DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2005/61

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

Summary report for the Sindri Group
September 2005

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Preface

This report forms part of the research project: “Stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussuaq Basin – Volcanic basin of the North Atlantic” jointly conducted by the Geological Survey of Denmark and Greenland (GEUS) and CASP (Formerly Cambridge Arctic Shelf Programme). The project is funded by the SINDRI programme: “Future Exploration Issues Programme of the Faroese Continental Shelf” (briefly referred to at the SINDRI programme) established by the Faroese Ministry of Petroleum and financed by the partners of the Sindri Group. The current licensees of the Sindri Group are: Agip Denmark BV, Amerada Hess (Faroes) Ltd., Anadarko Faroes Company, P/F Atlantic Petroleum, BP Amoco Exploration Faroes Ltd., British Gas International BV, DONG Føroyar P/F, Enterprise Oil Exploration Ltd., Føroya Kolvetni P/F, Petro-Canada Faroes GmbH, Phillips Petroleum Europe Exploration Ltd., Shell (UK) Ltd., and Statoil Færøyene AS.

Introduction

This report provides a concise review of the most important findings of the SINDRI Project "Stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussuaq Basin - Volcanic basin of the North Atlantic" and shows the key figures. For background data, descriptions and discussion, the reader is invited to read the full report (Larsen *et al.* 2005).

The most important results are:

1. A unified lithostratigraphy comprising three new formations and six new members (Fig 2). The section on lithostratigraphy includes sufficient information to justify formal member and formation status and is planned to be published in a Survey Bulletin.
2. Definition of six unconformity bounded sequences (EG1–EG6) forming a framework for future sequence stratigraphic interpretations (Fig. 3).
3. Sedimentological descriptions and interpretation of gross depositional environments for all units (Table 1).
4. Correlation chart for the principal Cretaceous macrofaunas with allocation of ammonite, belemnite, bivalve and dinoflagellate cyst biozones (Fig. 4). The work includes documentation of a rich Upper Cretaceous macrofauna including Campanian and Maastrichtian species hitherto unknown from East Greenland.
5. Description of Danian, Selandian and Thanetian dinoflagellate cyst assemblages from a number of Kangerlussuaq sections (Fig. 5). The presence of Paleocene strata in East Greenland has previously been disputed, and the new palynological data dramatically change the understanding of the Early Paleogene basin evolution.
6. Correlation chart with all major sections of the Kangerlussuaq Basin (Fig. 6). The correlation chart illustrates the stratigraphical and spatial relationship between sections.
7. Discussion on basin evolution and tectonic phases (Fig. 7).
8. Correlation chart showing the possible connection from Kangerlussuaq to the Faroes, West of Shetland basins (Fig. 8).
9. Interpretation of 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 (Figures 9–12).
10. Establishment of a GIS project for the Kangerlussuaq Basin with detailed and up-to-date information on geology and localities (Fig. 13; CD enclosed).

In addition the project has provided a stratigraphic framework for the following Sindri Projects investigating the East Greenland succession:
"Linking the Faroes and Greenland: An innovative, integrated provenance study"
"Phytogeographic evidence for sediment transfer pathways in the Faroe – Shetland region"

The field work performed within the Stratigraphy project (August 2004) has also provided essential sample material for the following associated Sindri projects:
"Investigation of hydrocarbon fluid inclusions in Cretaceous sandstones of the Kangerlussuaq Basin, SE Greenland"
"Stratigraphy, sedimentary provenance and sequence development of the Upper Cretaceous – Paleogene strata of East Greenland and the Faroe-Shetland region".

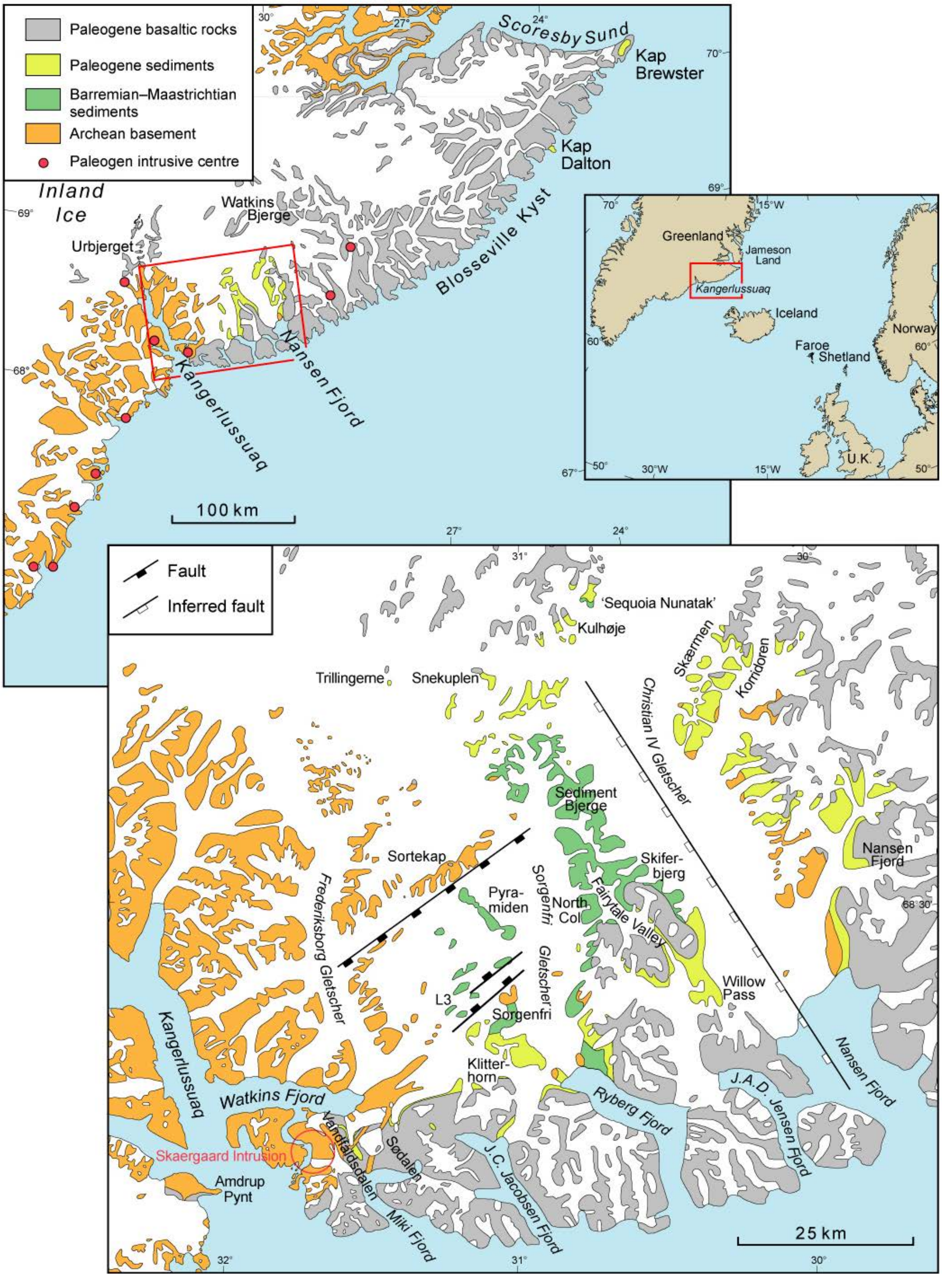

Figure 1. *Geological map of the Kangerlusssuaq Basin in southern East Greenland. The pre-basaltic succession consists of Barremian–Paleogene sediments onlapping Archean crystal-line basement. The succession is overlain by 4–6 km of Paleogene continental flood basalts.*

Lithostratigraphy of the Kangerlussuaq basin

The lithostratigraphic framework used here for the pre-basaltic sedimentary rocks of the Kangerlussuaq Basin (Fig. 1) consolidates 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. The evolution of the stratigraphic nomenclature of the pre-basaltic rocks of the basin is shown in Fig. 2.

The new lithostratigraphic scheme comprises three new formations and six new members. 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.

