish	*Ptychodus* (tooth)								●														
Vertebrates – Fish	*?Ischyodus* sp. (tooth)													○									
Vertebrates – Fish	Shark (tooth)													●									
Vertebrates – Fish	Teleost scales								●														
Vertebrates – Fish	Teleost vertebra								●														

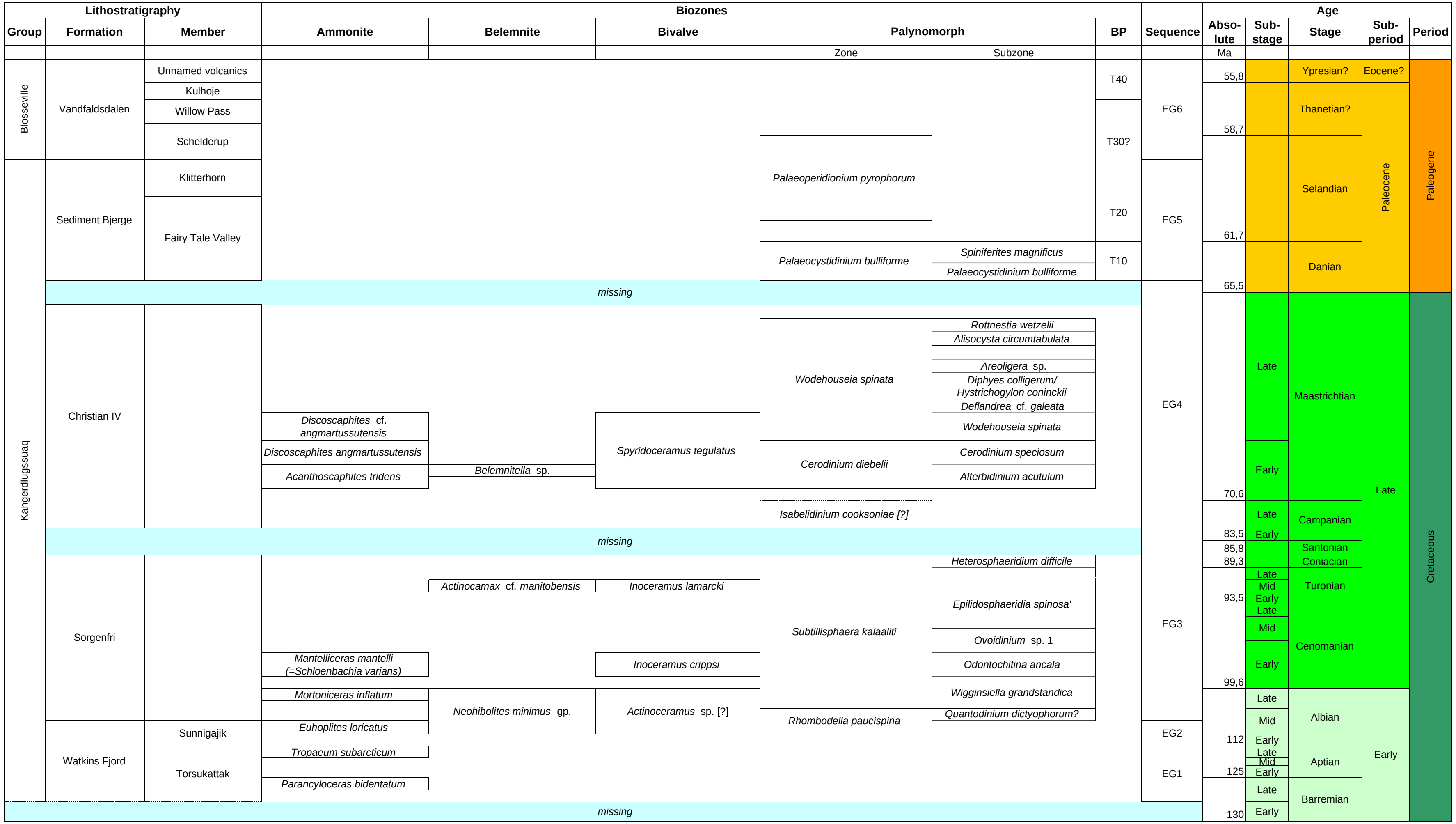
Formation	Member	Period	Stage	Substage
Vandfald-sdalen		Paleo-cene	Reworked	
Christian IV		Late Cretaceous	Maastrichtian	L, E
(gap)	(gap)	Late Cretaceous	Campanian	L, M, E
(gap)	(gap)	Late Cretaceous	Santonian	L, M, E
Sorgen-fri		Late Cretaceous	Coniacian	L, M, E
Sorgen-fri		Late Cretaceous	Turonian	L, M, E
Sorgen-fri		Late Cretaceous	Cenomanian	L, M, E
Sorgen-fri / Watkins Fjord	Sunni-gajik / Torsuk-attak	Early Cretaceous	Albian	L, M, E
Watkins Fjord	Torsuk-attak	Early Cretaceous	Aptian	L, M, E
Watkins Fjord	Torsuk-attak	Early Cretaceous	Barremian	L, E

Figure 9a. Distribution of Cretaceous macrofauna in the Kangerlussuaq Basin. Determinations by S.R.A. Kelly, with assistance in ammonites by W.J. Kennedy (Oxford) and H.G. Owen (London); belemnites by the late W.K. Christensen (Copenhagen); and echinoids by J. Jagt (Maastricht).

● Stratigraphic attribution sound
○ Stratigraphic attribution questionable

Ma Reworked from Christian IV Fm, Maastrichtian

Figure 10. *Integrated macropalaeontological and palynological biozonation schemes for the Cretaceous-Palaeogene of the Kangerlussuaq Basin.*


Lithostratigraphy
Biozones
Age
Group
Formation
Member
Ammonite
Belemnite
Bivalve
Palynomorph
BP
Sequence
Abso-lute
Sub-stage
Stage
Sub-period
Period
Zone
Subzone
Ma
Blosseville
Vandfaldsdalen
Unnamed volcanics
Kulhoje
Willow Pass
Schelderup
Kangerdlugssuaq
Sediment Bjerge
Klitterhorn
Fairy Tale Valley
Christian IV
Sorgenfri
Watkins Fjord
Sunnigajik
Torsukattak
T40
T30?
T20
T10
EG6
EG5
EG4
EG3
EG2
EG1
Palaeoperidionium pyrophorum
Palaeocystidinium bulliforme
Spiniferites magnificus
Palaeocystidinium bulliforme
missing
Rottnestia wetzelii
Alisocysta circumtabulata
Areoligera sp.
Diphyes colligerum/ Hystrichogylon coninckii
Deflandrea cf. galeata
Wodehouseia spinata
Wodehouseia spinata
Cerodinium diebelii
Cerodinium speciosum
Alterbidinium acutulum
Isabelidinium cooksoniae [?]
Discoscaphites cf. angmartussutensis
Discoscaphites angmartussutensis
Acanthoscaphites tridens
Belemnitella sp.
Spyridoceramus tegulatus
missing
Heterosphaeridium difficile
Actinocamax cf. manitobensis
Inoceramus lamarcki
Epilidosphaeridia spinosa'
Subtilisphaera kalaaliti
Ovoidinium sp. 1
Mantelliceras mantelli (=Schloenbachia varians)
Inoceramus crippsi
Odontochitina ancala
Mortoniceras inflatum
Wigginsiella grandstandica
Neohibolites minimus gp.
Actinoceramus sp. [?]
Quantodinium dictyophorum?
Rhombodella paucispina
Euhoplites loricatus
Tropaeum subarcticum
Parancyloceras bidentatum
missing
55,8
58,7
61,7
65,5
70,6
83,5
85,8
89,3
93,5
99,6
112
125
130
Ypresian?
Thanetian?
Selandian
Danian
Late
Early
Maastrichtian
Late
Early
Campanian
Santonian
Coniacian
Late
Mid
Early
Turonian
Late
Mid
Early
Cenomanian
Late
Mid
Early
Albian
Late
Mid
Early
Aptian
Late
Early
Barremian
Eocene?
Paleocene
Late
Early
Paleogene
Cretaceous

Albian–Santonian palynology

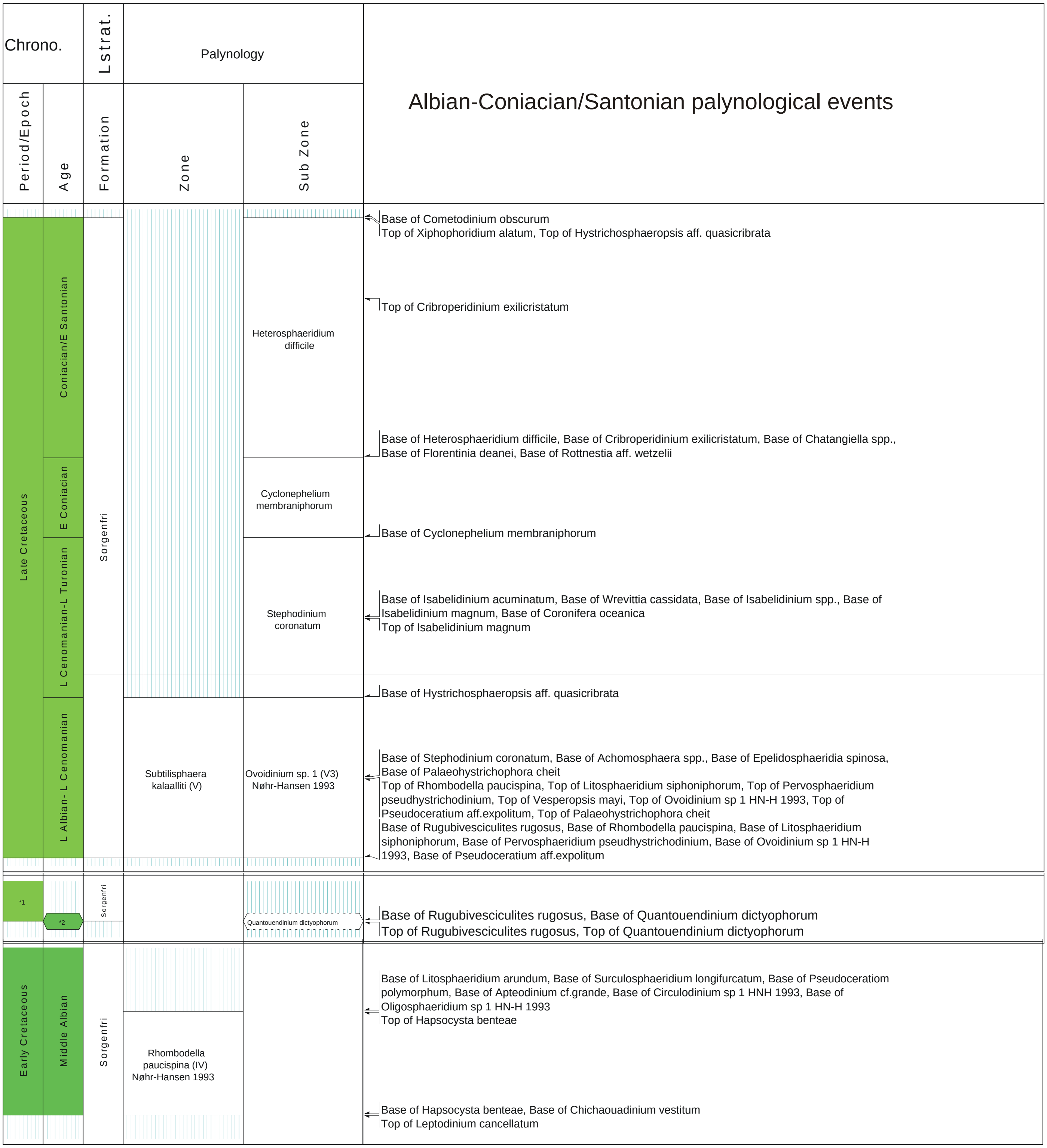
Based on palynological events, two zones and five subzones are recognised from the Mid Albian to uppermost Coniacian / ?Lower Santonian Sorgenfri Formation (Fig. 11).

The oldest marine palynological assemblage recorded from the 'Skiferbjerg Basal' section (Larsen *et al.* 2005b) corresponds to the Mid Albian *Rhombodella paucispinosa* Zone described from North-East Greenland (Nøhr-Hansen 1993).

The *Quantodinium dictyophorum* informal subzone recorded from the basal part of the Watkins Fjord 2004 section (Nøhr-Hansen *et al.* 2006) is characterised by common *Rugubivesciculites* pollen and a few brackish-water dinoflagellate cysts suggesting a restricted palaeoenvironment around the Albian–Cenomanian boundary. A similar flora has been recorded from West Greenland (Nøhr-Hansen 2005) and the Western Interior of U.S.A. (Bint 1986).

The Upper Albian/Cenomanian to Coniacian / Lower Santonian succession recorded from the Pyramiden section (Larsen *et al.* 2005b) is divided into 4 subzones. The lower part corresponds to the Late Albian/Cenomanian *Ovodinium* sp. 1 Subzone (upper part of the *Subtilisphaera kalaalliti* Zone of Nøhr-Hansen (1993)) and the upper part corresponds to the Coniacian / Lower Santonian *Heterosphaeridium difficile* interval described by Nøhr-Hansen (1996) from West Greenland. The palynological study of sections from Pyramiden and the Sediment Bjerge by Jolley & Whitham (2004b) support the present dating of the Sorgenfri Formation.

Figure 11. *Lower Cretaceous Albian to Santonian palynological event and biozonation of the Kangerlussuaq Basin*.


