# Late Cretaceous sediment provenance and transfer pathways in the Faroe  Shetland region

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## Preface

This report is presented in conclusion of the study entitled "Late Cretaceous sediment provenance and transfer pathways in the Faroe-Shetland region". Funding from this project was provided by the 'Sindri' consortium for a group of three projects under the umbrella title *Stratigraphy, Sedimentary Provenance and Sequence Development of the Upper Cretaceous – Paleogene Strata of East Greenland and the Faroe – Shetland Region*. It forms a part of the Sindri programme 'Future Exploration Issues of the Faroese Continental Shelf'. The two complimentary projects in this study are are:

*Biostratigraphy zonation (palynology and macrofossil) for the Upper Cretaceous – Lower Palaeogene based on the sedimentary succession in Kangerlussuaq, southern East Greenland*: Phase I report by Nohr Hansen, H., Larsen, M. Kelly S.R.A. & Whitham A.G. 2006.

*Developments in the stratigraphy of the pre-basaltic sucession of the Kangerlussuaq basin. Volcanic basins of the North Atlantic: Integration of data and conclusions*. Phase III report by Nohr Hansen, H., Kelly S.R.A., Whitham A.G. Larsen, M. & Jolley, D. 2006.

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## SUMMARY

Analysis of terrestrial palynofloras from east and west Greenland, offshore Norway and the Faroe-Shetland Basin has yielded evidence which can fingerprint argillaceous sedimentary sources. Within the region, phytogeographical analysis has isolated the following types in the Campanian - Masstrichtian interval:

A Norwegian flora, characteristic of this is the combination of triprojectate and Normapolles group pollen with pollen of laurel types.

A Greenland flora, which contains a moderately diverse triprojectate assemblage, and has a moderately diverse suite of bryophyte spores.

A Scottish flora, which is characterised by an abundant and diverse triprojectate flora. The remainder of the assemblage is composed of bryophyte spores, fern spores and gymnosperm pollen, and is not highly diverse.

Within the Faroe-Shetland region, the sediment supply is wholly derived from Greenland. Detrital white mica dating suggesting it was derived from the Caledonian fold belt, inland in an area now under the ice cap.

Although some Scottish input is identified into the Erlend area, the volumes of sediment derived from this are minimal. This is a direct contrast to north of 63°, where there is a almost equal input of westerly and easterly sourced argillaceous sediment into the northeast Atlantic.

Data for the older Turonian  Santonian interval is less equivocal, but indicates that the Campanian Maastrichtian argillaceous sediment transfer model applies here also.

Significant cooling is demonstrated to have occurred in terrestrial environments at the end of the Santonian, with subsequent warming occurring in the upper Campanian. This provides a stratigraphy for pollen and spore assemblages in the region, although currently it does not compare with the resolution available from other micropaleontological data.

In the region of the Faroe Islands a sediment bypass system developed in Santonian - Early Campanian (Larsen et al., 2005). The new data gathered here indicates that westerly sediment transfer into the Faroe-Shetland Basin dominated the Late Cretaceous period.  Although the lack of borehole coverage means that direct evidence is not available, sequences of Cenomanian - Coniacian and Late Campanian - Maastrichtian mudrocks could be expected to occur under the Faroe Islands. There remains the possibility that westerly sourced clastic sediments of Santonian - early Campanian age may occur in this area. These are more likely to host arenaceous beds by virtue of them being deposited during a period of low relative sea levels.

The dominance of Greenland sourced argillaceous sediment in the Late Cretaceous Faroe-Shetland Basin to the exclusion of any easterly source highlights the low lying topography of the Scottish region. With the initiation of rifting during the Danian, rift flank uplift was initiated and resulted in significant elements of basin fill being derived from both uplifted flanks.

## OBJECTIVES

This study uses biostratigraphy and phytogeographic analysis of Late Cretaceous sedimentary sections in Greenland and the Faroe-Shetland Basin to establish the extent of westerly derived sediment influence that would be expected to occur under the offshore Faroe Islands lava field. This phytogeographical analysis, is allied to detrital white mica isotopic dating of selected Faroe-Shetland and Greenland (Cenomanian Maastrichtian) sections. This analysis provides a test and calibration for the phytogeographic data. This will allow an insight into the likely composition of the Late Cretaceous component of the 2km+ of pre-rift to base basalt sequence predicted by White et al. (2003), for the East Faroe Platform area.