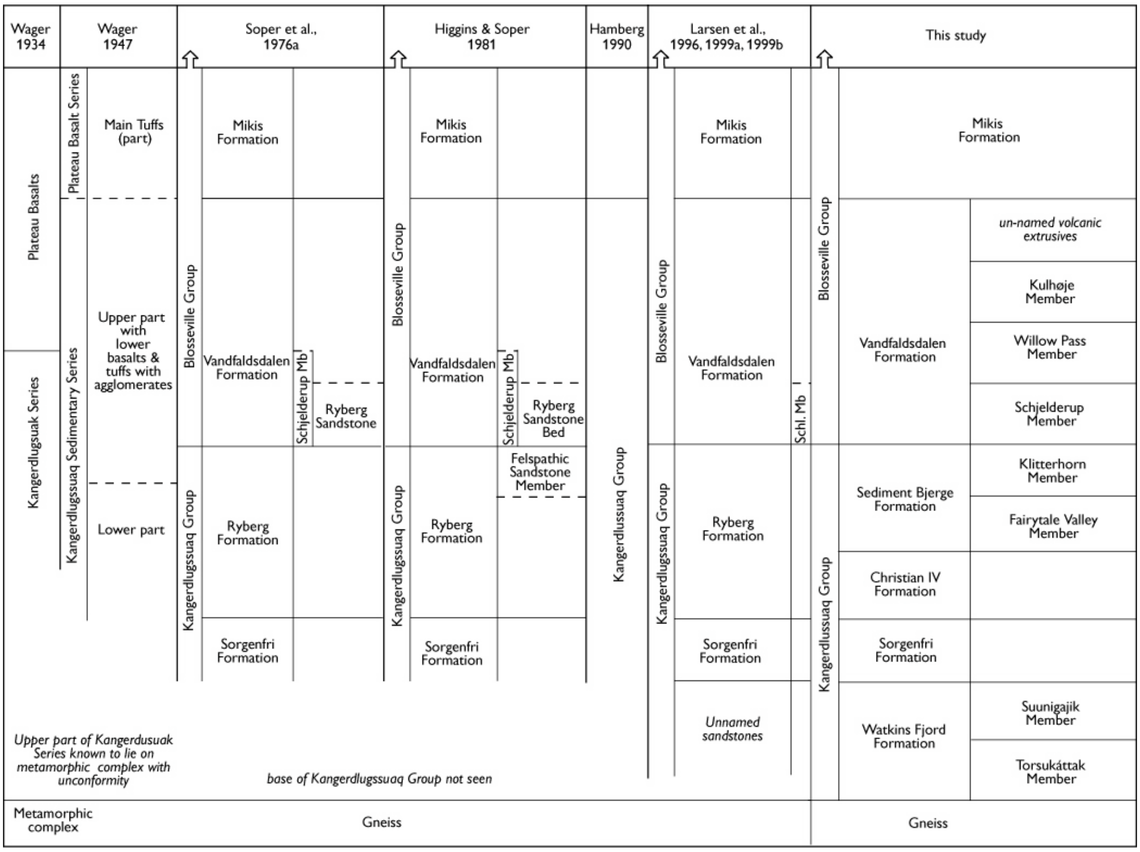

Figure 2. *Generalised history of the stratigraphic nomenclature for the pre-basaltic sedimentary succession in Kangerlussuaq.*

Unconformity bounded sequences (EG1–EG6)

The sedimentary succession of the Kangerlussuaq Basin is divided into six unconformity bounded sequences. 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 allows 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.

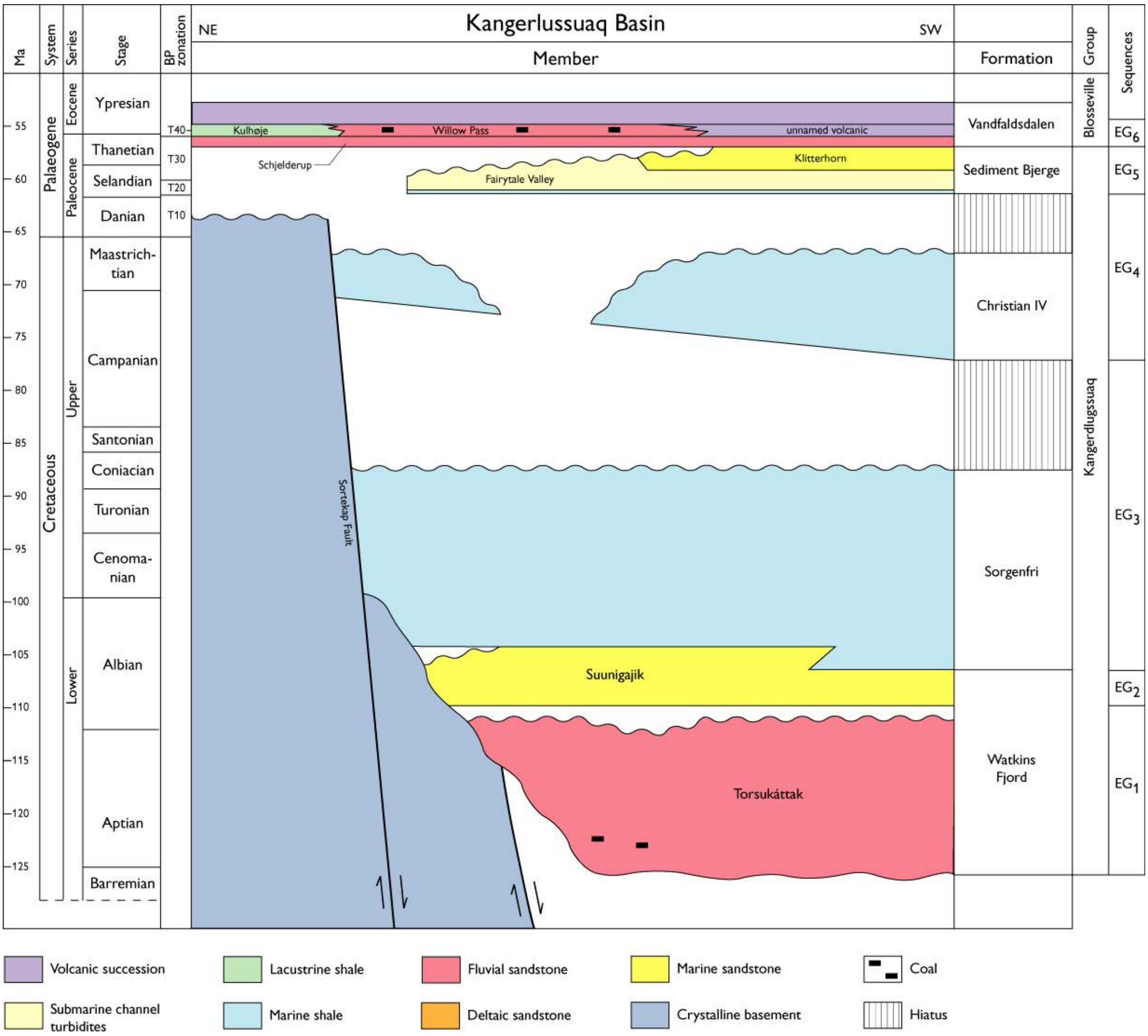

Figure 3. *Litho- and sequence stratigraphy of the Cretaceous–Paleogene succession in Kangerlussuaq, southern East Greenland. Timescale from Gradstein et al. 2004.*

Sedimentological description and interpretation

Formation/Member Age	Estimated thickness	Lithology	Sedimentary structures	Fossils/ trace fossils	Depositional 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
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 northeast and southeast	Ammonites *Skolithos* isp. *Ophiomorpha* isp. *Arenicolites* isp.	Channel-fill and sandbars in fluvio-estuarine environment
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 southeast	Belemnites Ammonites Dinoflagellate cysts Inoceramid bivalves; *Planolites* isp.	Shelf to offshore transition. Low sedimentation rates
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
Sediment Bjerge Fm./Fairytale Valley Mb. 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–southeast	Leaf imprints *Teichichnus* isp. *Planolites* isp. *Skolithos* isp. Bivalves, gastropods	Submarine fan and channel-levee, slope Post-depositional deformation (slump and sandstone injection)
Sediment Bjerge Fm./Klitterhorn Mb. ?Selandian/ Thanetian	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
Vandfaldsdalen Fm./Schjelderup Mb. Thanetian	20 m	Coarse-grained to pebbly sandstones	Large-scale trough cross-bedding Unidirectional towards east–southeast	Carbonaceous wood fragments and tree trunks	Proximal braided river channels
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 northwest, east and southeast	Carbonaceous wood fragments Leaf imprints Locally *Planolites* isp.	Continental volcanic terrain associated with fluvial, lacustrine and shallow marine environments
Vandfaldsdalen Fm./Kulhøje Mb. Late Paleocene	100 m	Mudstones and fine-grained sandstones, tuffaceous	Horizontal lamination Graded airfall tuffs	Leaf imprints	Volcanic dammed lakes

Table 1. *Sedimentology and gross depositional environments*

Macrofossil biostratigraphy

A rich macro fauna is present in the Cretaceous succession and allows identification of intervals not previously recognised in the basin. The most important new observations are recognition of Barremian age fauna in the basin, subdivision of the Lower Cretaceous sandstone dominated succession and presence of a rich Campanian–Maastrichtian macro fauna, which were hitherto unknown in East Greenland.