Chrono.
Lstrat.
Palynology
Albian-Coniacian/Santonian palynological events
Period/Epoch
Age
Formation
Zone
Sub Zone
Late Cretaceous
Coniacian/E Santonian
E Coniacian
L Cenomanian-L Turonian
L Albian- L Cenomanian
Sorgenfri
Heterosphaeridium difficile
Cyclonephelium membraniphorum
Stephodinium coronatum
Subtilisphaera kalaalliti (V)
Ovoidinium sp. 1 (V3) Nøhr-Hansen 1993
Base of Cometodinium obscurum
Top of Xiphophoridium alatum, Top of Hystrichosphaeropsis aff. quasicribrata
Top of Cribroperidinium exilicristatum
Base of Heterosphaeridium difficile, Base of Cribroperidinium exilicristatum, Base of Chatangiella spp.,
Base of Florentinia deanei, Base of Rottnestia aff. wetzelii
Base of Cyclonephelium membraniphorum
Base of Isabelidinium acuminatum, Base of Wrevittia cassidata, Base of Isabelidinium spp., Base of
Isabelidinium magnum, Base of Coronifera oceanica
Top of Isabelidinium magnum
Base of Hystrichosphaeropsis aff. quasicribrata
Base of Stephodinium coronatum, Base of Achomosphaera spp., Base of Epelidosphaeridia spinosa,
Base of Palaeohystrichophora cheit
Top of Rhombodella paucispina, Top of Litosphaeridium siphoniphorum, Top of Pervosphaeridium
pseudhystrichodinium, Top of Vesperopsis mayi, Top of Ovoidinium sp 1 HN-H 1993, Top of
Pseudoceratium aff.expolitum, Top of Palaeohystrichophora cheit
Base of Rugubivesciculites rugosus, Base of Rhombodella paucispina, Base of Litosphaeridium
siphoniphorum, Base of Pervosphaeridium pseudhystrichodinium, Base of Ovoidinium sp 1 HN-H
1993, Base of Pseudoceratium aff.expolitum
*1
*2
Sorgenfri
Quantouendinium dictyophorum
Base of Rugubivesciculites rugosus, Base of Quantouendinium dictyophorum
Top of Rugubivesciculites rugosus, Top of Quantouendinium dictyophorum
Early Cretaceous
Middle Albian
Sorgenfri
Rhombodella paucispina (IV) Nøhr-Hansen 1993
Base of Litosphaeridium arundum, Base of Surculosphaeridium longifurcatum, Base of Pseudoceratiom
polymorphum, Base of Apteodinium cf.grande, Base of Circulodinium sp 1 HNH 1993, Base of
Oligosphaeridium sp 1 HN-H 1993
Top of Hapsocysta benteae
Base of Hapsocysta benteae, Base of Chichaouadinium vestitum
Top of Leptodinium cancellatum

Maastrichtian correlations

Maastrichtian macrofossil zonal schemes and their attempted calibrations with the Maastrichtian Stage and its subdivisions are summarised in Figure 12. Greenland ammonite identifications are by W.J. Kennedy (Oxford University).

Early Maastrichtian

In northern Europe the *Belemnitella langei* Subzone traditionally marks the last division of the Late Campanian (e.g. Christensen 1996). Kennedy *et al.* (1992) demonstrated that the Western Interior ammonite *Nostoceras hyatti* of the *Baculites jenseni* Zone also occurs and in Poland in the *B. langei* Subzone, thus correlating the top of the Campanian in North America with Europe. Kennedy *et al.* (1992) argued for the use of the base of the *Belemnella lanceolata* Subzone for the base of the Maastrichtian Stage in northern Europe. The generally used Early Maastrichtian ammonite index, *Pachydiscus neubergicus*, appears within the *B. lanceolata* Subzone, and also *Acanthoscaphites tridens* appears at the base of it. *Baculites jenseni* is followed by *B. baculatus* in the Western Interior (Fig. 13), which Kennedy *et al.* (1992) take as being equivalent to the *Belemnella lanceolata* Subzone, thus correlating the base of the Maastrichtian between the two regions. Now that *Acanthoscaphites tridens* has been recognised in the Kangerlussuaq area, it is possible to tie the base of the Maastrichtian in East Greenland more accurately with the northern European and Western Interior successions.

Ogg *et al.* (2004, pp. 355, 364) admit some conflicting evidence concerning the revised callibration of the Maastrichtian Stage. In the text they retain *Pachydiscus neubergicus* as the primary biostratigraphic indicator for the Early Maastrichtian, whereas they in their figure correlate its appearance within the *Belemnella pseudobtusa* Zone in Europe and with the *Baculites eliasi* Zone in the Western Interior. In the text they argue that the base of the *B. lanceolata* Zone in the Western Interior may be within the latest Campanian, and that the base of the Maastrichtian may be within the *Baculites grandis* or *B. baculus* Zones.

Ogg *et al.* (2004, p. 346) also placed importance on the straight shafted ammonite *Diplomoceras cylindraceum* whose first appearance they stated was at the base of the Maastrichtian. However, several authors (including Machalski 1996) indicated that this species has its first appearance in the uppermost Campanian, in association with the *Nostoceras hyatti* Zone in Poland. Birkelund (1965) discovered relatively few specimens of *D. cylindraceum* in West Greenland, but the species is not recognised in the Western Interior. In East Greenland it is; however by far the most abundant ammonite species in the Maastrichtian (Nøhr-Hansen *et al.* 2006, plate 13b, c), and with shafts reaching at least 0.5 m in length, it is the largest ammonite of the latest Cretaceous in Greenland. No positive information has been obtained for its occurrence in the Upper Campanian of Greenland, but elsewhere it is known to range throughout the Maastrichtian Stage. In the field, its presence is used to discriminate the outcrop of the Christian IV Formation.

Figure 12. *Suggested correlation of biostratigraphic schemes for the Western Interior, Greenland and Europe with traditional and modern stage calibration from Ogg et al. (2004).*

AGE (Traditional) STAGE	AGE (Traditional) SUBS-TAGE	AGE (Ogg et al. 2005)) STAGE	AGE (Ogg et al. 2005)) SUBS-TAGE	WESTERN INTERIOR AMMONITE ZONE (Kennedy et al., 1998)	NORTHWEST EUROPE AMMONITE ZONE (Hancock in Gradstein, 1995)	NORTHWEST EUROPE AMMONITE ZONE (Ogg et al., 2005)	NORTHWEST EUROPE FAUNAL ZONE After Shulz & Schmid, 1983)	EAST GREENLAND AMMONITE ZONE (new)	EAST GREENLAND INOCERAMID BIVALVE ZONE	WEST GREENLAND AMMONITE ZONE (Kennedy et al., 1999)	WEST GREENLAND PALYNOLOGICAL ZONE (Nøhr-Hansen, 1996, 2002)	EAST GREENLAND PALYNOLOGICAL SUBZONE (Nøhr-Hansen, new)
Danian		Danian									*Palaeocystodium bulliforme*	*Palaeocystodium bulliforme*
											Senegalinium iterlaaense	
											Cerodinium pannuceum	
											Trithyrodinium evittii	
Maastrichtian	Late	Maastrichtian	Late	*Triceratops* Beds'	*Pachydiscus gollevillensis*	*Pachydiscus fresvillensis*	*Belemnella kazimiroviensis*				*Palynodinium grallator*	
										Discoscaphites aff. *angmartussutensis*		*Rottnestia wetzelii*
								Discoscaphites angmartussutensis		*Discoscaphites angmartussutensis*	*Wodehouseia spinata*	*Alisocysta circumtabulata*
				Jeletzkyites nebraskensis			*Tylocidaris baltica/ Oxytoma danica*					
							Oxytoma danica/ Tenuipteria argentea					*Areoligera*
				Hoploscaphites nicoletti			*Tenuipteria argentea/ Belemnitella junior*					*Diphyes colligerum / Hystrichostrogylon coninckii*
				Hoploscaphites birkelundi (=*H.* aff. *nicoletti)*			*Spyridoceramus tegulatus/ Belemnitella junior*					*Deflandrea* cf. *galatea*
									Spyridoceramus tegulatus			*Wodehouseia spinata*
	Early			*Baculites clinolobatus*	*Pachydiscus neubergicus / Acanthoscaphites tridens*		*Belemnella fastigata*					
							Belemnella cimbrica					
			Early			*Pachydiscus neubergicus*						
				Baculites grandis			*Belemnella sumensis*	*Acanthoscaphites tridens*			*Cerodinium diebelii*	*Cerodinium speciosum*
				Baculites baculus			*Belemnella obtusa*					
		Campanian	Late	*Baculites eliasi*			*Belemnella pseudobtusa*					*Alterbidinium acutulum*
							Belemnella lanceolata					
Campanian	Late			*Baculites jenseni*	*Neancyloceras bipunctatum*	*Nostoceras hyatti*	*Belemnitella langei*				*Isabelidinium cooksoniae [?]*	

Clearly there remain difficulties in calibrating the base of the Maastrichtian. If one follows the principal argument of Ogg *et al.* (2004), using the appearance of *Pachydiscus neubergicus* to define the early part of the stage, the appearance of *Belemnella lanceolata* and *Acanthoscaphites tridens* must be regarded as ranging down into the latest Campanian.

Until the implications of Ogg *et al.* (2004) have been more fully investigated, we follow a conservative approach and continue to pick the base of the Maastrichtian Stage at the appearance of *Belemnella lanceolata* in northern Europe (as in Christensen 1996) and at the appearance of *Baculites eliasi* in the Western Interior. Similarly, we recognise the base of the Late Maastrichtian at the appearance of *Belemnitella junior* in northern Europe and *Hoploscaphites birkelundi* in the Western Interior.

Late Maastrichtian

Pachydiscus gollevillensis has been used as the zonal indicator for the Late Maastrichtian (e.g. Hancock in Gradstein 1995). Although this species was recorded from the Kangerlussuaq region by Hancock (in Soper *et al.* 1976), the species has not been found during our investigations. More recently the appearance of *Pachydiscus fresvillensis* has been used to define the base of the Late Maastrichtian in the mid *Belemnella cimbrica* Zone (Fig. 12; *cf.* Ogg *et al.* 2004). Machalski (2005) showed how this species, now ascribed to *Menuites*, has its appearance at the base of the *B. cimbrica* Zone. Although this species was not identified in our studies, its appearance would be expected associated with *Discoscaphites angmartussutensis*.

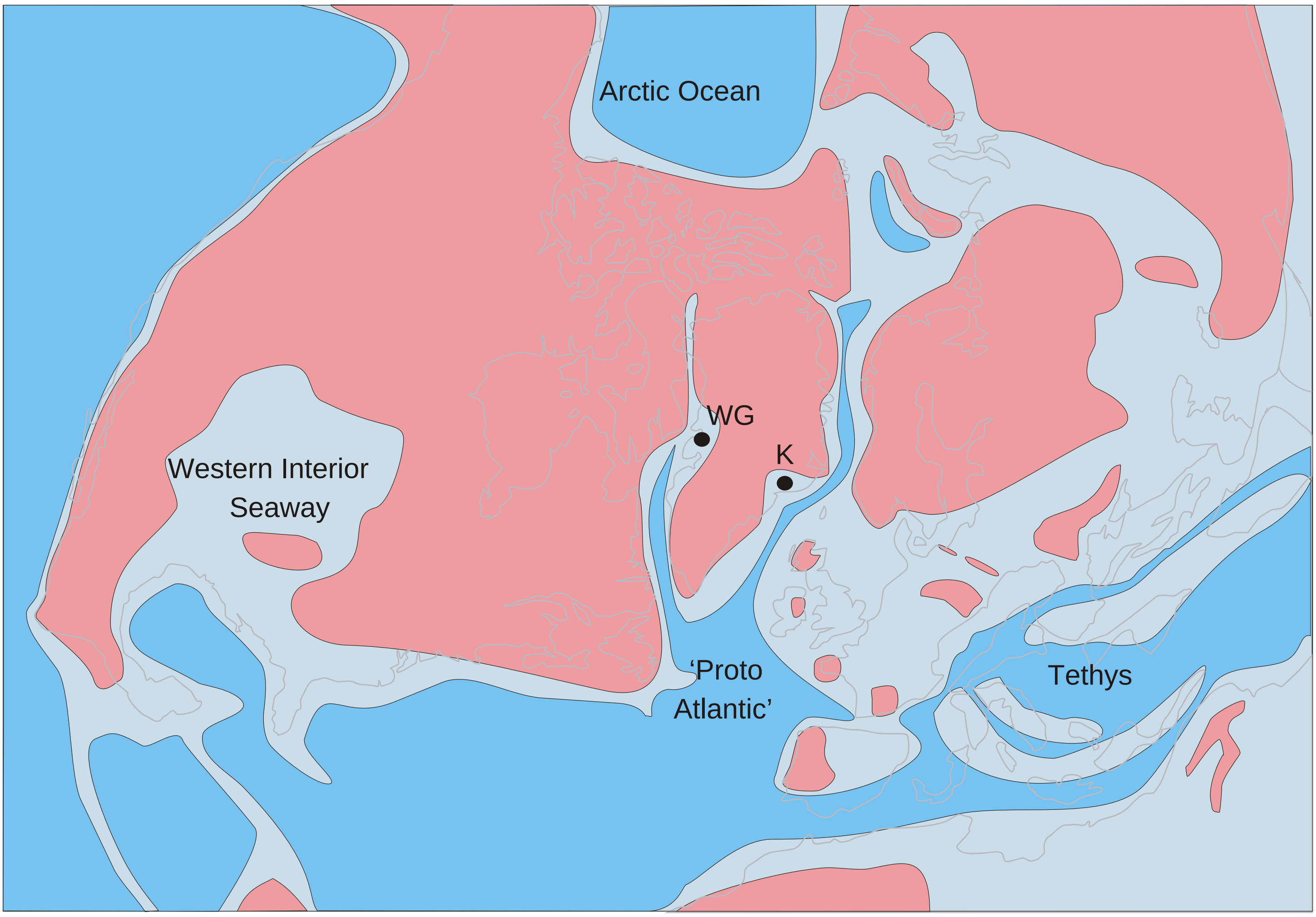
Maastrichtian ammonite faunas in Greenland.

The ammonite faunas discussed below in ascending order are suggested within the Maastrichtian of Greenland. Of principal importance are the scaphitids which demonstrate sexual dimorphism: large macroconchs (M) and smaller microconchs (m). The following associations may be suitable to form zones (see Fig. 12).

***Acanthoscaphites tridens* (Kner)**

This study has revealed for the first time the presence of *Acanthoscaphites tridens* (Kner) in the lower part of the Christian IV Formation in the Kangerlussuaq area, where it occurs as both macroconchs and microconchs. This ammonite occurs in a broad assemblage containing *Anagaudryceras* cf. *lueneburgense* (Schlüter), *Pachydiscus (Pachydiscus)* sp., *Jeletzkites* sp., *Baculites* sp. and *Diplomoceras cylindraceum* (Defrance). It indicates a previously unknown Greenland ammonite fauna which lies stratigraphically between the Late Campanian *Hoploscaphites greenlandicus* fauna of Donovan (1953) and the *Discoscaphites angmartussutensis* fauna of Birkelund (1965).

Figure 13. *Maastrichtian palaeogeography showing relative positions of the Greenland faunas (K=Kangerlussuaq; WG=West Greenland) with respect to the Western Interior seaway and Tethys (Reconstruction modified from Lawver et al. 2002 and University of Chicago 'Paleogeographic Atlas Project'; Embry, 1991; Roberts & Kirshbaum, 1995; Scott, 1984)*


Arctic Ocean
Western Interior Seaway
WG
K
'Proto Atlantic'
Tethys

In NW Europe the standard Early Maastrichtian ammonite zone is that of *Pachydiscus neubergicus* which ranges throughout the substage. Hancock (in Gradstein *et al.* 1995) referred to this zone as that of *Pachydiscus neubergicus/Acanthoscaphites tridens?*. However, Niebuhr (2003) demonstrated that the known range of *A. tridens* in NW Europe is only from the *Belemnitella lanceolata* to the top of the *Belemnella sumensis* Zones. Thus the species can only be used for the early to middle part of the Early Maastrichtian and not for equivalents of the *Belemnella cimbrica* and *B. fastigata* Zones. Most of the Kangerlussuaq occurrences, which have also been dated palynologically, fall into the *Cerodinium diebelii* Zone (Fig. 12). At Skiferbjerg, the lowest occurrence of *A. tridens* is in the *Alterbidinium acutulum* Subzone and the highest occurrence is in close association with the appearance of *D. angmartussutensis*, in the lower part of the *Wodehouseia spinata* Zone, *W. spinata* Subzone. Closely associated material from locality K7512 also suggests an association of *A. tridens* and *D. angmartussutensis.* However, these specimens were collected in float in and may represent more than one horizon within a few metres of each other.