In using palynomorphs to establish sedimentary provenance, it should be borne in mind that pollen behaves as silt sized particles in the sedimentary system. Transportation of pollen into basinal depositional environments is dependant on either salinity stratification in the basin watermass, or the location of a plume or plumes from major sedimentary input points. All of the palynofloras examined were dominated by *Inaperturopollenites hiatus* (Taxodiaceae, redwoods and swamp cypresses) and *Pityosporites* (*Pinus* types). Common occurrences of *Stereisporites* species are also recorded. These spores are either derived from mosses or liverworts, suggesting cooler, wet climatic conditions. Their occurrence also maps well onto the records of '*Liverwortiphylum*' macrofossils seem commonly in Campanian- Maastrchtian Arctic Canada (Spicer, pers comm., 2003).

## ORIGINS OF NE ATLANTIC PHYTOGEOGRAPHY

The period from the Campanian to the base of the Palaeocene was one of an overall cooling global climate. While the Cretaceous - Paleogene boundary was a catastrophic event in terms of the equatorial biota, Arctic floras show a more gradual change, if any change is evident at all. This change appears to have been, in part due to the climatic warming initiated at around the K/T boundary, leading to the global greenhouse of the Eocene Thermal Maximum at 52.5Ma.

Warm climate Palaeocene floras from Greenland are dominated by pollen from what is thought to have been a mixed mesophytic forest, typified by members of the Fagaceae (Jolley et al., 2005). Occurring with these, are rare occurrences of pollen, previously only described from North America, implying some connection with this separate phytogeographic province. A contrasting coeval flora is recovered from Ireland, Hebrides (Jolley, 1997), offshore Shetland Islands (Naylor et al., 2000; Ellis et al., 2002) and the North Sea Basin (Jolley and Morton, 1992), being dominated by pollen of the Juglandaceae. The dominant taxa have previously been recorded *insitu* as swampland primary colonisers (Wing & Hickey, 1984), and occur along the northeast Atlantic Margin in association with pollen from other wetland types. Only around the Palaeocene-Eocene Thermal Maximum (PETM) is this division between Greenland and northeast Atlantic Margin floras broken down. The thermal maximum forces high latitude warming, which combined with thermal uplift from the impact of the Iceland Plume under Greenland, creates a land bridge across which elements of floras from the northeast Atlantic margin, Greenland and North America intermix. This ends the trans-Atlantic segregation of floras, which up to this period had lead to widely different evolutionary pathways in North American and European angiosperms.

The origins of this Early Paleocene floral differentiation lie in the Late Cretaceous (Jolley & Whitham, 2004). The Campanian - Maastrichtian was a period of steady climate cooling and falling atmospheric $CO_2$ levels, terminating with the K/T boundary event and the subsequent gradual warming of the Palaeocene climate. Combined with rifting in the NW Atlantic and epicontinental seaways in the NE Atlantic, high sea levels may have forced segregation of the Arctic flora by marine barriers and a cooling pole. A barrier role is also probable for the central Asian seaway (Chlonova, 1981). Late Cretaceous plant macrofloras in Alaska and Siberia show the impact of the isolation of the Arctic Ocean from the proto-Pacific, and northward equatorial warm water transfer along the American Western Interior Seaway (Herman & Spicer, 1997). These oceanic barriers would have become increasingly effective as Campanian-Maastrichtian temperatures cooled. Plant microfossil floras recorded from the Late Cretaceous of the circum Arctic have been grouped into the *Aquilapollenites* province, variations in the composition of this providing evidence of the efficacy of the seaway barriers (Chlonova, 1981).