Lower Cretaceous (Barremian–Aptian)

The oldest macrofauna was collected from the Torsukáttak Member. It contains the small heteromorph ammonite *Parancyloceras bidentatum* (von Koenen), the zonal index of the latest Barremian in NW Europe. It also contains common *Lytoceras polare* (Frebold) and the bivalve *Arctica* sp. with poorly preserved *Entolium orbiculare* (J. Sowerby). The second principal macrofauna contains the large heteromorph ammonite, *Tropaeum subarcticum*, which characterises the *Acanthoplites nolani* Zone (formerly *Parahoplites nutfieldiensis* Zone), the older part of the Late Aptian, together with abundant bivalves, *Entolium orbiculare*, *Arctica* sp. and an astartid. The associated palynology of these faunas are unknown.

Lower Cretaceous (Albian)

Early Albian faunas have not been confirmed from the Kangerlussuaq Basin. The Mid Albian is characterised by a succession of hoplitid ammonite dominated faunas. The lowest horizon has been recognised in the upper part of the Suunigajik Member, which contains common large ammonites in concretions including *Euhoplites loricatus, Euhoplites ?aspasia* and *Anahoplites planus* gp., together with *Actinoceramus concentricus* (Parkinson), *Entolium orbiculare* (J. Sowerby) and *Arctica* sp. This horizon is well dated as *Anahoplites intermedius* Subzone of the *Euhoplites loricatus* Zone, Mid Albian. Two higher horizons in the lowest part of the Sorgenfri Formation contain crushed ammonites, probably true *Hoplites* spp. The lower of these two ammonite faunas occurs in association with dinoflagellate cysts of the *Rhombodella paucispina* Zone and are also of Mid Albian age. A higher horizon is known from one site, where a higher leaf of the Suunigajik Formation sandstones is exposed. A mudstone interval, within the sandstones, contained concretions that produced a sparse fauna of ammonites: *Mortoniceras (Dieradoceras)* sp., *Euhoplites boloniensis* and *Hamites* sp.; belemnite *Neohibolites* sp.; and bivalve *Actinoceramus* sp. The ammonite assemblage corresponds to the *Hysteroceras orbignyi* Subzone of the *Mortoniceras inflatum* Zone, Late Albian. Further work is ongoing with H.G. Owen (Natural History Museum, London) concerning the Mid Albian ammonites.

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

*only bold zones recognised in Kangerlussuaq Basin

Figure 4. *(Enclosed as high-resolution PDF file).The principal Cretaceous macrofaunas of the Kangerlussuaq Basin and the correlation with ammonite, belemnite and bivalve biozonation schemes. A composite palynological succession of Greenland is shown in a separate column.*

Cenomanian

The main macrofauna in the lower–middle part of the Sorgenfri Formation in the northern Sedimentary Mountains includes the ammonites *Schloenbachia varians* (J. Sowerby), *Gaudryceras (Gaudtrceras) cassissianum* (d'Orbigny), *G. (Mesogaudryceras) leptonema* (Sharpe), *Parapuzosia (Austiniceras) austeni* (Sharpe), and the bivalve *Inoceramus crippsi* Mantell. The ammonites indicate the *Mantelliceras saxbyi* Subzone of the *Mantelliceras mantelli* Zone, and the bivalves indicate the *I. crippsi* Zone. This fauna is associated with the *Ovoidinium* sp. 1 Subzone of the *Subtilisphaera kalaalliti* Zone. A higher fauna of *Gaudryceras (Mesogaudryceras) leptonema*, occurs in association with dinoflagellate cysts of the *Epilepidosphaeridia spinosa* Subzone.

Turonian

Early Turonian macrofaunas have not been recognised in the Kangerlussuaq Basin. However, levels in the upper part of the Sorgenfri Formation are characterised by abundant inoceramid bivalves, *Inoceramus lamarcki* Parkinson. Their occurrence is usually associated with that of the belemnite *Actinocamax* cf. *manitobensis* (Whiteaves). *I. lamarcki* is the zonal index for the eponymous zone, which is of mid Mid to mid Late Turonian age. *Actinocamax* cf. *manitobensis* was attributed to the Late Turonian. *A. manitobensis* and *I. lamarcki* are associated with the upper part of the *Epilepodosphaeridia spinosa* dinoflagellate cyst Subzone.

Coniacian–Santonian

Dinoflagellate cysts indicate the presence of Coniacian strata, however, no Coniacian macrofaunas have been found. The Santonian interval is represented by a hiatus.

Campanian

Unequivocal Campanian macrofauna including the ammonite *Jeletzkites compressus* (Roemer) have been found in the lower part of the Christian IV Formation.

Maastrichtian

The middle part of the Christian IV Formation across the whole Kangerlussuaq Basin contains an abundant shelly fauna, dominated by ammonites and echinoids. The ammonites include *Acanthoscaphites tridens* (Kner), and the large heteromorph, *Diplomoceras cylindraceum*, reaching over 50 cm in length. *Acanthoscaphites tridens* corresponds to the eponymous zone (formerly *Pachydiscus neubergensis*) of NW Europe where it is also associated with the *Belemnella lanceolata-sumensis* zones. A later fauna probably includes *Discoscaphites angmatussutensis* Birkelund. *Diplomoceras cylindraceum* is found in sections above occurrences of the *Wodehousia spinata* interval, of earliest Late Maastrichtian age. Further work is ongoing with W.J. Kennedy (Oxford University) concerning the Mid-Late Maastrichtian transition ammonites.

Paleocene–Early Eocene palynostratigraphy

Mudstone and fine-grained sandstone samples from the Kangerlussuaq Basin have been processed and their dinoflagellate cyst, spore and pollen contents analysed (Fig. 5). Most sections have a low recovery due to the intense heating by Paleogene intrusions, however, important observations are made:

- A pronounced reworking event is present in the Maastrichtian Christian IV Formation with recorded reworked material represented by specimens of Albian–Cenomanian age (*Rhombodella paucispinosa* & *Chlamydophorella nyei*) and of Campanian age (*Isabelidinium microarmum*).
- A marked decrease in 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 Danian interval is absent, this corresponds to the development of unconformities in marginal areas of the Faroe-Shetland Basin.
- Dating of the Selandian deep marine Fairytale Valley Member and its correlation with the Vaila Formation is based on the consistent occurrence of the dinoflagellate species *Palaeoperidinium pyrophorum* indicating an age no younger than latest Selandian (*Palaeoperidinium pyrophorum* Zone DP4 of Mudge & Bujak 1996; 2001). In Fairytale Valley, *Areoligera* spp*.* and *Palaeoperidinium pyrophorum* are common in the lower part of the succession and continue into the upper part, where a distinct dinoflagellate cyst *Spinidinium* sp*.* and *Suttilisphaera* sp. have their first occurrence. This age determination suggests correlating with NP5 and with the top of sequence T20 or lower part T30 of Ebdon *et al.* (1995). The age is confirmed by Jolley & Whitham (2004b) who suggested correlation of the Fairytale Member with T22 (TPaMFS60–TPaMFS75 interval).
- The onset of volcanism in East Greenland is constrained by an intrabasaltic mudstone containing the dinoflagellate cyst *Wetzeliella* (now *Apectodinium sp*.) (Soper *et al.* 1976a). The *Wetzeliella* flora indicates an early Sparnacian age (Soper *et al.* 1976a) corresponding the Ypresian (early Eocene). This early Eocene (T40) age is supported by Jolley & Whitham (2004a) based on samples from the Kulhøje Member and correlation with the North-East Greenland flora assemblages. The bloom of *Apectodonium* sp. in the North Atlantic region is attributed to the Late Paleocene Thermal Maximum (LPTM), which marks the boundary between the Paleocene and the Eocene. In the present study we were not able to locate the *Wetzeliella* horizon and therefore no new data on the age of the basalts can be given.

The palynology across the Cretaceous–Paleogene boundary is the subject of further research in the Sindri Project: “Stratigraphy, sedimentary provenance and sequence development of the Upper Cretaceous – Paleogene strata of East Greenland and the Faroe-Shetland region”.