An important macrofossil associated with *A. tridens* is the inoceramid bivalve *Spyridoceramus tegulatus*. In northern Europe *S. tegulatus* was recorded ranging from the Early Maastrichtian *Belemnitella obtusa* Zone into the *Belemnitella junior* Zone in the early part of the Late Maastrichtian (e.g. Abdel-Gawad 1986). *S. tegulatus* also occurs in association with *D. angmartussutensis* in the Christian IV Formation, where it is of Late Maastrichtian age (see comments under *D. angmartussutensis)*. Another important accessory macrofossil is the small the pectinid bivalve *Mimachlamys cretosus* subsp. *denticulata* (von Hagenow) which is recorded in Greenland for the first time but which Dhondt (1973) described from the Early Maastrichtian Schreibkreide of northern Europe.

***Discoscaphites angmartussutensis* Birkelund**

In West Greenland *D. angmartussutensis* was originally described from the 'Oyster-Ammonite Conglomerate' (Birkelund 1965). Two reworked faunas are represented in this bed. The first fauna contains *D. angmartussutensis*, *Neophylloceras groenlandicum* Birkelund, *Saghalinites wrighti* (Birkelund) and *Pseudophyllites* sp. whereas the second reworked fauna contains *Hoploscaphites greenlandicus* Donovan (1953), the last known Campanian ammonite fauna known from both East and West Greenland.

D. angmartussutensis occurs *in situ* in the upper part of the Christian IV Formation (CASP Collections). At the base of the formation it overlaps with *Acanthoscaphites tridens* and is associated with the *Wodehouseia spinata* Zone, ranging from the *W. spinata* to the *Alisocysta circumtabulata* Subzones at Skiferbjerg (Fig. 12; see Nøhr-Hansen *et al.* 2006). Other ammonites found in the Christian IV Formation include *Neophylloceras groenlandicum* Birkelund, *Saghalinites wrighti* (Birkelund), *Pseudophyllites* sp., *Anagaudryceras politissimum* (Kossmat), *Baculites* sp. and *Diplomoceras cylindraceum* (Defrance).

Machalski (2005, p. 690) recorded *Hoploscaphites* sp. ex. gr. *waagei-angmartussutensis* from the mid *Spyridoceramus tegulatus/Belemnitella junior* Zone to the end of the *B. kazimirovsiensis* Zone, i.e. almost throughout the whole of the Late Maastrichtian in the Netherlands, Poland and Denmark.

An important macrofossil associated with *H. angmartussutensis* is the inoceramid bivalve *Spyridoceramus tegulatus* (see occurrence with *A. tridens* above). It is also known from

West Greenland (as *Inoceramus* aff. *fibrosus*, e.g. Birkelund 1965) where it also occurs in association with *H. angmartussutensis*.

***Discoscaphites* aff. *angmartussutensis* (Birkelund)**

Discoscaphites aff. *angmartussutensis* was stated by Birkelund (1965) to occur stratigraphically below the 'Oyster Ammonite Conglomerate', but it was shown by Kennedy *et al.* (1999) to occur above, so it represents the highest ammonite occurrence in West Greenland. For comparison to European material see discussion of *D. angmartussutensis* above.

Maastrichtian palynology

Based on palynological events, two zones and eight subzones have been recognised in the Maastrichtian Christian IV Formation (Fig. 14).

The lower zone correlates with the *Cerodinium diebelii* interval described from the Early Maastrichtian in West Greenland (Nøhr-Hansen 1996). The lower part of the *Cerodinium diebelii* interval correlates with the *Alterbidinium acutulum* Subzone (Fig. 14) described from the Early Maastrichtian in the Danish part of the North Sea by Schiøler & Wilson (1993). The upper zone correlates with the *Wodehouseia spinata* interval described from the Late Maastrichtian in West Greenland (Nøhr-Hansen 1996). The absence of the uppermost Maastrichtian *Palynodinium grallator* Zone (Fig.12) reported from the North Sea (Schiøler & Wilson, 1993) and West Greenland (Nøhr-Hansen & Dam 1997) indicates a hiatus spanning the K/T boundary.

According to Ogg *et al.* (in Gradstein *et al.* 2004) is it still debated where to place the boundary between the Early and Late Maastrichtian. A discussion of the discrepancies between the palynological and macrofossil dating of the Maastrichtian succession from the Kangerlussuaq area has been presented above and in Nøhr-Hansen *et al.* (2006).
From the 'Skiferbjerg 2004' section Kelly & Whitham (in Nøhr-Hansen *et al.* 2006) recorded the presence of the bivalve *Spyridoceramus tegulatus*, suggesting an Early Maastrichtian age, approximately 30 m above the first record of the palynological upper Maastrichtian marker (*Wodehouseia spinata*). However, *Spyridoceramus tegulatus* ranges from the Early Maastrichtian into the early part of the Late Maastrichtian in northern Europe according to Abdel-Gawad (1986; see above).

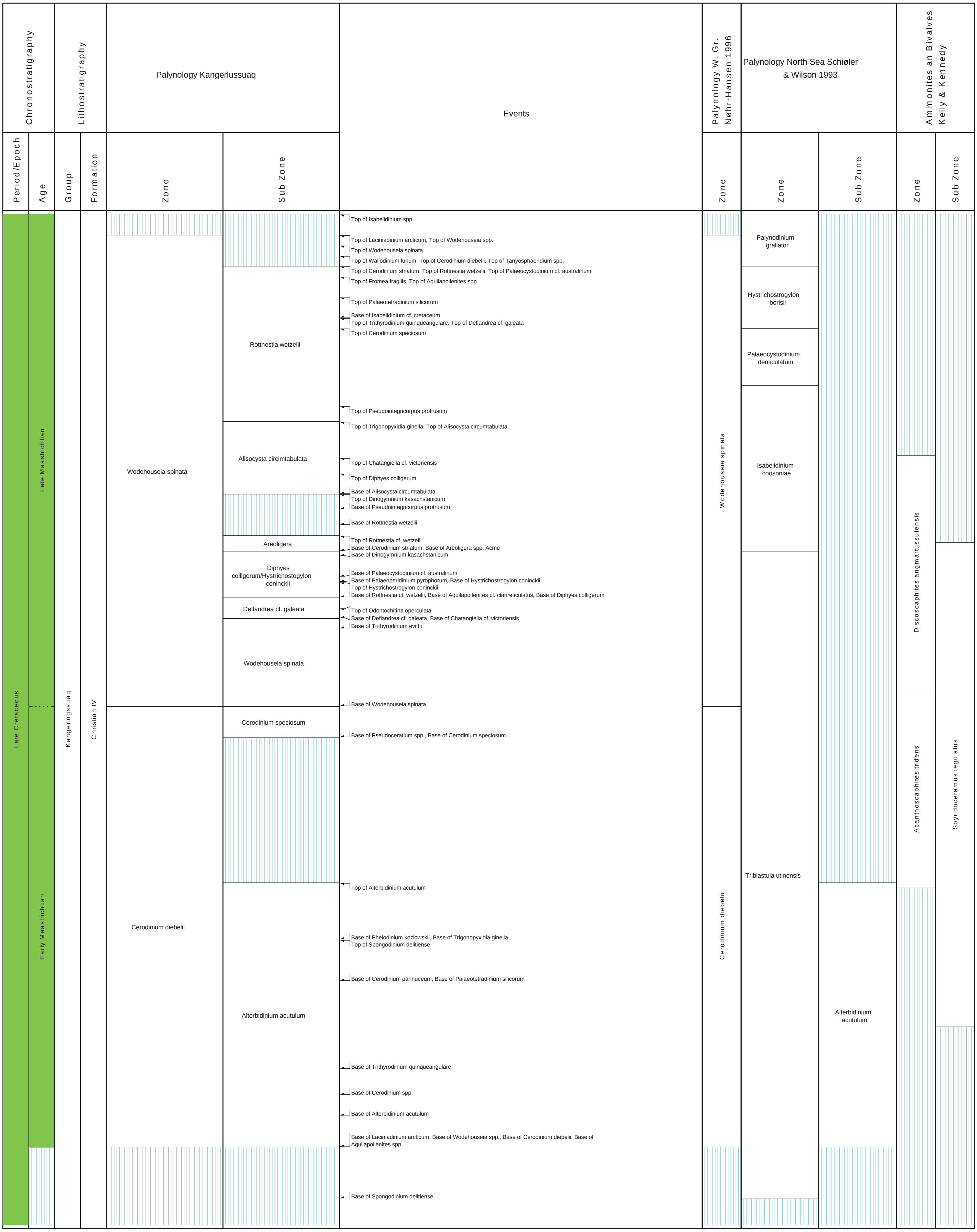
Nichols & Sweet (1993) recorded the first occurrence (FO) of *Wodehouseia spinata* at the base of Upper Maastrichtian in the Western Interior Basin (Fig. 13). They mentioned that the lowest occurrence in the central part of the basin of *Wodehouseia spinata* occurred in the ammonite zone of *Hoploscaphites* aff. *H. nicolleti* (Fig. 12) in Montana and in the equivalent *Sphenodiscus* Zone in Wyoming, whereas it ranges as low as strata just above the *Sphenodiscus* Zone or possibly as low as the underlying ammonite *Baculites clinolobatus* Zone in the southern part of the basin, Colorado (Fig. 12). The lowest occurrence of the ammonite *Hoploscaphites birkelundi* (formerly *Hoploscaphites* aff. *H. nicolleti*) is, according to Ogg *et al.* (in Gradstein *et al.* 2004) an informal marker for the base of the Late Maastrichtian in the Western Interior and they illustrated that the *Baculites clinolobatus* Zone occured just below the informal Early-Late Maastrichtian boundary, indicating that the possible occurrence of *Wodehouseia spinata* in the ammonite *Baculites clinolobatus* Zone (Fig. 12) in Western Interior may represent a FO of latest Early Maastrichtian age. Srivastava (1970) originally erected the *Wodehouseia spinata* Zone for the Late Maastrichtian in Alberta, Canada and subdivided the zone into three subzones. However, Catuneanu & Sweet (1999) erected a fourth subzone in the lowermost part of the *Wodehouseia spinata* Zone and suggested a latest Early Maastrichtian age for the new Subzone A. The Subzone A was recognised by the presence and co-occurrence of *Wodehouseia spinata* and *Scollardia trapaformis*, the general absence of other taxa typical of early Late Maastrichtian age and a reverse polarity chron (30r).

The discussion above indicates that the lower part of the *Wodehouseia spinata* interval (the *Wodehouseia spinata* sub-interval) from the Kangerlussuaq area may be of latest Early Maastrichtian age. However, it has tentatively been dated as Late Maastrichtian (Fig. 14) based on the presence of *Wodehouseia spinata* and by the general absence of spores and pollen, especially the lower Maastrichtian marker *Scollardia trapaformis.* The younger *Deflandrea* cf. *galeata* sub-interval could bee of latest Early Maastrichtian age as Kirsch (1991) recorded the FO of *Deflandrea galeata* from the middle Maastrichtian. The overlying *Diphyes colligerum-Hystrichostrogylon coninckii* sub-interval, however, strongly suggest a Late Maastrichtian age (Fig. 14) based on the presence of several Late Maastrichtian marker species. Evidence that the bivalve *Spyridoceramus tegulatus* ranges into the early Late Maastrichtian (Figs 9, 10, 12) suggests that the co-occurrence of *Wodehouseia spinata* and *Spyridoceramus tegulatus* may indicate an early Late Maastrichtian age.

An event of pronounced reworked specimens of Albian–Cenomanian age (*Rhombodella paucispinosa* and *Chlamydophorella nyei*) and of Campanian age (*Isabelidinium microarmum*) is present in the Maastrichtian Christian IV Formation.

Evidence from the palynological study of the Christian IV Formation from a section at Sequoia Nunatak by Jolley & Whitham (2004b) supports the present Maastrichtian dating.

Figure 14. *Maastrichtian, Upper Cretaceous palynological event and biozonation and macro biozonation of the Kangerlussuaq Basin correlated palynological zonations from West Greenland and the North Sea.*