The dominance of the enigmatic angiosperm pollen taxon *Aquilapollenties* in the circum Arctic, continued until the end of the Campanian. From the early Maastrichtian, these triprojectate pollen decline in frequency, their place being taken by pollen from low diversity, Taxodiaceae (Swamp Cypresses and Dawn Redwood types) dominated vegetation. While there is some evidence that west Greenland continued to host an *Aquilapollenties* rich flora into the latest Maastrichtian, the decline in their dominance is seen across the Arctic. This simplification of the Maastrichtian flora is combined with records of Normapolles pollen (some are proto- Hickories and Pecans) in these Arctic sediments. A small number of taxa from this warmer Normapolles phytogeographic province, are also seen in a mixed Normapolles/Aquilapollenites zone recorded from western Canada and Siberia. These taxa, *Plicapollis* and *Trudopollis,* are characteristic accessories of Palaeocene northeastern Atlantic margin microfloras. Within the Normapolles phytogeographic province, different species characterise North American and European floras. This is a reflection of the physical barrier of the North Atlantic, which was re-enforced by the cooling climate. Late Cretaceous evolutionary pathways within angiosperm groups differed on opposite sides of the Atlantic. In particular, the Juglandaceae, which form an important part of the northeastern Atlantic margin flora, evolved from a Normapolles lineage. Other Siberian and western Canadian angiosperm pollen *Alnipollenites trina* (?Betulaceae - birches) and *Triatriopollenites triangulus* (?Myricaceae - myrtles) are also present in the northeast Atlantic margin and North American Palaeocene floras.

## NE ATLANTIC CAMPANIAN - MAASTRICHTIAN PALYNOFLORAS

Prior to the commencement of this study, we undertook a research and development project for an industry partner which has direct relevance to the results presented here. This research involved palynofloral analysis of the Maastrichtian interval in wells between 63°N and 67°N and the Campanian in a well from 64°N offshore Norway. This research was undertaken (Jolley, 2004), to determine if any evidence existed for some of the palynofloras being sourced from the western, Greenland side of the northeast Atlantic.

Multivariate statistical analysis of the combined dataset from these wells showed significant differences between the floras. Campanian to Maastrichtian sections in westernmost wells at 64° and 67° had a flora of moderate diversity, with a suite of triprojectate and Fagaceae pollen similar to that which defines the Paleocene phytogeography of the Greenland area. The flora of other analysed wells was significantly different, with an abundance of triporate angiosperm pollen, some of which is of Normapolles affinity. This is accompanied by a diverse suite of triprojectate pollen taxa. Fagaceous pollen was however lacking in this assemblage. It was concluded that there are two floras represented in these wells, one of which was probably derived from Greenland in eastward flowing sediment transportation systems.

When these data are subjected to statistical analysis, a clear division is demonstrated between two types of Campanian to Maastrichtian flora. The palynofloras of these wells are dissimilar to those recovered from wells known to have no westerly sedimentary input.

The principle floras are:

1. A Norway derived flora (Figures 1,2). This is of high diversity, with a diverse triprojectate pollen suite including species not seen in the westerly sourced sediments. It includes diverse Normapolles pollen and accompanying Lauraceae (laurel) types. The diversity of this flora decreases to the north, reflecting a lattitudinal lapse in land surface temperature.
2. A westerly, Greenland derived flora (Figures 1,2). This is seen in offshore wells, and in the field samples examined. There is a moderate diversity of triprojectate pollen, and little or no Normapolles pollen. These taxa are accompanied by common specimens of *Cupuliferoipollenites* and *Cupuliferoidaepollenites* species (chestnut types). These taxa, only occurring in very low frequencies in the Norway sourced flora, are characteristic of the Paleocene 'Greenland Flora' (Jolley et al., 2005; Jolley & Morton, 2007). This initial evidence suggested that the Paleocene 'Greenland Flora' originated prior to the late Campanian.

However, little is currently known about the Late Cretaceous terriginous palynoflora of east Greenland. Unfortunately, the palynofloral zones determined by Chlonova (1981) for the Late Cretaceous northern hemisphere, do not correspond with the taxa recorded in these preliminary studies. Analysis of further Cenomanian to Maastrichtian north-east Atlantic sections is necessary to establish a more detailed model for sediment transport.