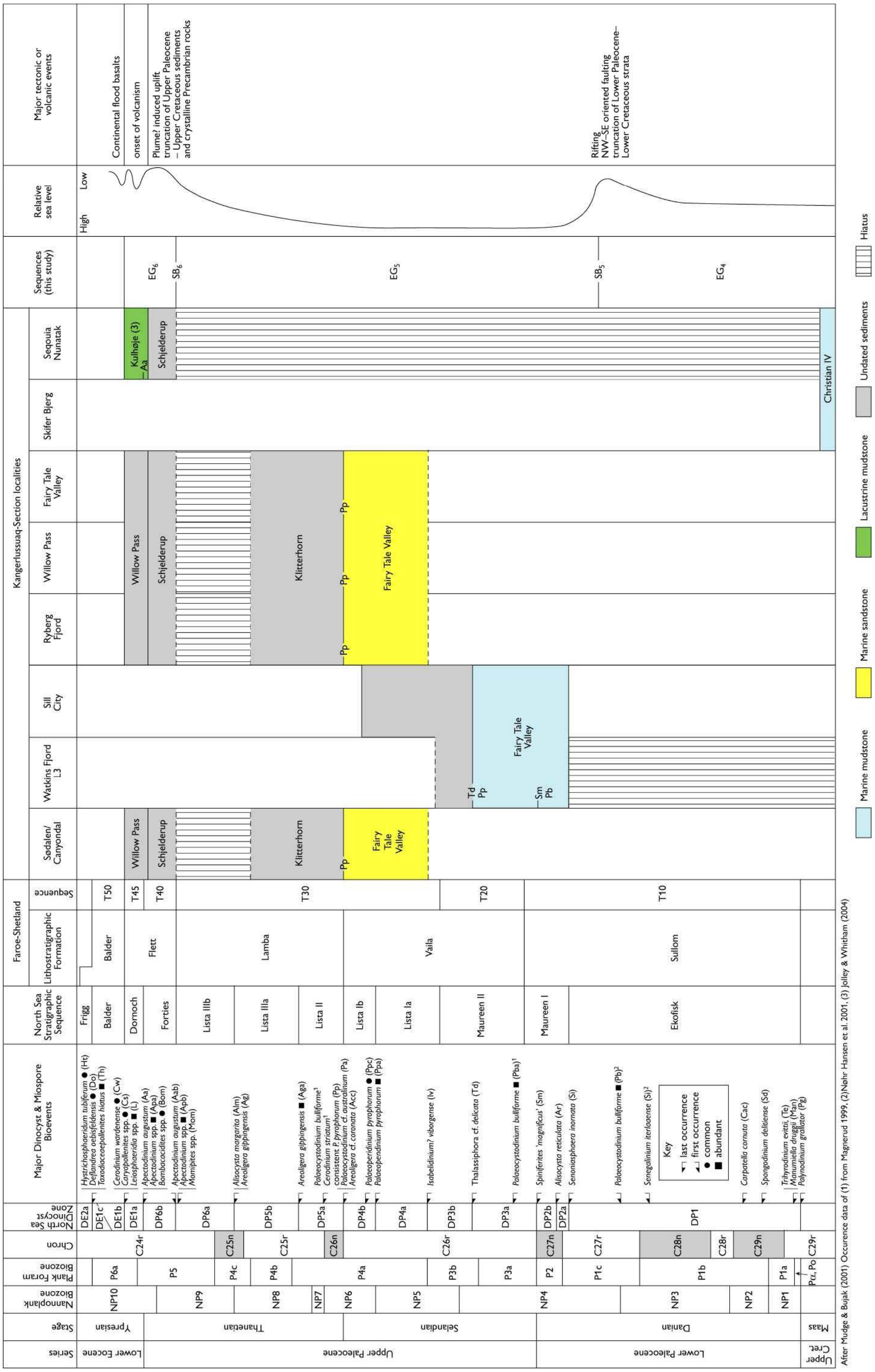

Figure 5. *(Enclosed as high-resolution PDF file). Palynostratigraphy of the Paleogene sections of the Kangerlussuaq Basin. The sections are dated using the composite event charts of West Greenland, the Faroe-Shetland region and the North Sea.*

Correlation chart of the Kangerlussuaq Basin

In August 2004, field work was performed within the Sindri project and important new sections were measured and key sections were revisited. The final interpretation based on 23 key sections is shown in Figure 6. It forms the basis for interpretation of lithostratigraphic units, sedimentary environments and reconstruction of the basin evolution. Important observations are thickness variations and identification of hiatuses and angular unconformities. Two of the most important observations are:

- The thickness variation seen in the Christian IV Formation, is probably the result of movement on Christian IV fault zone and subsequent erosion.
- The basinwide presence of the sheet-like fluvial sandstones of the Schjelderup Member indicates widespread and deep erosion of the East Greenland margin in the Late Paleocene.

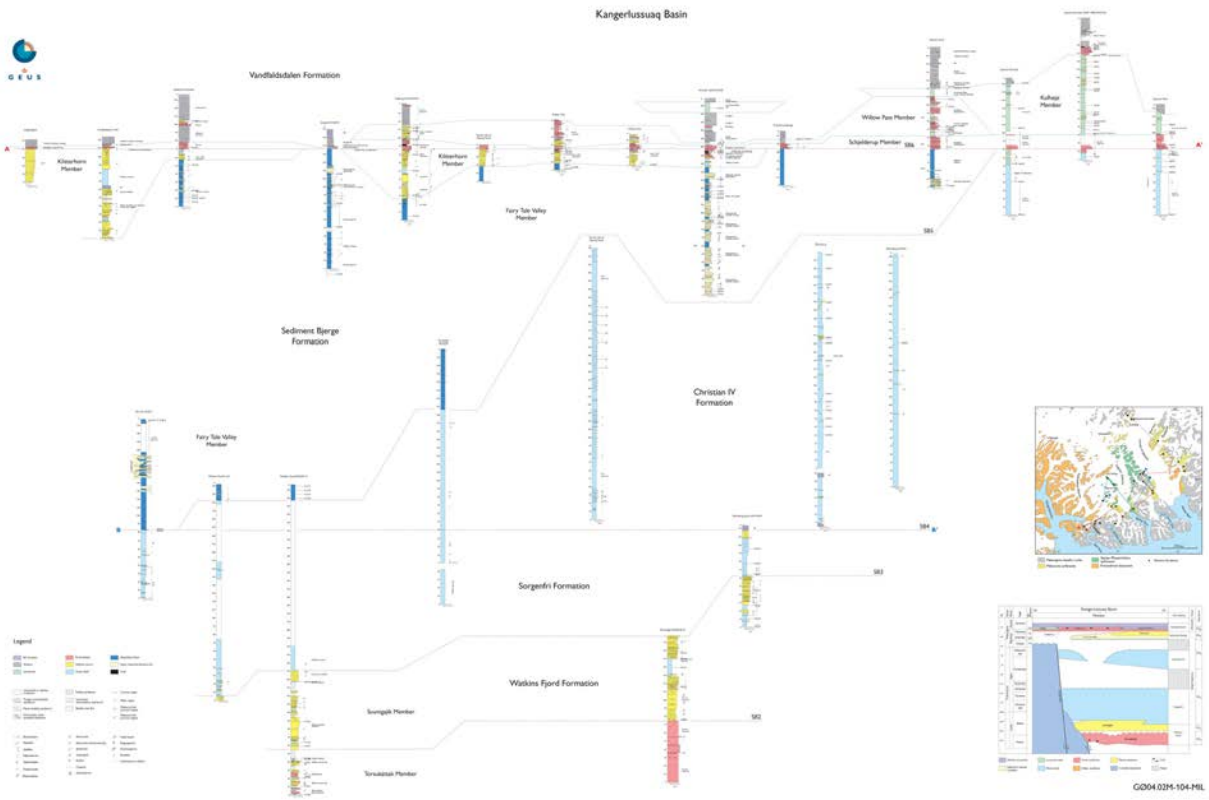

Figure 6. *(Enclosed as high-resolution PDF) Correlation chart showing the main sections, lithostratigraphic units and facies associations. Note datum for the Cretaceous sections is SB4 (top of Sorgenfri Formation.) and SB6 (base of Schjelderup Member) for the Paleogene sections.*

Basin evolution and tectonic phases

The succession in Kangerlussuaq has been divided into six unconformity bounded units (sequences) that form the basis for interpretation of basin evolution and tectonic phases. 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 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. The shallowing upward succession from the Klitterhorn Member to the Schjelderup Member probably represents the progradation of a sequence recognised in the Faroe-Shetland Basin that reached its maximum basinward extent in T40 time.
- 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.