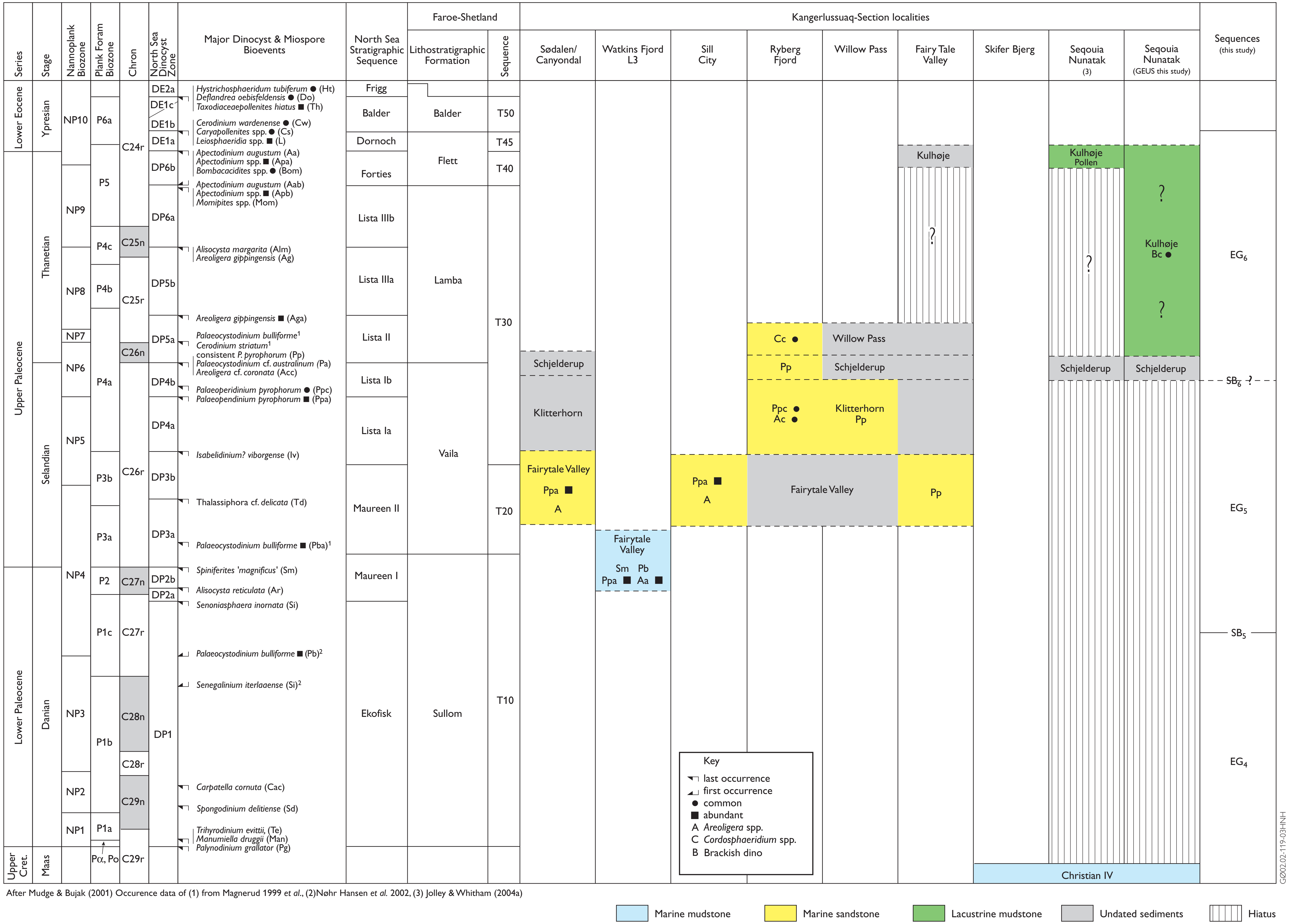

Chronostratigraphy
Lithostratigraphy
Palynology Kangerlussuaq
Events
Palynology W. Gr. Nøhr-Hansen 1996
Palynology North Sea Schiøler & Wilson 1993
Ammonites an Bivalves Kelly & Kennedy
Period/Epoch
Age
Group
Formation
Zone
Sub Zone
Zone
Zone
Sub Zone
Zone
Sub Zone
Late Cretaceous
Late Maastrichtian
Early Maastrichtian
Kangerlugssuaq
Christian IV
Wodehouseia spinata
Cerodinium diebelii
Rottnestia wetzelii
Alisocysta circimtabulata
Areoligera
Diphyes colligerum/Hystrichostogylon coninckii
Deflandrea cf. galeata
Wodehouseia spinata
Cerodinium speciosum
Alterbidinium acutulum
Top of Isabelidinium spp.
Top of Laciniadinium arcticum, Top of Wodehouseia spp.
Top of Wodehouseia spinata
Top of Wallodinium lunum, Top of Cerodinium diebelii, Top of Tanyosphaeridium spp.
Top of Cerodinium striatum, Top of Rottnestia wetzelii, Top of Palaeocystodinium cf. australinum
Top of Fromea fragilis, Top of Aquilapollenites spp.
Top of Palaeotetradinium silicorum
Base of Isabelidinium cf. cretaceum
Top of Trithyrodinium quinqueangulare, Top of Deflandrea cf. galeata
Top of Cerodinium speciosum
Top of Pseudointegricorpus protrusum
Top of Trigonopyxidia ginella, Top of Alisocysta circumtabulata
Top of Chatangiella cf. victoriensis
Top of Diphyes colligerum
Base of Alisocysta circumtabulata
Top of Dinogymnium kasachstanicum
Base of Pseudointegricorpus protrusum
Base of Rottnestia wetzelii
Top of Rottnestia cf. wetzelii
Base of Cerodinium striatum, Base of Areoligera spp. Acme
Base of Dinogymnium kasachstanicum
Base of Palaeocystodinium cf. australinum
Base of Palaeoperidinium pyrophorum, Base of Hystrichostrogylon coninckii
Top of Hystrichostrogylon coninckii
Base of Rottnestia cf. wetzelii, Base of Aquilapollenites cf. clarireticulatus, Base of Diphyes colligerum
Top of Odontochitina operculata
Base of Deflandrea cf. galeata, Base of Chatangiella cf. victoriensis
Base of Trithyrodinium evittii
Base of Wodehouseia spinata
Base of Pseudoceratium spp., Base of Cerodinium speciosum
Top of Alterbidinium acutulum
Base of Phelodinium kozlowskii, Base of Trigonopyxidia ginella
Top of Spongodinium delitiense
Base of Cerodinium pannuceum, Base of Palaeotetradinium silicorum
Base of Trithyrodinium quinqueangulare
Base of Cerodinium spp.
Base of Alterbidinium acutulum
Base of Laciniadinium arcticum, Base of Wodehouseia spp., Base of Cerodinium diebelii, Base of Aquilapollenites spp.
Base of Spongodinium delitiense
Wodehouseia spinata
Cerodinium diebelii
Palynodinium grallator
Hystrichostrogylon borisii
Palaeocystodinium denticulatum
Isabelidinium coosoniae
Triblastula utinensis
Alterbidinium acutulum
Discoscaphites angmartussutensis
Acanthoscaphites tridens
Spyridoceramus tegulatus

Developments in Palaeogene palynostratigraphy

Mudstone and fine-grained sandstone samples from the Kangerlussuaq Basin have been processed and their dinoflagellate cyst, spore and pollen contents analysed (Fig. 15). Most sections have a low recovery due to the intense heating by Palaeogene intrusions. However, the following important observations have been made:

- A marked decrease in marine species diversity and abundance occurs across the boundary between the Christian IV Formation (Maastrichtian) and Fairytale Valley Member (Paleocene). This may indicate a change in basin configuration leading to restricted marine circulation. Similar changes are observed in wells of the Faroe-Shetland area and the change may have been a regional North Atlantic event.
- Detailed studies of the upper part of the Kangerlussuaq succession have made it possible to subdivide the Paleocene succession in Kangerlussuaq. Most of the Early Danian interval is absent, this corresponds to the development of unconformities in the marginal areas of the Faroe-Shetland Basin.
- Based on the few and thermally affected dinoflagellate cysts it has been possible to correlate the lower part of the Sediment Bjerge Formation (lower part of the Fairytale Valley Member at Watkins Fjord section, Fig 15) with the Late Danian *Palaeocystodinium bulliforme* Zone described from the Late Danian in West Greenland by Nøhr-Hansen *et al.* (2002; see Figs 16, 17). The upper part of the Zone is correlated with the *Spiniferites magnificus* Subzone which Mudge & Bujak (1996) described from the latest Danian in the North Sea.
- Dating of the Late Danian to Selandian deep marine Fairytale Valley Member and its correlation with the Vaila Formation (Fig. 20) is based on the consistent occurrence of the dinoflagellate species *Palaeoperidinium pyrophorum.* In the Fairytale Valley Member *Areoligera* spp*.* and *Palaeoperidinium pyrophorum* are common throughout the succession and continue up in the shallow marine Klitterhorn Member (Fig. 15), indicating that the Sediment Bjerge Formation is no younger than latest Selandian (*Palaeoperidinium pyrophorum* Zone DP4 of Mudge & Bujak 1996, 2001; Figs 15, 17). This age determination suggests correlation with NP5 and with the top of sequence T20 or lower part T30 of Ebdon *et al.* (1995; Fig. 15). The age is confirmed by Jolley & Whitham (2004b) who suggested correlation of the Fairytale Member with T22 (TPaMFS60–TPaMFS75 interval from the Faroe-Shetland Basin).

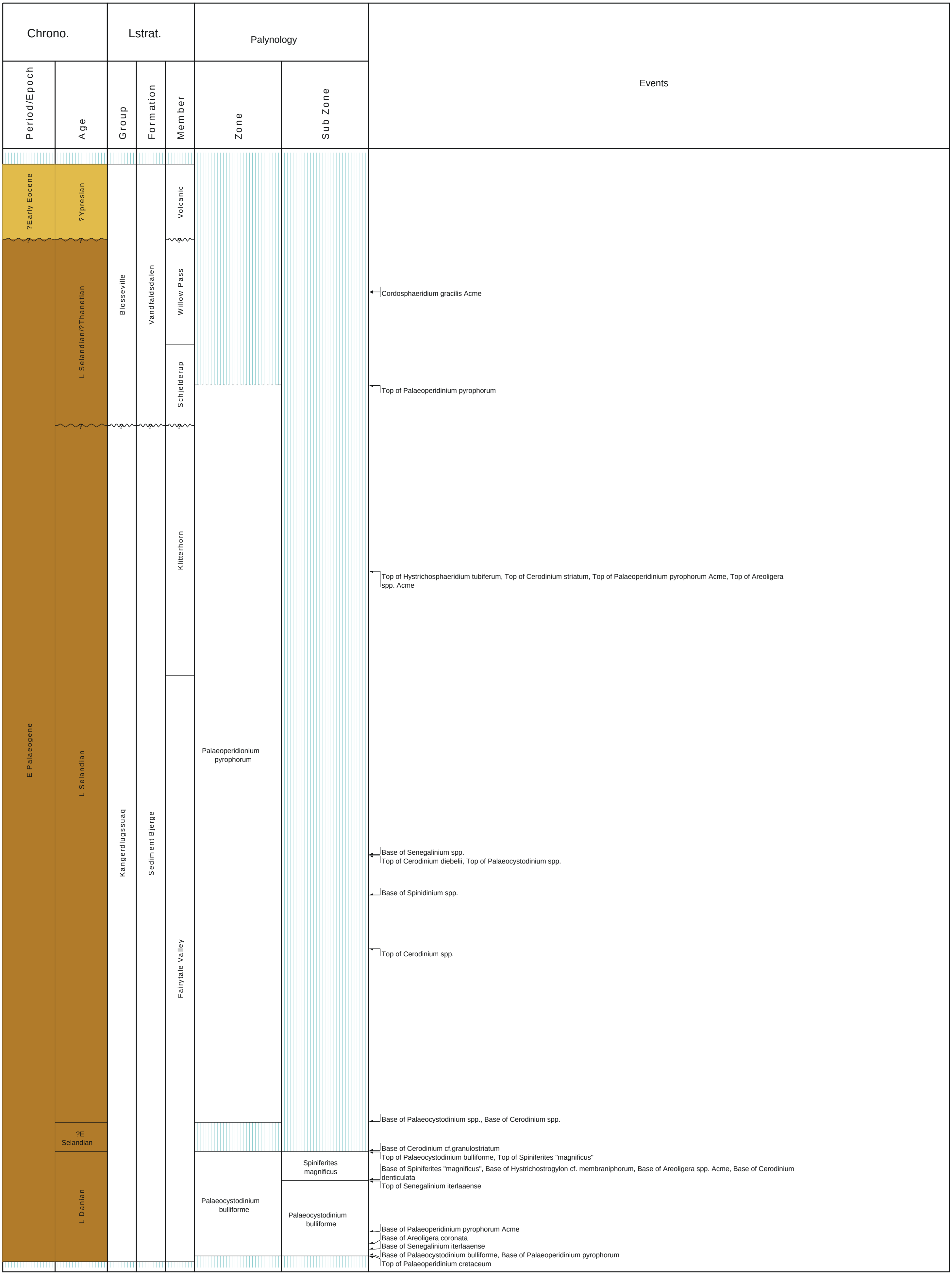
Figure 15. *Palynostratigraphy of the Palaeogene sections of the Kangerlussuaq Basin. The sections are dated using the composite event charts of West Greenland, the Faroe-Shetland region and the North Sea.*



After Mudge & Bujak (2001) Occurence data of (1) from Magnerud 1999 *et al.*, (2)Nøhr Hansen *et al.* 2002, (3) Jolley & Whitham (2004a)

- New information from the Rybjerg Fjord section (Fig. 17) suggests that at least part of the Schjelderup Member and perhaps the Willow Pass Member (lower part of the Vandfaldsdalen Formation) is of latest Selandian / earliest Thanetian age whereas the Kulhøje Member may be within the Selandian/Thanetian to latest Thanetian / ?earliest Ypresian age range (see description and discussion below).
- The onset of volcanism in East Greenland has previously been constrained by an intrabasaltic mudstone containing the dinoflagellate cyst *Wetzeliella* (now *Apectodinium sp.*; Soper *et al.* 1976). The *Wetzeliella* flora indicates an early Sparnacian age (Soper *et al.* 1976) corresponding the Ypresian (Early Eocene). The original sample material has, however, not been available to the present project and the determination is solely based on the published description. An attempt in 2004 to resample the section and inaccurate descriptions of the original sample location. The Early Eocene (T40) age was later supported by Jolley & Whitham (2004a, b) based on samples from the Kulhøje Member and correlation with North-East Greenland flora assemblages. The bloom of *Apectodinium* spp. and the presence of *Apectodonium augustum* in the North Atlantic region are attributed to the Late Paleocene Thermal Maximum (LPTM), which marks the boundary between the Paleocene and the Eocene. It should be noted that the species *Apectodinium augustum* has not been described in sample material from Kangerlussuaq and the T40 age is based on correlation of the pollen *Caryapollenites veripites* and *Alnipollenites verus* with sections in North-East Greenland containing the *Apectodinium augustum* (Jolley & Whitham 2004a).
- Two models are presented for the onset of volcanism in southern East Greenland.

Figure 16. *Paleocene palynological event and biozonation of the Kangerlussuaq Basin*.


Chrono.
Lstrat.
Palynology
Events
Period/Epoch
Age
Group
Formation
Member
Zone
Sub Zone
?Early Eocene
?Ypresian
Volcanic
E Palaeogene
L Selandian/?Thanetian
Blosseville
Vandfaldsdalen
Willow Pass
Schjelderup
Klitterhorn
L Selandian
Kangerdlugssuaq
Sediment Bjerge
Fairytale Valley
?E Selandian
L Danian
Palaeoperidionium pyrophorum
Palaeocystodinium bulliforme
Spiniferites magnificus
Palaeocystodinium bulliforme
Cordosphaeridium gracilis Acme
Top of Palaeoperidinium pyrophorum
Top of Hystrichosphaeridium tubiferum, Top of Cerodinium striatum, Top of Palaeoperidinium pyrophorum Acme, Top of Areoligera spp. Acme
Base of Senegalinium spp.
Top of Cerodinium diebelii, Top of Palaeocystodinium spp.
Base of Spinidinium spp.
Top of Cerodinium spp.
Base of Palaeocystodinium spp., Base of Cerodinium spp.
Base of Cerodinium cf.granulostriatum
Top of Palaeocystodinium bulliforme, Top of Spiniferites "magnificus"
Base of Spiniferites "magnificus", Base of Hystrichostrogylon cf. membraniphorum, Base of Areoligera spp. Acme, Base of Cerodinium denticulata
Top of Senegalinium iterlaaense
Base of Palaeoperidinium pyrophorum Acme
Base of Areoligera coronata
Base of Senegalinium iterlaaense
Base of Palaeocystodinium bulliforme, Base of Palaeoperidinium pyrophorum
Top of Palaeoperidinium cretaceum

Rybjerg Fjord and 'Sequoia Nunatak' sections (new palynological data)

The stratigraphically youngest succession containing marine dinoflagellate cysts is exposed at Rybjerg Fjord (Fig. 17). The Sediment Bjerge Formation is represented by the Fairytale Valley Member (27 m) and the Klitterhorn Member (58 m) unconformably overlain by the Vandfaldsdalen Formation, which is represented by the Schjelderup Member (14 m), the Willow Pass Member (18 m) and unnamed volcanic rocks.