### Sedimentary Provenance

Recently published seismic interpretations (White et al., 2004) across the Faroe Islands East Faroe Platform area, have indicated 1-2km thickness of pre-rift to base basalt strata. Isopach data given by these authors also suggests that the Judd and Westray Transfer Zones controlled stratal thickness during this Late Cretaceous Palaeogene period. With the recent discovery of a hydrocarbon system in Quadrant 6004, it has become imperative to gain an understanding of the sedimentary dispersal patterns in the potential Late Cretaceous reservoirs of the Faroese area. Currently, there are no wells drilled in Faroese waters which penetrate the Cretaceous. To circumvent this lack of direct evidence, we will use comparative studies between east Greenland and the Faroe-Shetland Basin. Using these data, we will interpret sediment distribution pathways in the Faroese area.

Sedimentary bypass of the Kangerlussuaq shelf by arenaceous sediment may have resulted in deposition of sediment in the Faroe Islands area. In addition, the unconformity present in Kangerlussuaq between the Cenomainan-Coniacian (Sorgenfri Formation) and the Campanian-Maastrichtian (Christian IV Gletshcer Formation) would have shifted the sedimentary system to the basinward side (Whitham et al., 1998). The stratigraphical interval represented by this unconformity is known to be sand prone in the Nyk High, Vøring basin. Samples from the Late Cretaceous of wells in this area have recently yielded Greenland derived terriginous floras. In the Faroe-Shetland Basin, wells penetrating the Cretaceous show that Cenomanian-Turonian sands are developed on the downthrown side of active faults (e.g. in 206/3-1 to the NW of the Rona Ridge Fault). Similar, thinner sands are also developed on the top of the Corona Ridge (eg 213/23-1).