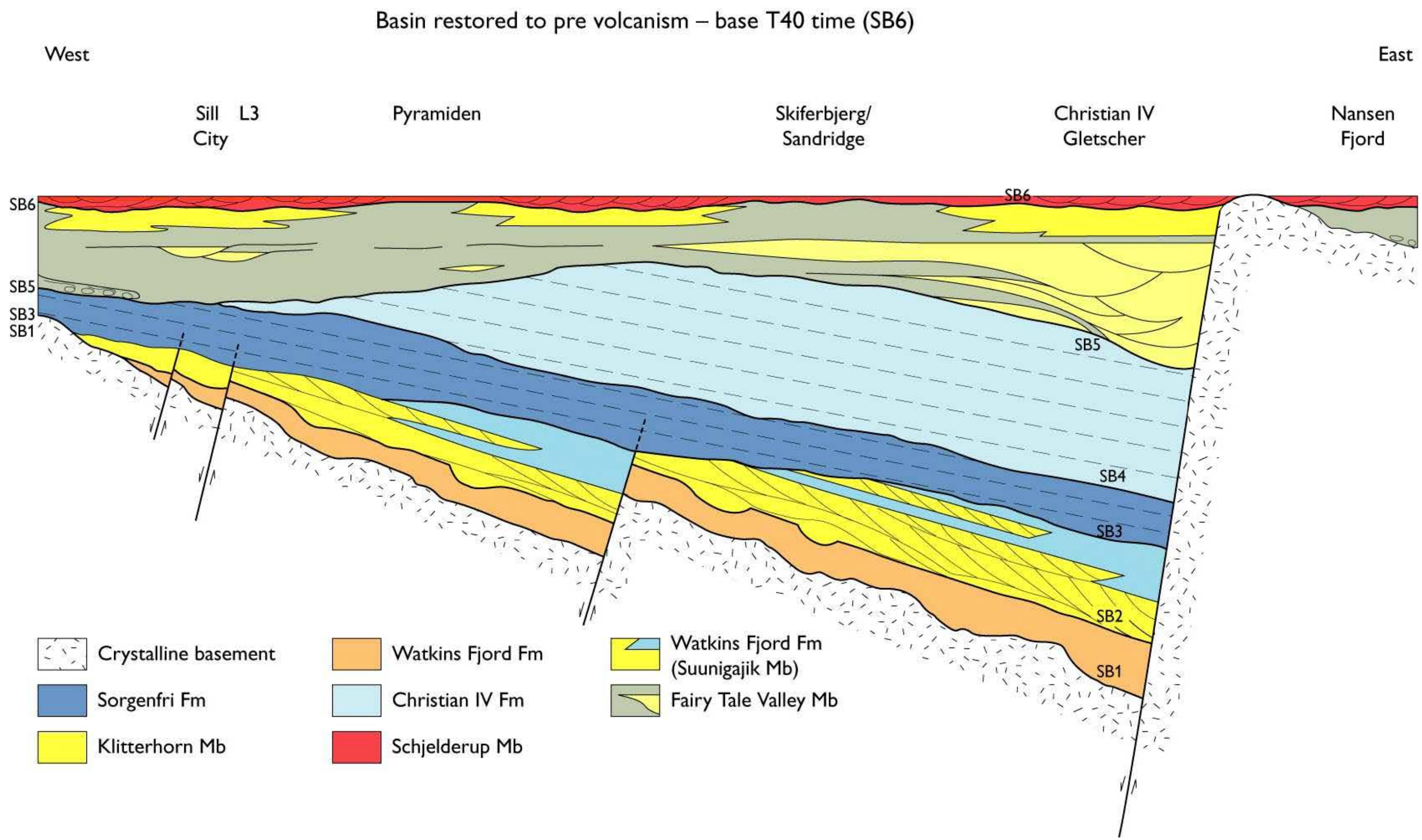

Figure 7. *Schematic Southwest–Northeast cross-section of the Kangerlussuaq Basin restored to SB6 time (Base T40, Thanetian).*

Correlation of the Jurassic – Paleogene successions West of Shetland, the Faroes and SE Greenland

The sedimentological evolution of the Cretaceous–Early Paleogene succession in Kangerlussuaq finds strong parallels with successions of equivalent age on the eastern margins of the Faroe-Shetland rift. In both areas shallow marine sandstones of Early Cretaceous (?Barremian–Albian) age are overlain by a by Late Cretaceous mudstones. In both areas there is an influx of deep marine sandstones in the Paleocene. Deep marine sediments are succeeded by a prograding package of pro-delta, fluvio-deltaic and finally fluvial sediments. An important sequence boundary occurs at the base of the fluvial sediments (EG SB_6) and probably corresponds to a major sequence boundary of T40 age in the Faroe Shetland region

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 occurs between the Christian IV and Sediment Bjerge formations and spans the Late Maastrichtian–Danian interval (SB_5). 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 Kangerlussuaq region (Whitham & Morton 2004). Recent studies by Jolley *et al.* (2005) based on pollen frequency data however, suggest that sediment derived from Greenland is present in several wells of the Faroe–Shetland Basin.

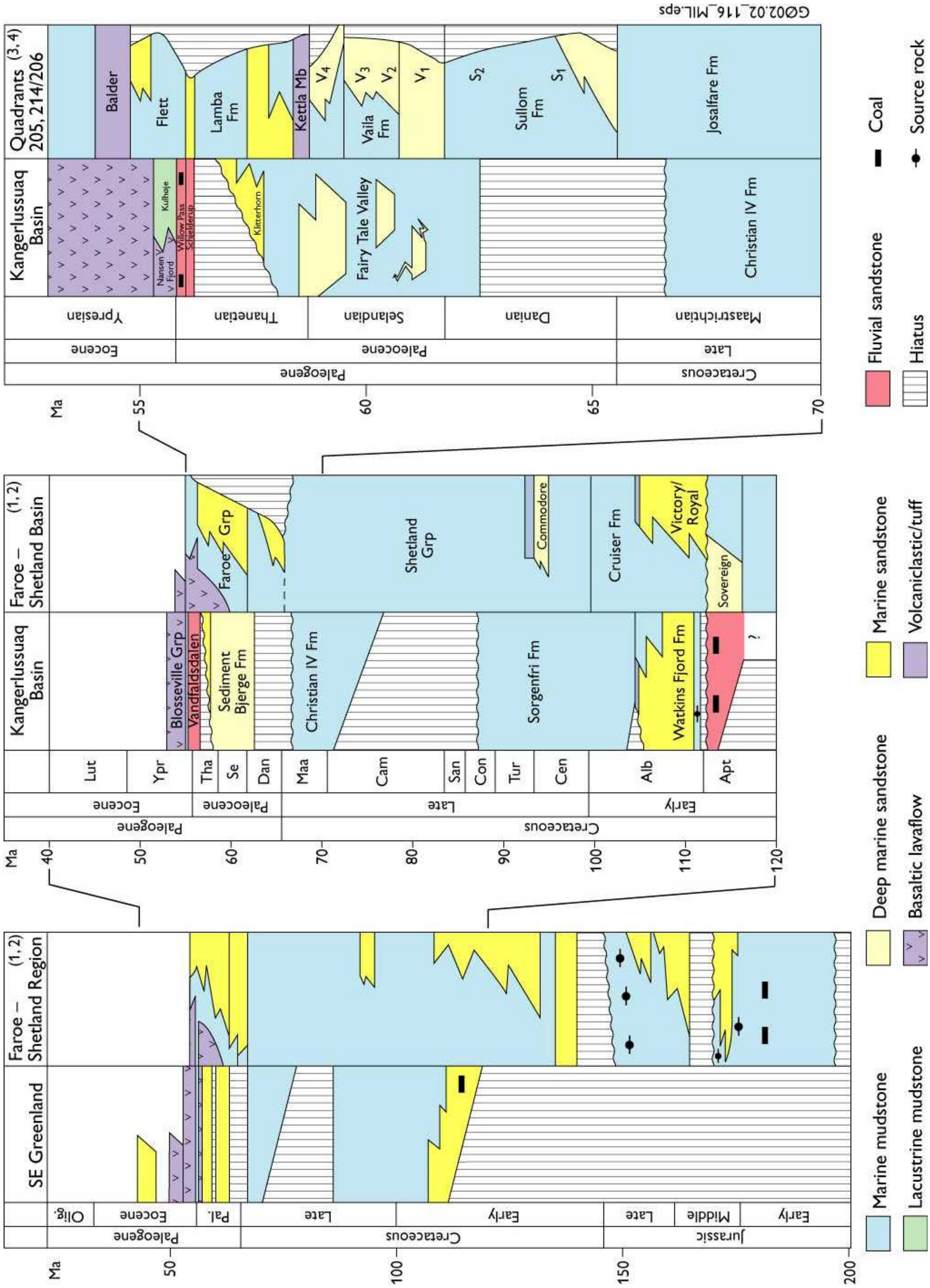

Figure 8. *Correlation of the Jurassic – Early Paleogene successions West of Shetland, the Faroes and in southern East Greenland. Stratigraphic information in the Faroe–Shetland region from 1) Grant et al. 1999; 2) Ellis et al. 2002; 3) Knox et al. 1997; 4) Mudge & Bujak 2001. Timescale from Gradstein et al. 2004.*

Palaeogeographic maps of the Faroe-Shetland region

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

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

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

The Albian was a time of coarse clastic sedimentation on the margins of the rift. Sediments accumulated in high-energy shallow marine depositional environments. Local highs in the rift may also have accumulated fringes of sandy shallow marine strata, but it is thought that these would have been of limited thickness and aerial extent. Mudstones would have been the dominant deposit in more basinal areas. Deposition of mudstones with oil-source rock potential occurred in low energy shallow marine environments between areas of shallower high-energy sedimentation. Following faulting in the Mid to Late Albian, mudstone deposition became more widespread as coarse clastic sedimentation stepped back on to the basin margins during post-rift thermal subsidence.