A sample (455426) from the middle part of the Klitterhorn Member contains common *Palaeoperidinium pyrophorum* and common *Areoligera* spp. indicating an age not younger than latest Selandian (the *Palaeoperidinium pyrophorum* Zone DP4 of Mudge & Bujak 1996, 2001; Figs 15, 17).

The very poor preservation state of organic walled fragments recorded from samples from the Schjelderup and Willow Pass Members make species identification almost impossible. However, new studies of a sample (455448) from the middle part of the Schjelderup Member revealed fragments of *Palaeoperidinium pyrophorum* suggesting that at least part of the Schjelderup Member is of latest Selandian age.

The presence of common *Cordosphaeridium* sp. fragments, possible *Cordosphaeridium gracilis* in the uppermost sample (455439) from the Willow Pass Member (Figs 15, 17), may suggest a Selandian or questionable a Thanetian age.

Hjortkjær & Jolley (1999) correlated the non-marine Kulhøje palynoflora with palynoassociations from the Lamba Formation (T36) and the lower and mid Flett formation (T40) in the Faroe-Shetland basin. D.J. McIntyre (in Larsen *et al.* 2005b) described the palynology of Kulhøje Member from 'Sequoia Nunatak' (Kulhøje area) and suggested a Paleocene age based on spores and pollen. D.J. McIntyre recorded abundant bisaccate pollen especially from the lower part of the section and mentioned that the freshwater algae *Pediastrum* occurs in most samples, whereas no evidence of any marine algal types (including dinoflagellate cysts) was recorded. Re-examination of the Kulhøje Member samples have illustrated that the bisaccate pollen peak in the lower part (samples 84-132 to 84-135) is followed by abundant *Pediastrum* specimens (samples 84-136 to 84-137) whereas common specimens of the dinoflagellate cyst Gen et. sp. indet. of Piasecki *et al.* (1992) occur in the middle part (sample 84-137). The new record of Gen et. sp. indet. is interesting as it is regarded to be a fresh to brackish water indicator; it was first recorded from shale clasts in subaqueous volcanic breccias from the lower Rinksdal Member in West Greenland (Piasecki *et al.* 1992), dated as 60.5 ± 0.4 Ma by $^{40}Ar/^{39}Ar$ measurements (Storey *et al*. 1998) suggesting a Selandian age. Later the species has been recorded common in some offshore wells of eastern Canada (Nøhr-Hansen unpublished data 2006) in sediment just above the *Apectodinium* sp. maximun (latest Thanetan; Fig. 15). The new record indicates that the Gen et. sp. indet. species range from Selandian to latest Thanetian / ?earliest Ypresian and that the age of the Kulhøje Member is within that range; however, the data are not conflicting with the Thanetian age (T36 and T40) by Hjortkjær & Jolley (1999) or with the late Thanetian, latest Paleocene / early Ypresian, earliest Eocene age (late T40) by Jolley & Whitham (2004b) based on the study of the Kulhøje section.

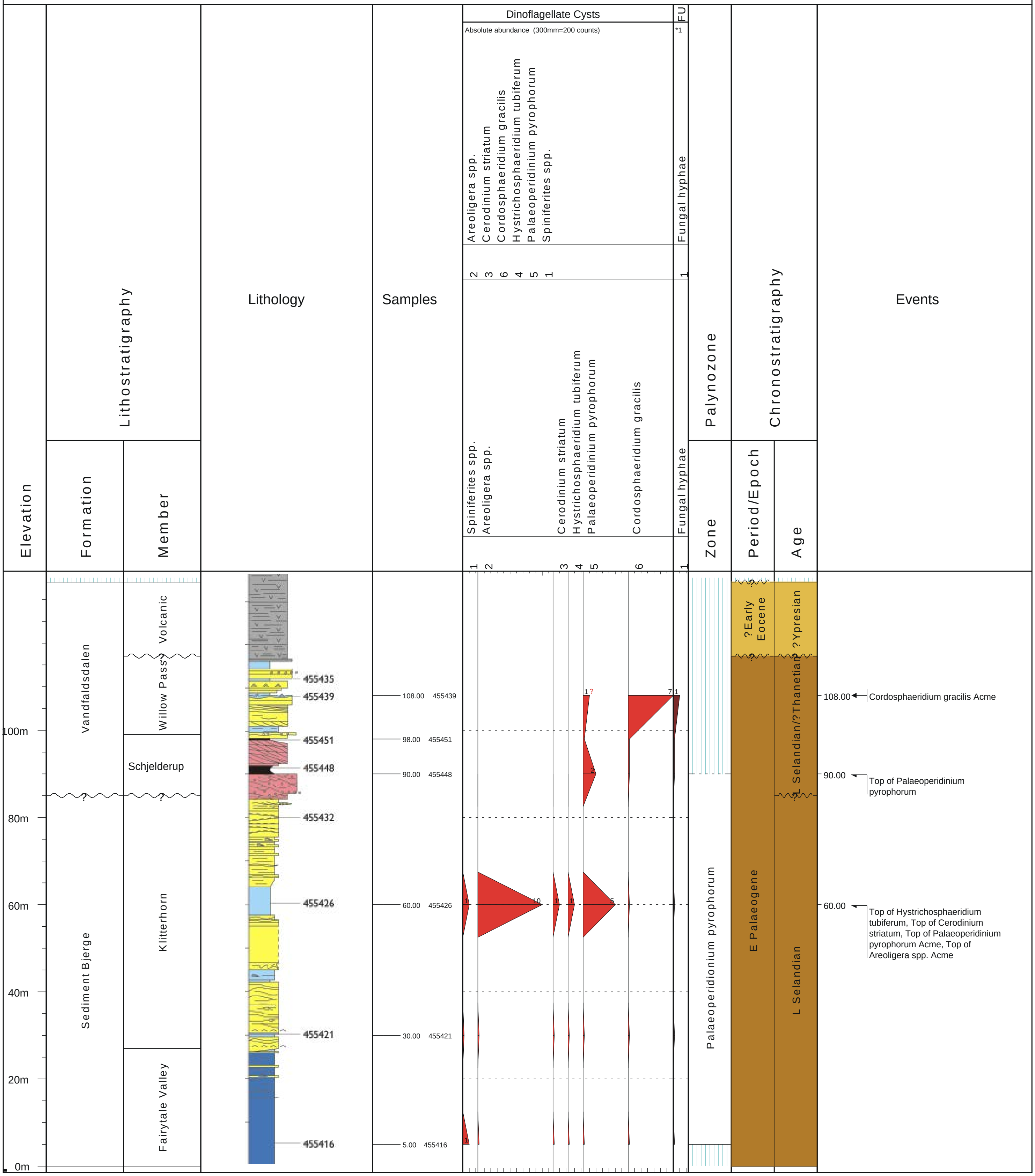
Figure 17. *Range chart for the palynomorphs of the Sediment Bjerge and Vandfaldsdalen Formations at the Rybjerg Fjord section.*

Section : Rybjerg Fjord

Interval : 135m - 0m

Scale : 1:1000

Chart date : 06 February 2007



Discussion of the palynological dating of the Vandfaldsdalen Formation

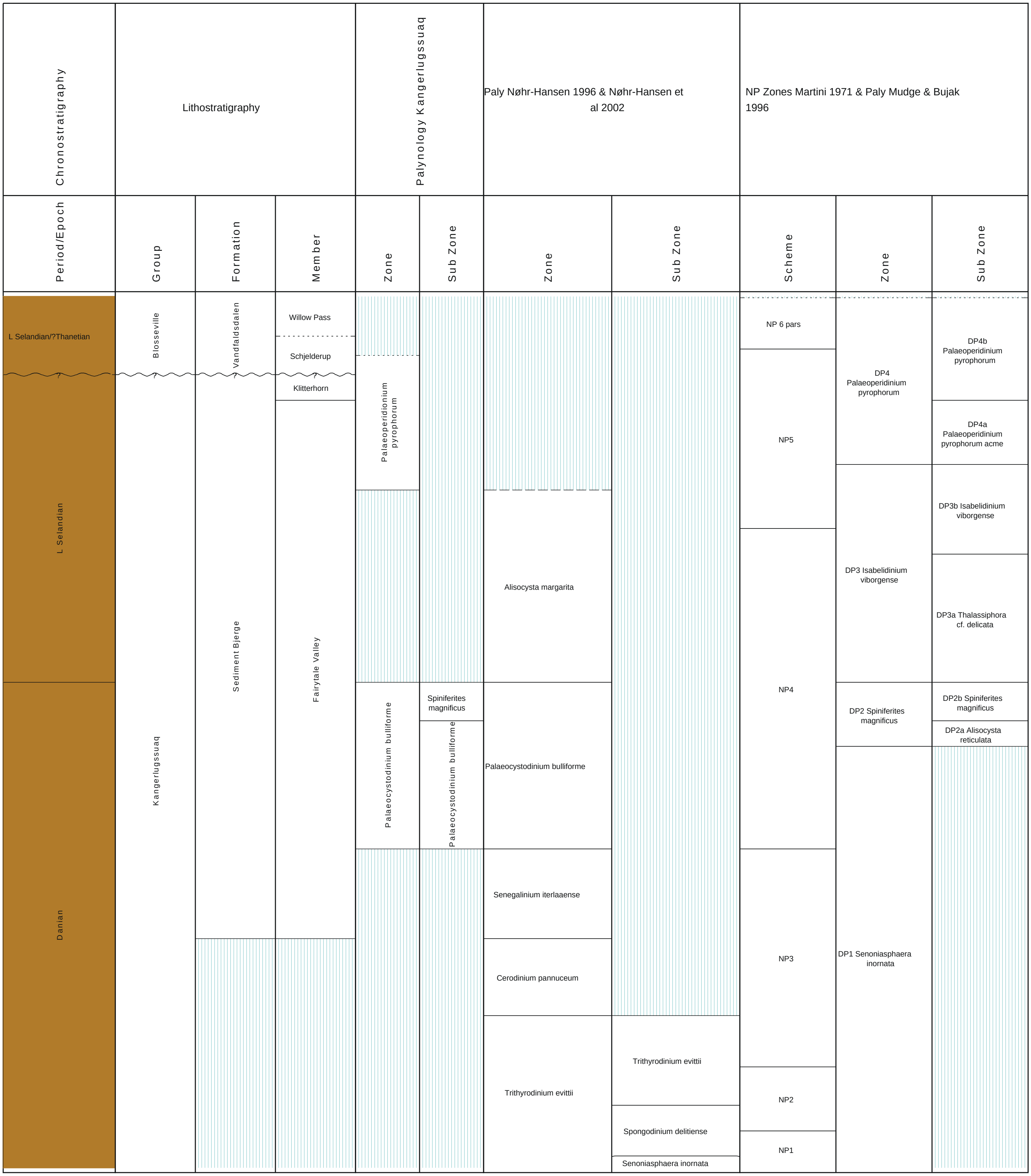
Jolley & Whitham (2004a) previously dated their Unit 1 or ‘Upper’ Rybjerg Formation (now Sediment Bjerge Formation) in the Sorgenfri/W4218 section and the Pyramiden/W4229 section as T40 (late Thanetian) based on common *Caryapollenites veripites* and *Alnipollenites verus.* According to Jolley & Whitham (2004a) *Caryapollenites veripites* has its first appearance in NW Europe at the T38/T40 boundary and common to abundant occurrence of this taxon is restricted to the T40 interval succeeding the Late Paleocene Thermal Maximum (LPTM). The Kulhøje Member also included palynofloras typical of T40 interval (Jolley & Whitham 2004a). Based on the presence of *Caryapollenites veripites* and *Alnipollenites verus* Jolley & Whitham (2004a) dated the Sediment Bjerge and Vandfaldsdalen Formations (not specified into members) as Late Thanetian (upper part of T40).

Larsen *et al.* (2005a, b) and Nøhr-Hansen (unpublished data 2004) recorded the presence of Selandian dinoflagellate cysts from the Fairytale Valley Member (lower part of the Sediment Bjerge Formation) at Sødalen. This age was after a re-examination of samples provided by GEUS confirmed by Jolley & Whitham (2004b), who correlated the Sediment Bjerge Formation to T22 or to the TPaMFS60–TPaMFS75 interval.

The present study of the Rybjerg Fjord section (Fig. 17) suggests that the Klitterhorn Member (upper part of Sediment Bjerge Formation) and the Schjelderup Member (basal unit of the Vandfaldsdalen Formation) are not younger than Late Selandian and that the Willow Pass Member (middle part Sediment Bjerge Formation) may be of Selandian or Thanetian age.

The present record of fragments of *Palaeoperidinium pyrophorum* in the Schjelderup Member suggests a hiatus between this member (T22) and the overlying Kulhøje Member dated as Thanetian (T36 and T40) by Hjortkjær & Jolley (1999) and Late Thanetian (T40 or TPaMFA130–TPaMFS150) by Jolley & Whitham (2004a, b). The possibility mentioned above that the Willow Pass Member may also be of Selandian or questionable Thanetian age suggests that a shorter hiatus may be situated in the middle of the Vandfalsdalen Formation between the Willow Pass and Kulhøje Members. A third explanation could be that the non-marine to brackish-water Kulhøje Member palynoflora is Selandian / earliest Thanetian in age and that the first occurrence of *Caryapollenites veripites* could be diacronous. This possibility is indicated by its record from the ‘Upper’ Rybjerg Formation (Jolley & Whitham 2004a) and from the Vandfaldsdalen Formation (Jolley & Whitham 2004b). Furthermore the new brackish-water dinoflagellate cyst data obtained during the re-examination of the Kulhøje Member (see above), suggest an age within the Selandian to latest Thanetian / ?earliest Ypresian range (Fig. 15). A Selandian age of the Vandfaldsdalen Formation is in accordance with the earliest dating (61 Ma) of basaltic volcanism in southern East Greenland (Hansen *et al.* 2002), and may be supported by resent dating of the Nansen Fjord Formation to 59.2 ± 1.4 and 57.7 ± 0.5 Ma by $^{40}Ar/^{39}Ar$ (Storey *et al. In Press*).