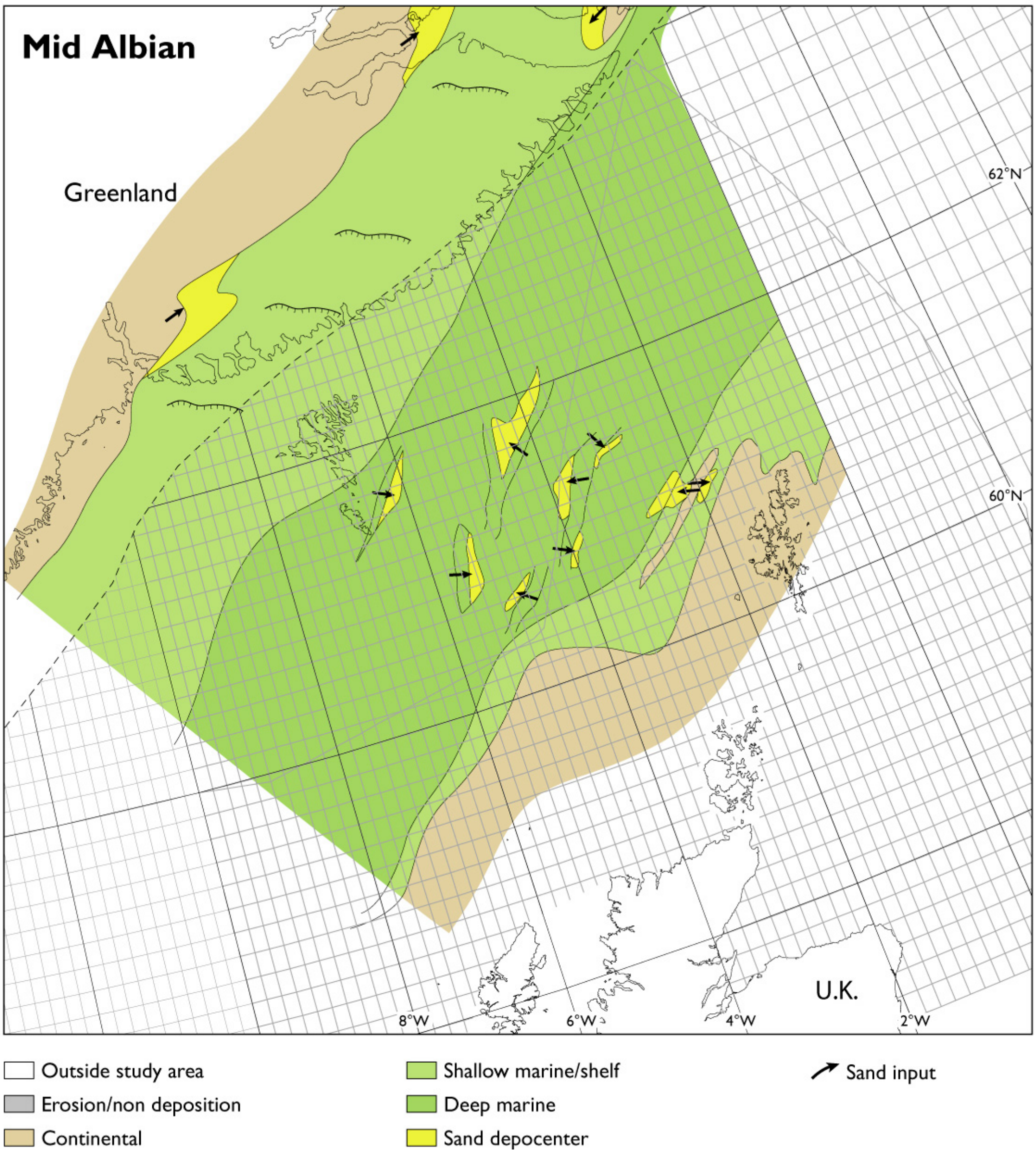

Figure 9. *Mid-Albian.*

Rising sea levels and limited extension in basins meant that areas of coarse clastic sedimentation stepped backwards from the rift onto the basin flanks. At times the Orkney Shetland Platform probably was totally submerged. A little way to the south around the latitude of Skye chalk sedimentation occurred possibly extending across the entire Scottish mainland at times. Given the limited source areas for sediment on the southwest side of the Faroe-Shetland Basin, the large thickness of Campanian mudstone found in the Faroe-Shetland Basin must have been derived from Greenland. During the Early Campanian there was a major fall in sea level leading to the formation of a sequence boundary in East Greenland. The reasons for this sea level fall are uncertain, but may have their origins in the rifting and plume impact on the western side of Greenland (Dam *et al.* 1998). Sands associated with the formation of this sequence boundary in East Greenland would have been deposited in basinal areas to the east.

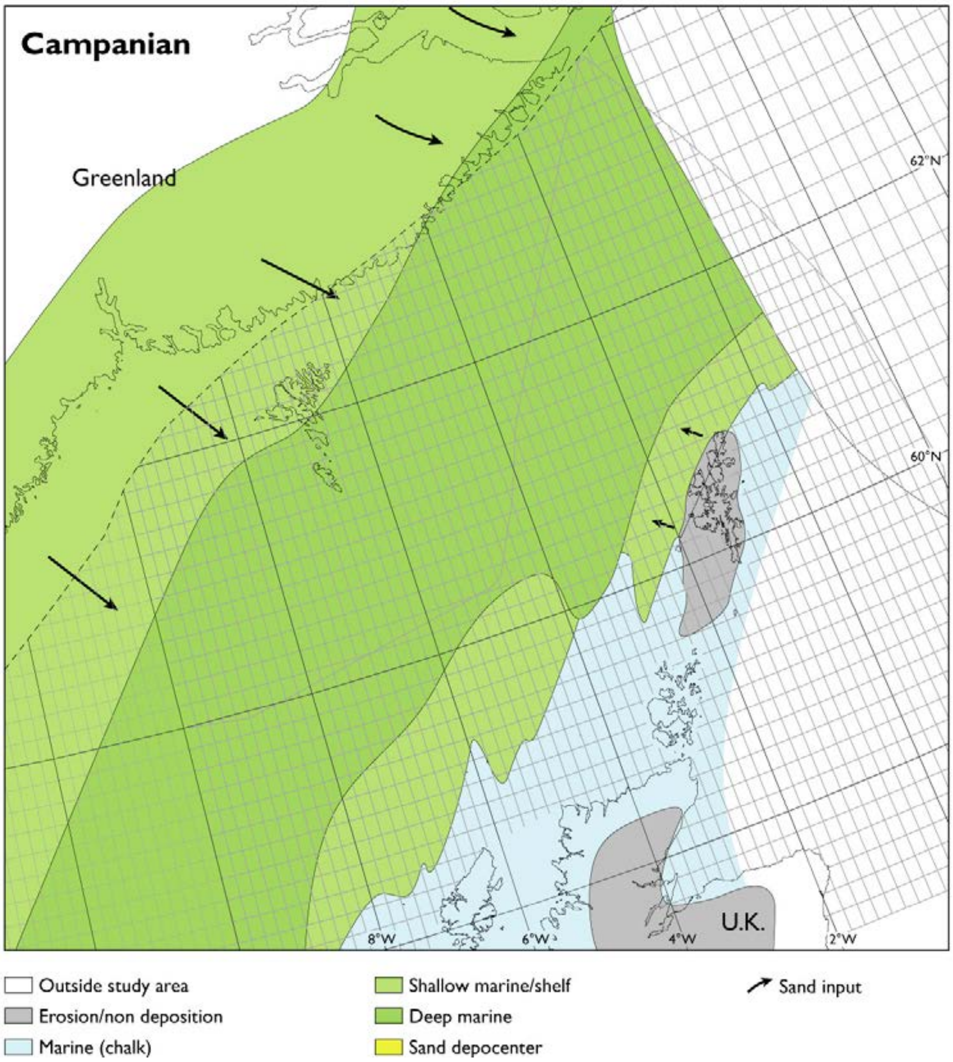

Figure 10. *Campanian*

During the Early Paleocene the Faroe-Shetland Basin came under the influence of rifting and the direct influence of the Iceland hotspot. As a result the basin margins were rapidly uplifted and denuded and large quantities of sediment were eroded and transported to the Faroe Shetland Basin. With the uplift of the rift flanks, sands were supplied from the Orkney Shetland Platform to deep marine fans in the Faroe-Shetland Basin (Lamers & Carmichael 1999). Sediment derived from the Greenland side of the rift reached as far east as wells 204/20-3 and 205/9-1 as indicated by the presence of a distinctive Greenland flora (Jolley & Whitham 2004b). In the light of active rifting at the time, sediment transport across the structural grain of the rift from East Greenland seems unlikely. Although transfer zones, that transect the rift (Naylor *et al.* 1999; Larsen & Whitham 2005), may have allowed southeasterly sediment transport. In the light of the fault orientation in the rift, relative to the trend of the Blosseville Kyst on reconstructions, the most likely sediment transport path from Greenland, to the Faroe-Shetland Basin would appear to be from the Blosseville Kyst region down the axes of the graben.

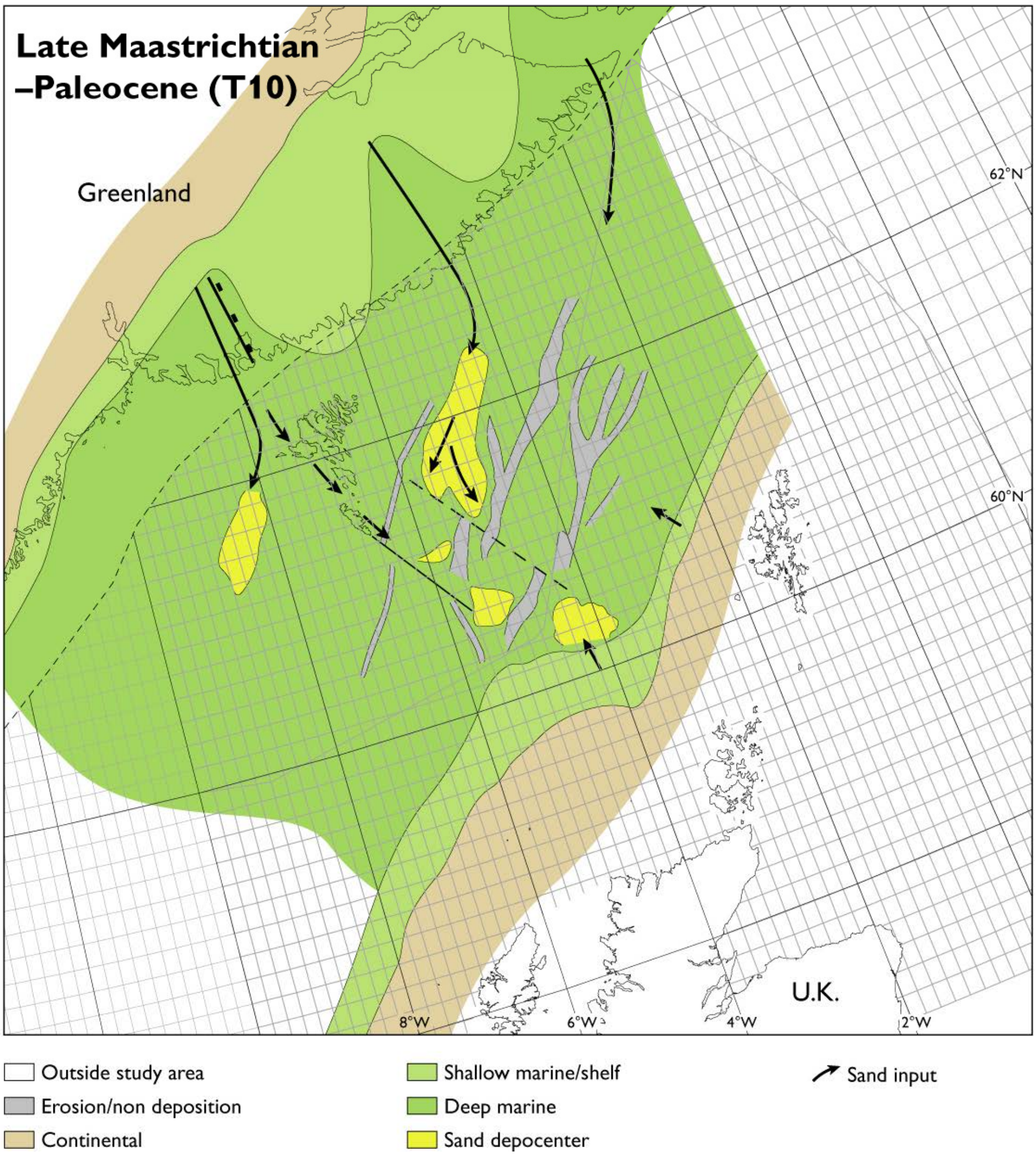

Figure 11. *Late Maastrichtian–Paleocene T10*

The presence of basaltic material in the Kettla Member of T36 age, which is derived from the west (Lamers & Carmichael 1999), is evidence for volcanic activity in the Faroe-Shetland Basin by the end of the Paleocene. Sediment from the Orkney-Shetland Platform prograded out into the basin, with sands deposited at the toesets of clinoforms forming important reservoir targets in T40 time (Roberts *et al.* 1999). Similar clinoforms may well have been developed along the western margin of the basin. 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). Although Paleocene–Eocene sands in Kangerlussuaq do not contain any evidence for basaltic volcanism, basaltic volcanic centres may have created a barrier to the eastward transport of sand from Greenland to the Faroe-Shetland Basin at this time, deflecting sediment to the north or the south. Any Greenland sourced sediment is likely to have come down the axis of the rift from the Blosseville Kyst region in a scenario similar to that described for the Early Paleocene.