Figure 18. *Paleocene palynological biozonation of the Kangerlussuaq Basin correlated palynological zonations from West Greenland and the North Sea.*

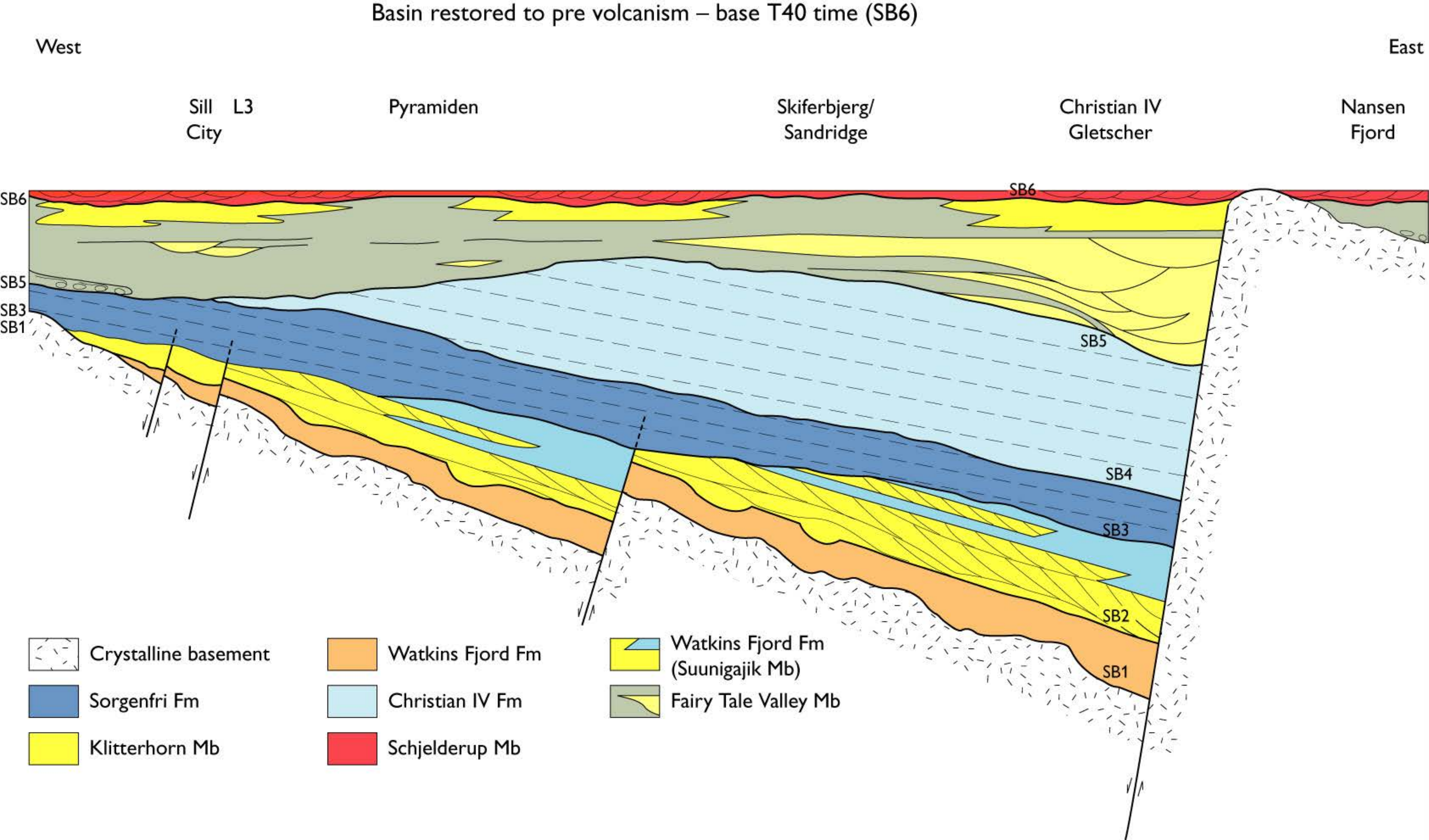

Chronostratigraphy
Lithostratigraphy
Palynology Kangerlugssuaq
Paly Nøhr-Hansen 1996 & Nøhr-Hansen et al 2002
NP Zones Martini 1971 & Paly Mudge & Bujak 1996
Period/Epoch
Group
Formation
Member
Zone
Sub Zone
Zone
Sub Zone
Scheme
Zone
Sub Zone
L Selandian/?Thanetian
L Selandian
Danian
Blosseville
Kangerlugssuaq
Vandfaldsdalen
Sediment Bjerge
Willow Pass
Schjelderup
Klitterhorn
Fairytale Valley
?
Palaeoperidionium pyrophorum
Palaeocystodinium bulliforme
Spiniferites magnificus
Palaeocystodinium bulliforme
Alisocysta margarita
Palaeocystodinium bulliforme
Senegalinium iterlaaense
Cerodinium pannuceum
Trithyrodinium evittii
Trithyrodinium evittii
Spongodinium delitiense
Senoniasphaera inornata
NP 6 pars
NP5
NP4
NP3
NP2
NP1
DP4 Palaeoperidinium pyrophorum
DP3 Isabelidinium viborgense
DP2 Spiniferites magnificus
DP1 Senoniasphaera inornata
DP4b Palaeoperidinium pyrophorum
DP4a Palaeoperidinium pyrophorum acme
DP3b Isabelidinium viborgense
DP3a Thalassiphora cf. delicata
DP2b Spiniferites magnificus
DP2a Alisocysta reticulata

Basin evolution and tectonic phases

The succession in the Kangerlussuaq region has been divided into six unconformity-bounded units (sequences) that form the basis for interpretation of basin evolution and tectonic phases (Fig.19). In summary the main events are:

- Transgression and onlap of the undulating crystalline basement surface (SB1) in the Barremian. Deposition of coarse-grained fluvial sandstones with locally derived source areas (Torsukáttak Member).
- Relative sea-level fall (SB2) in the Early Albian followed by progradation of fluvial and deltaic systems (Suunigajik Member).
- Mid- to Late Albian tectonic phase with minor block rotation and formation of (local) angular unconformity (SB3).
- Widespread and uniform marine, mud-dominated, deposition (Sorgenfri Formation)
- Basin-wide submarine erosion and formation of a marked unconformity spanning the Late Coniacian – mid-Campanian (SB4).
- Widespread and uniform marine, mud-dominated deposition (Christian IV Formation).
- Initiation of rifting with faulting along NW–SE oriented faults. Block rotation followed by deep updip erosion of footwall blocks (SB5).
- Abrupt deepening of the basin and formation of gravity-driven deposition in possibly restricted marine basins (Fairytale Valley Member).
- Regional uplift and widespread erosion at the Cretaceous–Paleocene transition (SB6). This boundary is recognised by an abrupt change of facies from shallow marine outer shelf to low-sinuosity fluvial (Schjelderup Member) indicating a fall in sea-level and the development of a sequence boundary.
- Formation of lava-dammed lakes (Kulhøje Member), floodplains and shallow marine basins (Willow Pass Member). The basin formation may have been controlled by differential subsidence related to the intense volcanic activity.

Figure 19. *Schematic southwest-northeast cross-section of the Kangerlussuaq Basin restored to SB6 time (Base T40, Thanetian).*


Basin restored to pre volcanism – base T40 time (SB6)
West
East
Sill City
L3
Pyramiden
Skiferbjerg/ Sandridge
Christian IV Gletscher
Nansen Fjord
SB6
SB5
SB3
SB1
SB6
SB5
SB4
SB3
SB2
SB1
Crystalline basement
Sorgenfri Fm
Klitterhorn Mb
Watkins Fjord Fm
Christian IV Fm
Schjelderup Mb
Watkins Fjord Fm (Suunigajik Mb)
Fairy Tale Valley Mb

Correlation of the Cretaceous–Palaeogene successions West of Shetland, the Faroes and SE Greenland

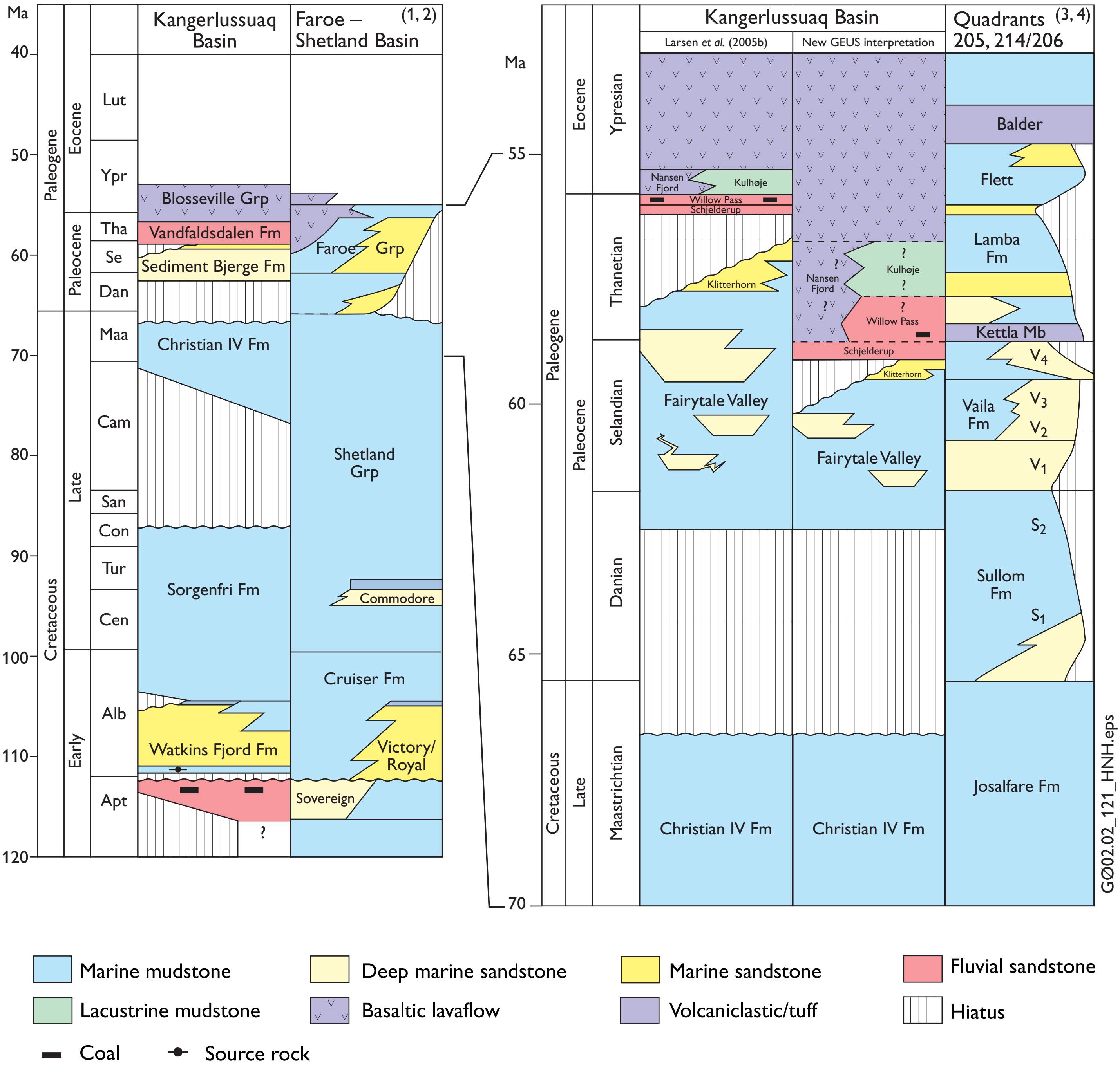
The sedimentological evolution of the Cretaceous – Early Palaeogene succession in the Kangerlussuaq area finds strong parallels with successions of equivalent age on the eastern margins of the Faroe-Shetland rift. In both areas Lower Cretaceous (?Barremian–Albian) shallow marine sandstones are overlain by Upper Cretaceous mudstones. In both areas an influx of deep marine sandstones occurs during in the Paleocene. Deep marine sediments are succeeded by a prograding package of pro-delta, fluvio-deltaic and finally fluvial sediments. The shallowing upward succession from the Klitterhorn Member to the Schjelderup Member and the formation of an important sequence boundary occurs at the base of the fluvial sediments (EG SB_6, Fig.15). This probably corresponds to the progradation of a sequence recognised in the Faroe-Shetland Basin that reached its maximum basinward extent during T40 time.

In the Kangerlussuaq succession, two major unconformities occur, which have not been recognised in the Faroe-Shetland region. The lower unconformity is between the Sorgenfri and Christian IV Formations and spans the Coniacian – Late Campanian interval (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.

The other unconformity (SB_5) occurs between the Christian IV and Sediment Bjerge Formations and spans the Late Maastrichtian–Danian interval. In contrast to the lower unconformity the development of this unconformity is thought to have been controlled by 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. 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 the Kangerlussuaq region (Whitham *et al.* 2004). Recent studies by Jolley *et al.* (2005) based on pollen frequency data suggest, however, that sediment derived from Greenland is present in several wells of the Faroe-Shetland Basin.

Figure 20. *Correlation of the Cretaceous – Early Palaeogene successions West of Shetland, the Faroes and in southern East Greenland. Stratigraphic information in the Faroe-Shetland region from 1) Grant et al. 1999; 2) Ellis et al. 2002; 3) Knox et al. 1997; 4) Mudge & Bujak 2001. Timescale from Gradstein et al. 2004.*



Ma
Kangerlussuaq Basin
Faroe – Shetland Basin (1, 2)
Paleogene
Eocene
Paleocene
Cretaceous
Late
Early
Lut
Ypr
Tha
Se
Dan
Maa
Cam
San
Con
Tur
Cen
Alb
Apt
Blosseville Grp
Vandfaldsdalen Fm
Sediment Bjerge Fm
Christian IV Fm
Sorgenfri Fm
Watkins Fjord Fm
Faroe Grp
Shetland Grp
Commodore
Cruiser Fm
Victory/ Royal
Sovereign
Kangerlussuaq Basin
Larsen et al. (2005b)
New GEUS interpretation
Quadrants 205, 214/206 (3, 4)
Ypresian
Thanetian
Selandian
Danian
Maastrichtian
Nansen Fjord
Kulhøje
Willow Pass
Schjelderup
Klitterhorn
Fairytale Valley
Christian IV Fm
Balder
Flett
Lamba Fm
Kettla Mb
Vaila Fm
Sullom Fm
Josalfare Fm
GØ02.02_121_HNH.eps
Marine mudstone
Deep marine sandstone
Marine sandstone
Fluvial sandstone
Lacustrine mudstone
Basaltic lavaflow
Volcaniclastic/tuff
Hiatus
Coal
Source rock

Palaeogeographic maps of the Faroe-Shetland region

Four palaeogeographic maps for the Early Cretaceous to the Late Paleocene have been constructed for the Faroe-Shetland-Greenland (Fig. 21; Larsen *et al.* 2005b). The maps show the distribution of depositional environments, potential sediment transport paths and the distribution of reservoir sands.