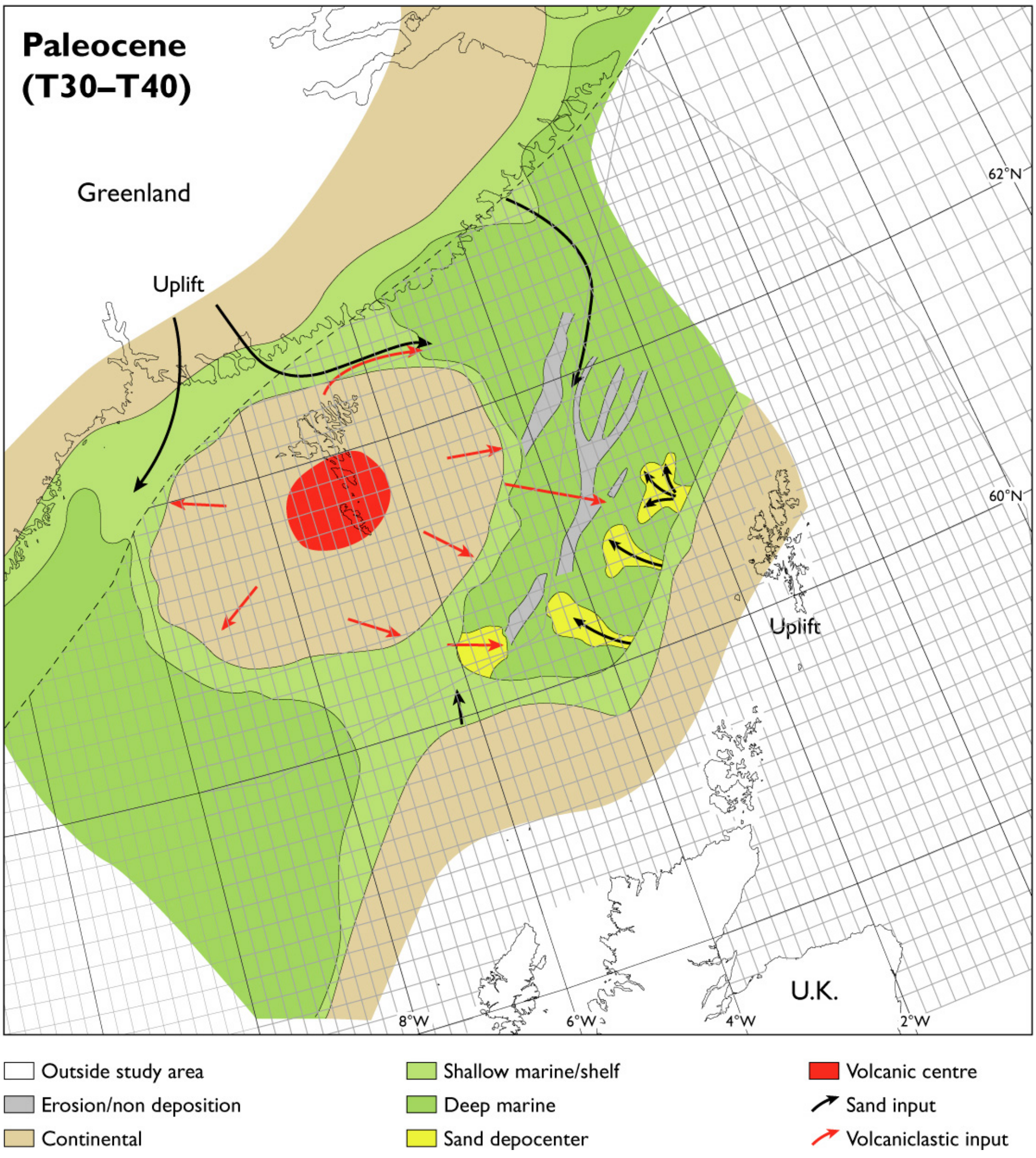

Figure 12. *Paleocene T30–40*

GIS project for the Kangerlussuaq Basin

A new geological map was created in this project and uses the advantages of Geographical Information Systems (GIS) (Fig. 13). The project is created in ArcView 3.2. The topographic base for the map was done by the Department of Mapping in GEUS.

The sedimentary succession is divided into four mapable units: Watkins Fjord Formation, Sorgenfri Formation, Christian IV Formation of Cretaceous age and Paleogene sediments consisting of Sediment Bjerge Formation and the sedimentary succession of the lower Vandfaldsdalen Formation (Schjelderup, Willow Pass and Kulhøje Members).

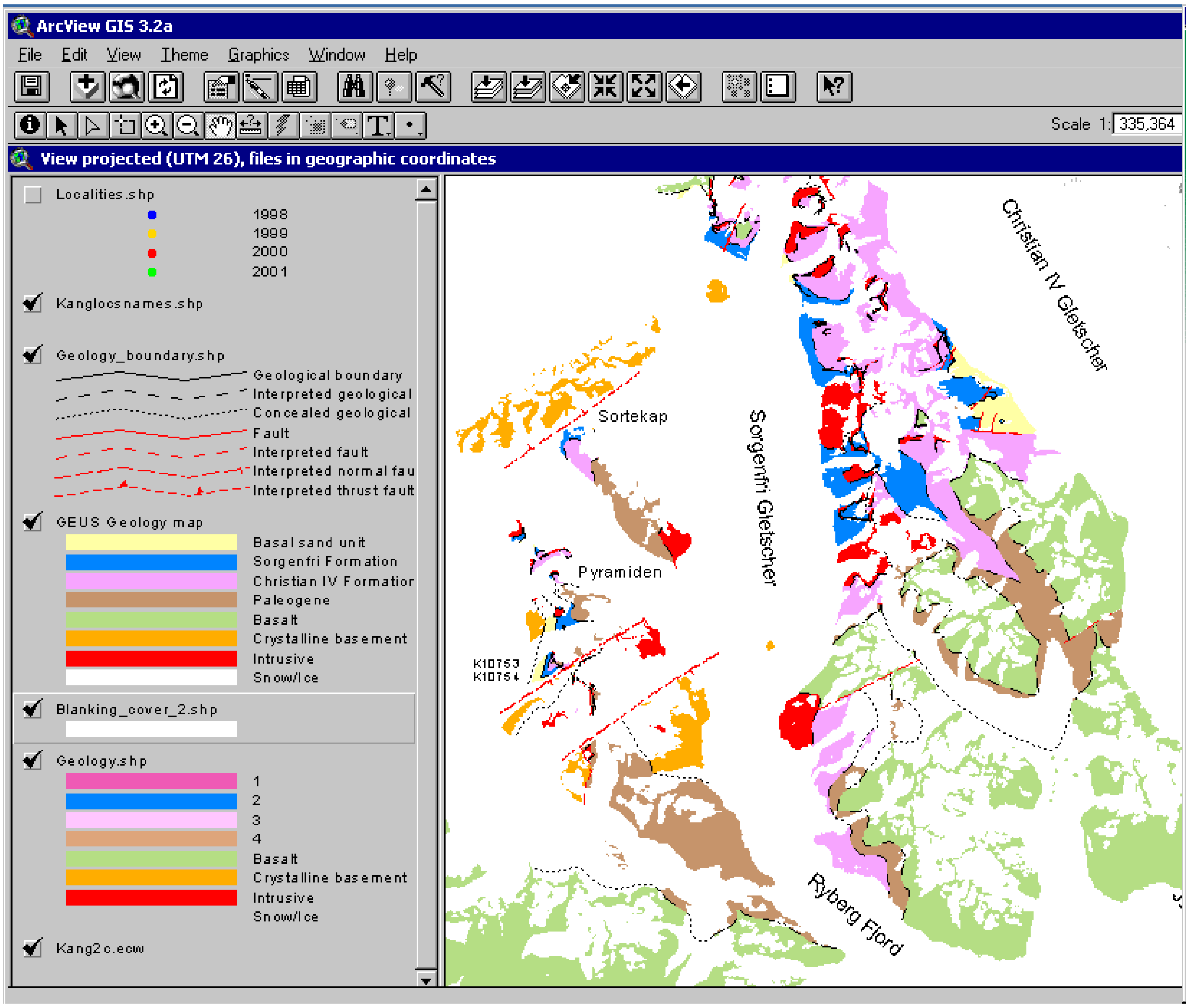

Figure 13. *Screenprint showing detail of the new GIS based geological map developed for the Sindri project.*

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References

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.

Doré, A.G., Lundin, E.R., Jensen, L.N., Birkeland, Ø., Eliassen, P.E. and Filcher, C. 1999. Principal tectonic events in the evolution of the northwest European Atlantic margin. *In:* A.J. Fleet and S.A.R. Boldy (Eds.), *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. Geological Society of London, London, 41–61.

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.

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.

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

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.

Jolley, D.W. and Whitham, A.G. 2004a. A stratigraphical and palaeoenvironmental analysis of the sub-basaltic Paleogene 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.

Kimbell, G.S., Ritchie, J.D., Johnson, H. and Gatliff, R. 2005. Controls on the structure and evolution of the NE Atlantic margin revealed by regional potential field imaging and 3D modelling. *In:* A. Doré and B. Vining (Eds.), *Petroleum Geology: North-West Europe and global perspective - Proceedings of the 6th petroleum geology conference*. Geological Society, London, **2,** 933–945.

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. & Stemmerik, L. 1996: Cretaceous–Tertiary pre-drift sediments of the Kangerlussuaq area, southern East Greenland. Bulletin Grønlands Geologisk Undersøgelse **172**, 37–41.

Larsen, M., Hamberg, L., Olaussen, S., Nørgaard-Pedersen, N. and Stemmerik, L. 1999a. 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., Hamberg, L., Olaussen, S., Preuss, T. and Stemmerik, L. 1999b. Sandstone wedges of the Cretaceous–Lower Tertiary Kangerlussuaq basin, East Greenland-outcrop analogues to the offshore North Atlantic. *In:* A.J. Fleet and S.A.R. Boldy (Eds.), *Petroleum geology of northwest Europe: Proceedings of the 5th Conference*. London: The Geological Society, London, 337–348.

Larsen, M. and Whitham, A.G. 2005. Evidence for a major sediment input point into the Faroe-Shetland Basin from the Kangerlussuaq region of southern East Greenland. In: A. Doré and B. Vining (Eds.), Petroleum Geology: North-West Europe and global perspective - Proceedings of the 6th petroleum geology conference. Geological Society, London, 2, 913–922.

Larsen, M., Nøhr-Hansen, H., Whitham, A.G. & Kelly, S.R.K. 2005. 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.

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.

Naylor, P.H., Bell, B.R., Jolley, D.W., Durnall, P. and Fredsted, R. 1999. Paleogene magmatism in the Faeroe-Shetland Basin: influences on uplift history and sedimentation. *In:* A.J. Fleet and S.A.R. Boldy (Eds.), Petroleum Geology of Northwest Europe, Proceedings of the 5th Conference. Geological Society of London, 545–558.

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. & 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.

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.

White, N. and McKenzie, D.P. 1988. Formation of the "steer's head" geometry of sedimentary basins by differential stretching of the crust and mantle. *Geology,* **16**, 250–253.

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.