- During the Albian, coarse clastic sedimentation occurred along the margins and intrabasinal highs of the Faroe-Shetland/Kangerlussuaq Basins. Deposition of mudstones with oil-source rock potential may have occurred in low-energy, shallow marine environments between areas of shallower high-energy sedimentation. Following faulting during 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.
- During the Campanian, sea level continued to rise. Given a limited source area for sediment on the southwest side of the Faroe-Shetland Basin, the large thickness of Campanian mudstone found in the Faroe-Shetland Basin was most likely derived from Greenland. In East Greenland a major relative sea level fall is recorded during the Early Campanian that may be a result of rifting and uplift associated with incipient plume impact (Dam *et al.* 1998).
- During the Latest Maastrichtian to Early Paleocene, the Faroe-Shetland Basin was influenced by further rifting and uplift as a consequence of the arrival of the Iceland hotspot. As a result the basin margins were rapidly denuded and large quantities of sediment were eroded and transported to the Faroe Shetland Basin. Sand was supplied to the deep marine environment from the Orkney Shetland Platform (Lamers & Carmichael 1999). Sediment derived from the Greenland side of the rift reached as far east as wells 204/20-3 and 205/9-1 (Jolley & Whitham 2004b).
- At the end of the Paleocene evidence for volcanic activity in the Faroe-Shetland Basin is given by the presence of the volcaniclastic Kettla Member of T36 age (Lamers & Carmichael 1999). Sediment from the Orkney-Shetland Platform prograded into the basin and form important reservoir targets (Roberts *et al.* 1999). A major source of sediment to the west is indicated by the substantial thicknesses of sand found in well 6004/16-1z (Smallwood & Kirk 2005) and the presence of a distinctive Greenland flora in strata as young as T36 age (Jolley & Whitham 2004b). Later Paleocene–Eocene sediments in the Kangerlussuaq region contain evidence for basaltic volcanism and volcanic centres may have created a barrier to the eastward transport of sand from Greenland to the Faroe-Shetland Basin at this time. Thus, any Greenland sourced sediment is likely to have come down the axis of the rift in the Blosseville Kyst region.

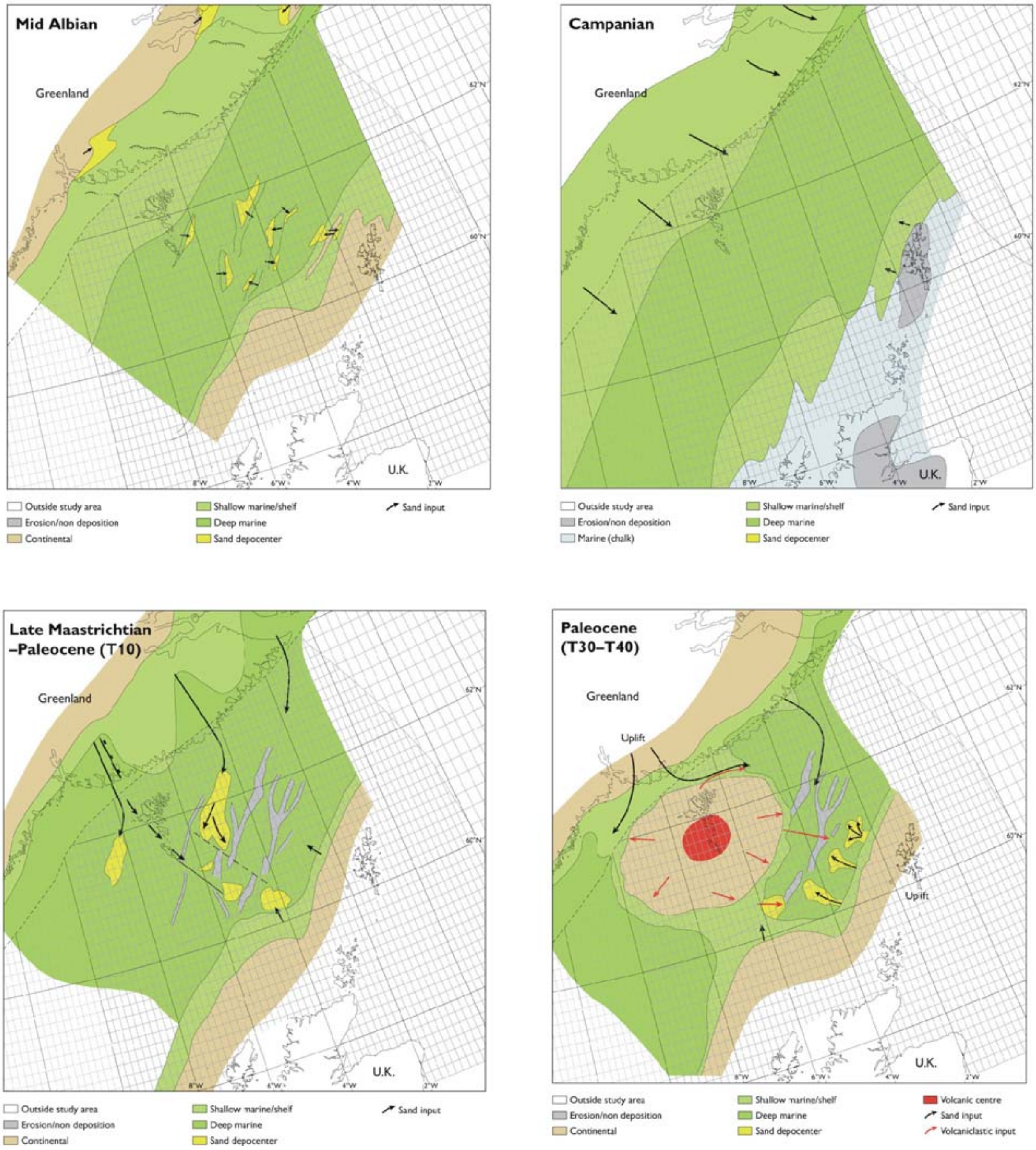


Figure 21. *Palaeogeographical reconstruction for the central part of the North Atlantic re gion.*

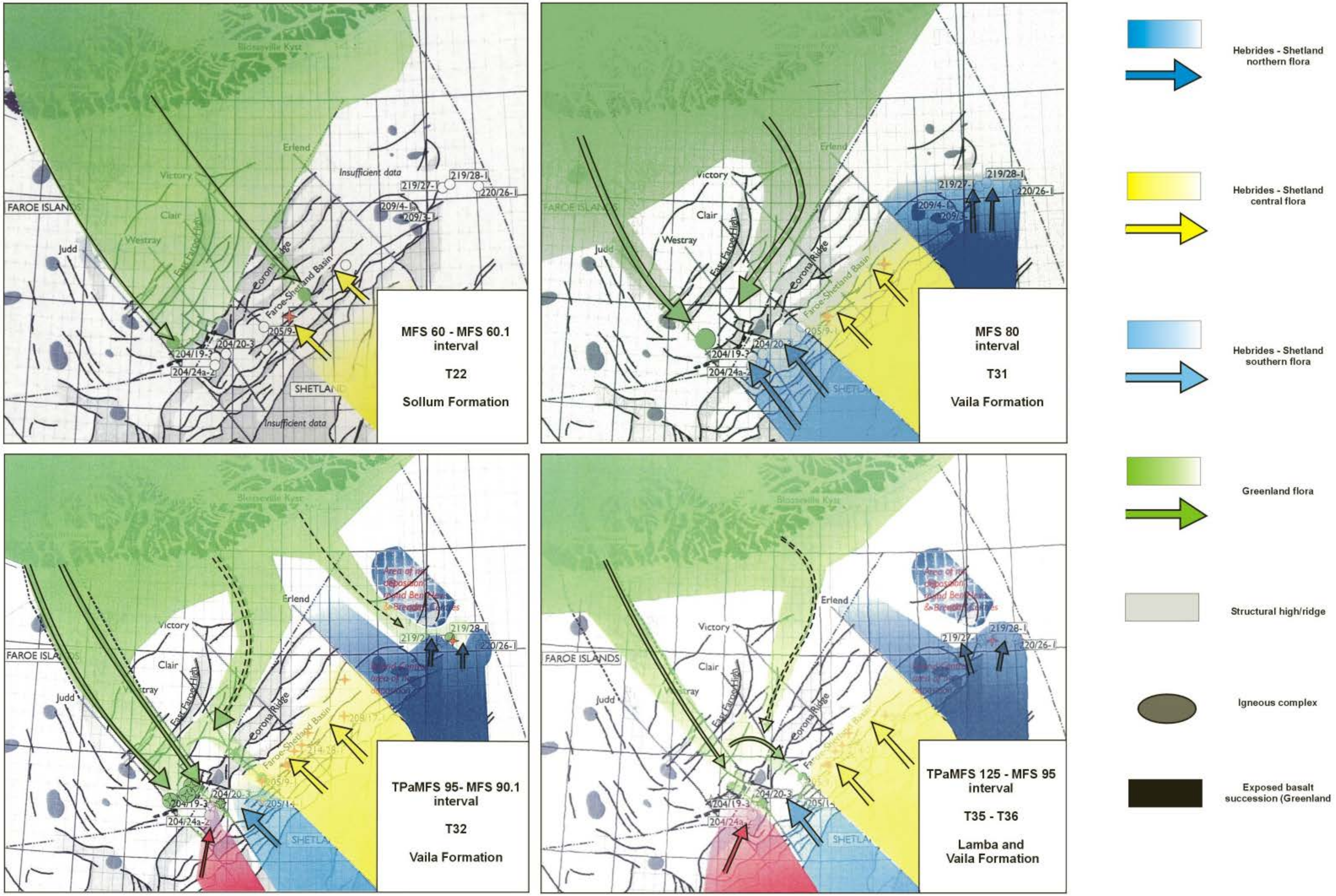
Phytogeographic evidence for sediment transfer pathways in the Palaeogene

The Paleocene sedimentary successions of the Faroe-Shetland Basin in the north-east Atlantic contain an abundant terriginous palynoflora, which can be traced back to two primary sources. The most common are easterly derived angiosperm floras dominated by hickory types (*Momipites* species). These floras are common in most Faroe-Shetland Basin wells throughout the Lower and mid Paleocene succession.

Less common is a westerly derived Greenland flora, which is dominated by ash and chestnut types (*Cupuliferoipollenites* and *Cupuliferoidaepollenites* species) and restricted to the Lower and mid Paleocene succession in the western part of the Faroe-Shetland Basin.

The Greenland flora is confined to four main stratigraphical pulses in the Lower and mid Paleocene, occurring more commonly in proximity to the major transfer zones (e.g. Chair, Westray and Judd) and west of the Corona Ridge (Fig. 22). This distribution pattern provides evidence of argillacerous sediment transport from the west into the Faroe-Shetland Basin via major transfer zones and the deposits may be controlled by pulses of igneous activity in the North Atlantic Igneous Province.

Figure 22. *Phytogeographic sources for the central part of the North Atlantic region in the Paleocene T22-T36 (after Jolley & Whitham 2004b)*



Blosseville Kyst
Erlend
Victory
Clair
Westray
Judd
FAROE ISLANDS
East Faroe High
Corona Ridge
Faroe-Shetland Basin
SHETLAND
Insufficient data
219/27-1
219/28-1
220/26-1
209/4-1
209/3-1
204/20-3
204/19-3
204/24a-2
205/9-1
205/14-1
208/17-1
214/28-1
Area of no deposition round Ben Nevis & Brendan Centres
MFS 60 - MFS 60.1 interval
T22
Sollum Formation
MFS 80 interval
T31
Vaila Formation
TPaMFS 95- MFS 90.1 interval
T32
Vaila Formation
TPaMFS 125 - MFS 95 interval
T35 - T36
Lamba and Vaila Formation
Hebrides - Shetland northern flora
Hebrides - Shetland central flora
Hebrides - Shetland southern flora
Greenland flora
Structural high/ridge
Igneous complex
Exposed basalt succession (Greenland

Acknowledgements

The companies of the Sindri Group are gratefully acknowledged for their generous support of the project. 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. The interpretations given in this report is based on field work by GEUS and CASP in the period 1995–2004 and includes primary field data collected by several geologists. We direct our thanks to M. Bjerager, L. Hamberg, S. Olaussen, C.S. Pickles, C. Johnson and T. Nedkvitne. Professor W.J. Kennedy, Oxford University, is thanked for ammonite determinations.

References

Abdel-Gawad, G.I. 1986: Maastrichtian non-cephalopod molluscs (Scaphopoda, Gastropoda and Bivalvia) of the Middle Vistula valley, central Poland. Acta Geologica Polonica **36**, 69-224.

Bint, A.N. 1986: Fossil Ceratiaceae: A restudy and new taxa from the mid-Cretaceous of the Western Interior, USA. Palynology, **10**, 135–180.

Birkelund, T. 1965: Ammonites from the Upper Cretaceous of West Greenland. Meddelelser om Grønland **179(7),** 1-192, 49 pls.

Catuneanu, O. and Sweet, A.R. 1999: Maastrichtian–Paleocene foreland-basin stratigraphies, western Canada: a reciprocal sequence architecture. Canadian Journal of Earth Sciences **36**, 685–703.

Christensen, W.K. 1996: A review of the Upper Campanian and Maastrichtian belemnite biostratigraphy of Europe. Cretaceous Research **17**, 751-766.

Dam, G., Larsen, M. & Sønderholm, M. 1998: Sedimentary response to mantle plumes: implications from Paleocene onshore successions, West and East Greenland. Geology **26**, 207–210.

Dhondt, A.V. 1973: Systematic revision of the Chlamydinae (Pectinidae, Bivalvia, Mollusca) of the European Cretaceous. Part 3: *Chlamys* and *Mimachlamys*. Bulletin de l'Institut Royal des Sciences Naturelles de Belgique, Sciences de la Terre – Aardwetenschappen, **49(1),** 1-134, 9 pls.

Donovan, D.T. 1953: The Jurassic and Cretaceous stratigraphy and palaeontology of Traill Ø, East Greenland. Meddelelser om Grønland **111(4),** 1-150, 25 pls.

Ebdon, C.C., Granger, P.J., Johnson, H.D. and Evans, A.M. 1995: Early Tertiary evolution and sequence stratigraphy of the Faeroe-Shetland Basin: implication for hydrocarbon prospectivity. *In:* R.A. Scrutton, M.S. Stoker, G.B. Shimmield and A.W. Tudhope (Eds.), The Tectonics, sedimentation and palaeoceanography of the North Atlantic Region. London: Geological Society, **90**, 51–69.

Ellis, D., Bell, B.R., Jolley, D.W. & O'Callaghan, M. 2002: The stratigraphy, environment of eruption and age of the Faroes Lava Group, NE Atlantic Ocean. In Jolley, D.W. & Bell, B.R. (eds) The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic processes. Geological Society, London, Special Publications **197**, 253–269.

Embry, A.F. 1991: Mesozoic history of the Arctic islands. In: Trettin, H.P. (ed.) pp. 371-433. Geology of Canada, no. 3, Geology of the Inuitian Oreogen and Arctic Platform of Canada and Greenland, Geological Survey of Canada, Ottawa.

Gradstein, F.M., Ogg, J.G., Smith A.G. *et al*. 2004:. A Geological time scale 2004. Cambridge University Press and International Comission on Stratigraphy (ICS).

Grant, N., Bouma, A. and McIntyre, A. 1999: The Turonian play in the Faeroe-Shetland Basin. In: A.J. Fleet and S.A.R. Boldy (Eds.), Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference. London: Geological Society, 661–673.

Hamberg, L. 1990: The pre-basaltic Upper Cretaceous–Tertiary sediments of the Kangerdlugssuaq area: evidence of submarine syn-rift deposits. In: Brooks, C.K. (ed.): Kangerdlugssuaq studies: processes at a continental rifted margin. Procedings from meeting 24 January 1990, 46–55. Geologisk Institut, Copenhagen.

Hancock,J.M. European ammonites. In: Gradstein, F.M., Agterberg, F.P. Fischer, A.G., Hardenbol, J., van Veen, P., Thierry, J. and Huang, Z. 1995: Triassic, Jurassic and Cretaceous time-scale. In: Berggren, W.A., Kent, D.V., Aubry, M-P. and Hardenbol, J. (eds) Geochronology, time scales and global stratigraphic correlation. SEPM Special Publication **54**, 95-126.

Hansen, H., Pedersen, A.K., Duncan, R.A., Bird, D.K., Brooks, C.K., Fawcett, J.J., Gittings, J., Gorton, M. and O'Day, P. 2002: Volcanic stratigraphy of the southern Prinsen of Wales Bjerge region, East Greenland. In Jolley, D.W.& Bell, B.R. (eds.) *The North Atlantic Igne-*

ous Province: Stratigraphy, Tectonic, volcanic and Magmatic Processes. Geological Society, London. Special Publication **197**, 183-218.

Higgins, A.C. and Soper, N.J. 1981: Cretaceous–Palaeogene sub-basaltic and intrabasaltic sediments of the Kangerdlugssuaq area, Central East Greenland. Geological Magazine **118**(4), 337–354.

Hjortkjær, B.F. and Jolley, D.W. 1999: A spore and pollen assemblage from the Late Paleocene sedimentary section at Kulhøje, East Greenland. Implications for the break-up history of the North Atlantic. Abstracts and Programme, The North Atlantic Igneous Province: Magmatic controls on sedimentation, Geological Society, Burlington House, London 1pp.

Jolley, D.W. and Whitham, A.G. 2004a: A stratigraphical and palaeoenvironmental analysis of the sub-basaltic Palaeogene sediments of East Greenland. Petroleum Geoscience **10**, 53–60.

Jolley, D.W. and Whitham, A.G. 2004b: Phytogeography, provenance and sediment transport pathways in the Paleocene strata of the Faroe-Shetland region. Final report for the Sindri Group. July 2004, 41 pp.

Jolley, D.W. ,Morton, A. and Prince, I. 2005: Volcanogenic impact on phytogeography and sediment dispersal patterns in the northeast Atlantic. In Doré, A.G. & Vining, B. (eds) Petroleum Geology: North-West Europe and global perspectives – Proceedings of the 6th Petroleum Geology Conference. Geological Society, London, 969–975.

Kelly, S.R.A., Braham, B., Whitham, A.G. & Gregory, J. 2000: Revised integrated biostratigraphy & palaeoenvironmental history of the Cretaceous–Tertiary rocks of the Kangerlussuaq Basin, southern East Greenland. Unpublished CASP report. MPS. **2**, 78 pp. [Confidential Report]

Kennedy, W.J., Cobban, W.A. and Scott, G.A. 1992: A correlation of the uppermost Campanian of Western Europe, the U.S. Gulf Coast Atlantic Seabord and Western Interior, and the numerical age of the base of the Maastrichtian. Geological Magazine **129** (4) 497-500.

Kennedy, WJ., Landman, N.H., Christensen, W.K., Cobban, W.A., and Hancock, J.M. 1998: Marine connections in North America during the Late Maastrichtian. Cretaceous Research **19**, 745-775

Kennedy, W.J., Nøhr-Hansen, H. & Dam, G. 1999: The youngest Maastrichtian faunas from Nuussuaq, West Greenland. Geology of Greenland Survey Bulletin **184,** 13-17.

Kirsch, K.-H. 1991: Dinoflagellatenzysten aus der Oberkreide des Helvetikums und Nordultrahelvetikums von Oberbayern. Münchner Geowiss. Abh. A **22,** 306 pp.

Knox, R.W.O'B., Holloway, S., Kirby, B.A. & Baily, H.E. 1997: Stratigraphic nomenclature of the UK North West Margin. 2. Early Paleogene lithostratigraphy and sequence stratigraphy. The British Geological Survey, Nottingham. 113 pp.

Lamers, E. and Carmichael, S.M.M. 1999: The Paleocene deepwater sandstone play West of Shetland. In: A.J. Fleet and S.A.R. Boldy (Eds.), Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference. London: Geological Society of London, 645–659.

Larsen, M., Hamberg, L., Olaussen, S., Nørgaard-Pedersen, N. and Stemmerik, L. 1999: Basin evolution in southern East Greenland: an outcrop analog for the Cretaceous–Paleogene *basins on the* North Atlantic volcanic margin. American Association of Petroleum Geologists, Bulletin **83(8),** 1236–1261.

Larsen, M., Nøhr-Hansen, H., Whitham, A.G. & Kelly, S.R.A. 2005a: Stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussaq Basin. Volcanic basins of the North Atlantic. Summary report for the Sindri Group. September 2005. Report, Geological Survey of Denmark and Greenland 2005/61, 25 pp.

Larsen, M., Nøhr-Hansen, H., Whitham, A.G. & Kelly, S.R.A. 2005b: Stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussaq Basin. Volcanic basins of the North Atlantic. Final report for the Sindri Group. September 2005. Report, Geological Survey of Denmark and Greenland 2005/62, 141 pp.

Lawver, L.A., Grantz, A. and Gahagan, LM. 2002: Plate kinematic evolution of the present Arctic Ocean since the Ordovician. Geological Society of America, Special Paper **360**. 333-358.

Machalski, M. 1996: *Diplomoceras cylindraceum* (Defrance, 1816): a typical Maastrichtian ammonite in the Piotrawin section, central Poland. Przeglad Geologiczny **44,** 953-954.

Machalski, M. 2005: Late Maastrichtian and earliest Danian scaphitid ammonites from central Europe: taxonomy, evolution, and extinction. Acta Palaeontologica Polonica **50(4),** 653-696.

Mangerud, G. Dreyer, T., Søyseth, L., Martinsen, O. & Ryseth, A. 1999: High resolution biostratigraphy and sequence development of the Palaeocene succession, Grane Field, Norway. In: Underhill, J.R. (ed.) Development and evolution of the Wessex Basin, Geological Society, London, Special Publication **133**, 167–184.

Mudge, D. C. & Bujak, J. P. 1996: Paleocene biostratigraphy and sequence stratigraphy of the UK central North Sea. Marine and Petroleum Geology, **13**, 295–312.

Mudge, D.C. and Bujak, J. 2001: Biostratigraphic evidence for evolving palaeoenvironment in the Lower Paleogene of the Faeroe-Shetland Basin. Marine and Petroleum Geology **18**, 577–590.

Nichols, D.J. & Sweet, A. R. 1993: Biostratigraphy of the Upper Cretaceous non-marine palynofloras in a north-south transect of the Western Interior Basin. In Caldwell, W. G. E. & Kauuffman, E. G. (ed.) Evolution of the Western Interior Bain: Geol. Ass. Can, Spec. Pap. **39**, 539–584.

Niebuhr, B. 2003: Late Campanian and Early Maastrichtian ammonites from the white chalk of Kronsmoor (northern Germany) – taxonomy and stratigraphy. Acta Geologica Polonica **53**, 257-281.

Nøhr-Hansen, H. 1993: Dinoflagellate cyst stratigraphy of the Barremian to Albian, Lower Cretaceous, East Greenland. Bulletin Grønlands geologiske Undersøgelse **166**, 171 pp.

Nøhr-Hansen, H., 1996: Upper Cretaceous dinoflagellate cyst stratigraphy, onshore West Greenland. Bulletin Grønlands geologiske Undersøgelse **170**, 104 pp.

Nøhr-Hansen, H. 2005: Composition and distribution of Lower Cretaceous brackish water dinoflagellate cyst assemblages. Palynology, Palaeolattitudes, Paleoaltitudes, Joint meeting APLF-TMS-LSPG Paris 3–7 October 2005. Abstract volume p. 87.

Nøhr-Hansen, H.& Dam, G. 1997: Palynology and sedimentology across a new marine Cretaceous/Tertiary boundary section on Nuussuaq, West Greenland. Geology **25; 9**. 851-854.

Nøhr-Hansen, H., Sheldon, E. and Dam, G. 2002: A new biostratigraphic scheme for the Paleocene onshore West Greenland and its implications for the timing of the pre-volcanic evolution. In Jolley, D.W.& Bell, B.R. (eds.) *The North Atlantic Igneous Province: Stratigraphy, Tectonic, volcanic and Magmatic Processes.* Geological Society, London. Special Publication **197** 111–156.

Nøhr-Hansen, H., Larsen, M., Kelly, S.R.A. & Whitham, A.G.2006: Biotratigraphy zonation (palynology and macrofossil) for the Upper Cretaceous – Lower Paleocene based on the sediomentary succession in Kangerlussaq southern East Greenland. Volcanic basins of the North Atlantic. Phase 1 report for the Sindri Group. March 2006. Report, Geological Survey of Denmark and Greenland 2006/23, 90 pp.

Ogg, J.G., Agterberg, F.P. and Gradstein, F.M. 2004: Chapter 19, The Cretaceous Period. *In*: Gradstein, F.M., Ogg, J.G. and Smith A.G. (eds) A Geological time scale 2004. Cambridge: Cambridge University Press and International Commission on Stratigraphy (ICS).

Piasecki, S., Larsen, L. M., Pedersen, A. K. & Pedersen, G. K. 1992: Palynostratigraphy of the Lower Tertiary volcanics and marine clastic sediments in the southern part of West Greenland Basin: implications for the timing and duration of the volcanism. Rapport Grønlands Geologiske Undersøgelse, **154**, 13–31.

Roberts, L.N.R. and Kirshbaum, M.A. 1995: Palaeogeography of the Late Cretaceous of the Western Interior of Middle North America- Coal distribution and sedimentary accumulation. US Geological Survey, Professional Paper **1561**, 1-115.

Schiøler, P. & Wilson, G. J. 1993: Maastrichtian dinoflagellate zonation in the Dan Field, Danish North Sea. Review of Palaeobotany and Palynology **78**, 321–351.

Shulz, M.G. and Schmid, F. 1983: Das Ober-Maastricht von Hemmoor (N-Deutschland): Faunenzonen Gliederung und Korrelationen mit dem Ober-Maastricht von Danemark und Limburg. Newsletters on Stratigraphy **13**, 21-39

Smallwood, J.R. and Kirk, W.J. 2005: Paleocene exploration in the Faroe-Shetland Channel: disappointsments and discoveries. In: Dore, A.G. and Vining, B.A. (Eds.), Petroleum Geology: Northwest Europe´and Global perspectives - Proceedings of the 6th Petroleum Geology Conference. London: Geological Society, 977–991.

Soper, N.J., Downie, C., Higgins, A.C. and Costa, L.I. 1976: Biostratigraphic ages of Tertiary basalts on the East Greenland continental margin and their relationship to plate separation in the North-East Atlantic. Earth and Planetary Science Letters **32**, 149–157.

Srivastava, S.K. 1970: Pollen biostratigraphy and paleoecology of the Edmonton Formation (Maestrichtian), Alberta, Canada. Palaeogeography, Palaeoclimatology, Palynology. **7**, 221–276.

Storey, M., Duncan, R. A., Pedersen, A. K., Larsen, L. M. & Larsen, H. C., 1998: $^{40}Ar/^{39}Ar$ geochronology of the West Greenland Tertiary volcanic province. Earth and Planetary Science Letters, **160**, 569–586.

Storey, M., Duncan, R. A. & Tegner, C: *In Press* Timing and Duration of Volcanism in the North Atlantic Igneous Province: Implications for Geodynamics and Links to the Iceland Hotspot Chemical Geology, Accepted Manuscript.

Scott, D.F. 1984:. Cretaceous sequences of the foothills of the Canadian Rocky Mountains. In: Stott, D.F. and Glass, D.G. (eds) The Mesozoic of Middle North America. Canadian Society of Petroleum Geologists, Memoir **9**, 85-107.

University of Chicago. 2002: The paleogeograohic atlas project in 2002. http://pgap.uchicago.edu/PGAP2000/1.html.

Wager, L.R. 1934: Geological investigations in East Greenland. Part I: General Geology from Angmassalik to Kap Dalton. Meddelelser om Grønland **105(2)**, 46 pp.

Wager, L.R. 1947: Geological investigations in East Greenland. Part IV: The stratigraphy and tectonics of Knud Rasmussens Land and the Kangerdlussuaq region. Meddelelser om Grønland **134(5),** 64 pp.

Whitham, A.G., Morton, A.C. and Fanning, C.M. 2004: Insights into Cretaceous–Paleocene sediment transport paths and basin evolution in the North Atlantic from a heavy mineral study of sandstones from southern East Greenland. Petroleum Geoscience **10**, 61–72.

Sindri bibliography

Jolley, D.W. and Whitham, A.G. 2004b: Phytogeography, provenance and sediment transfer pathways in the Paleocene strata of the Faroe-Shetland region. Final report for the Sindri Group. July 2004.

Larsen, M., Nøhr-Hansen, H., Whitham, A.G. & Kelly, S.R.A. 2005a: Stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussaq Basin. Volcanic basins of the North Atlantic. Summary report for the Sindri Group. September 2005. Report, Geological Survey of Denmark and Greenland 2005/62, 25 pp.

Larsen, M., Nøhr-Hansen, H., Whitham, A.G. & Kelly, S.R.A. 2005b: Stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussaq Basin. Volcanic basins of the North Atlantic. Final report for the Sindri Group. September 2005. Report, Geological Survey of Denmark and Greenland 2005/62, 141 pp.

Nøhr-Hansen, H., Larsen, M., Kelly, S.R.A. & Whitham, A.G.2006: Biotratigraphy zonation (palynology and macrofossil) for the Upper Cretaceous – Lower Paleocene based on the sediomentary succession in Kangerlussaq southern East Greenland. Volcanic basins of the North Atlantic. Phase 1 report for the Sindri Group. March 2006. Report, Geological Survey of Denmark and Greenland 2006/23, 90 pp.