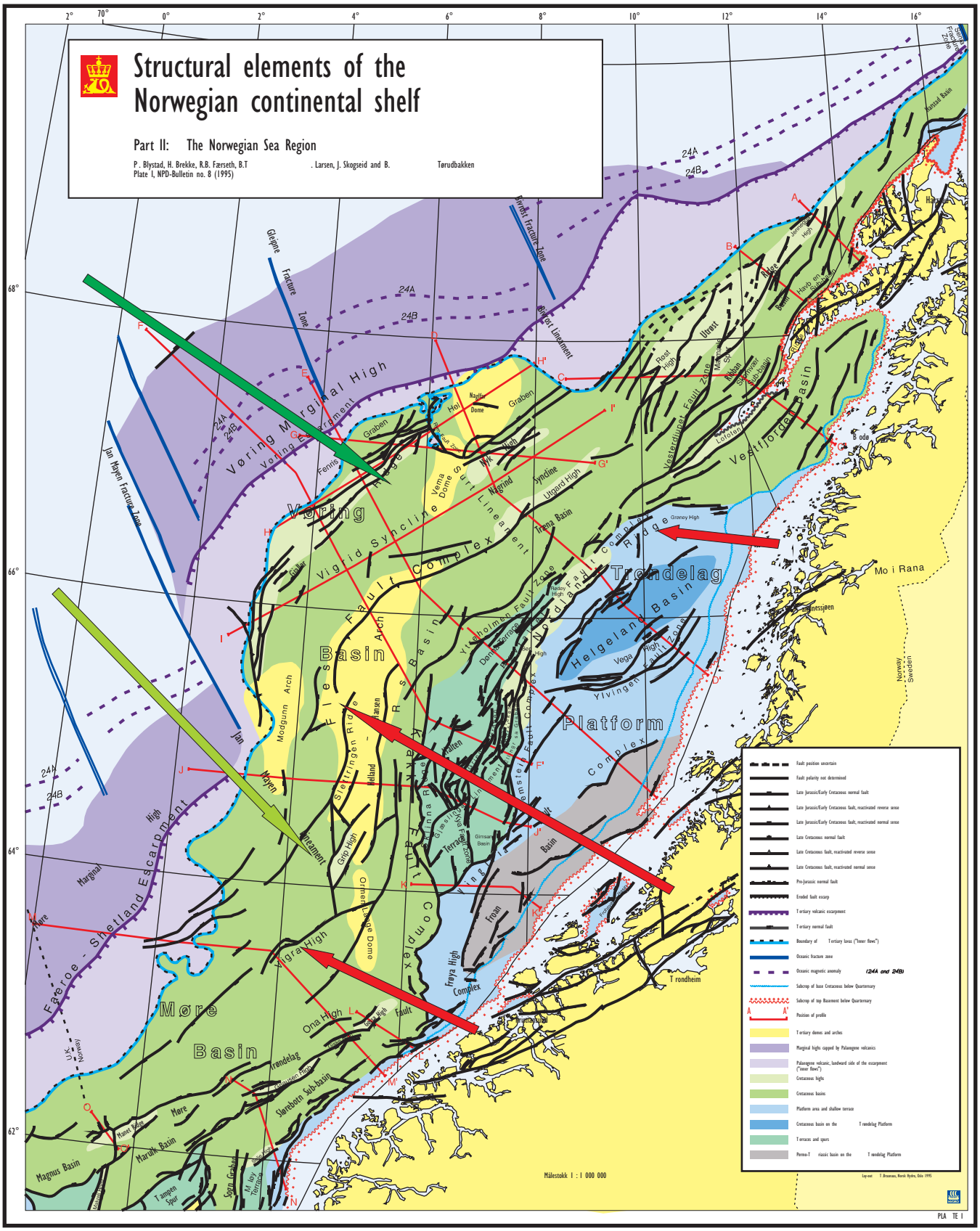
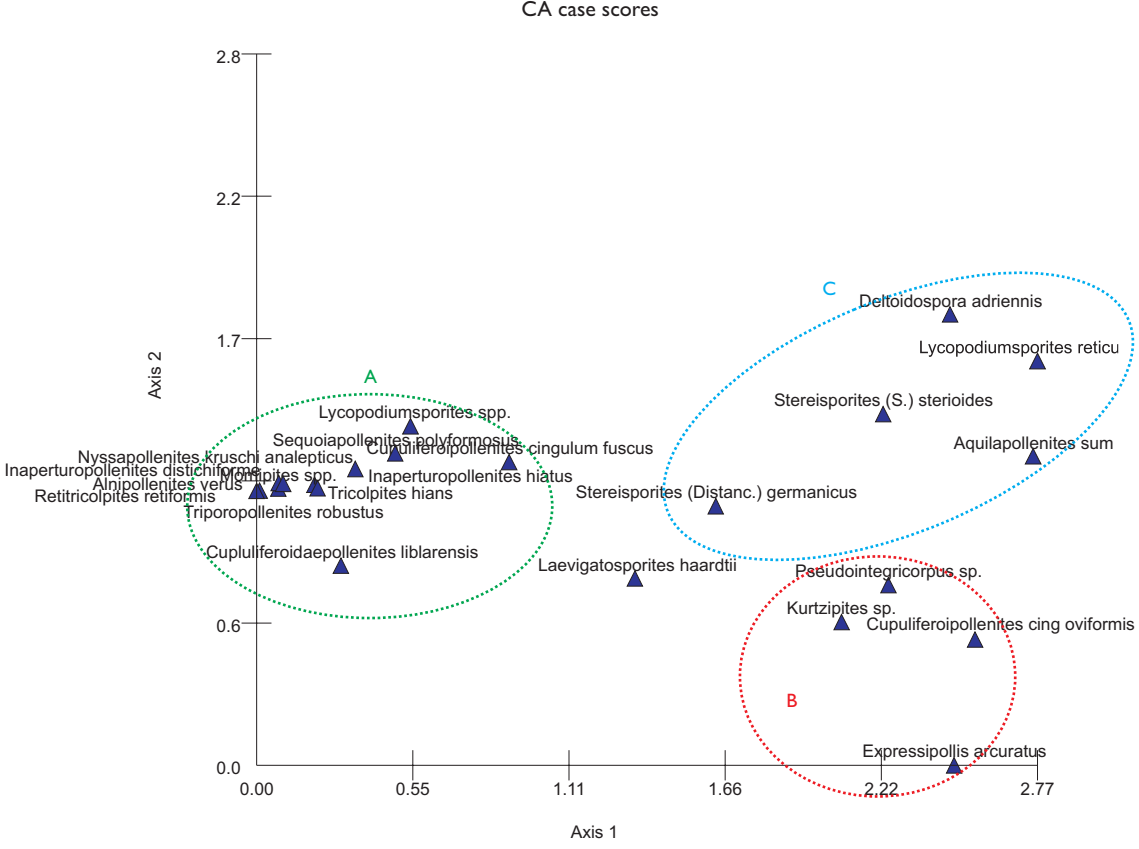
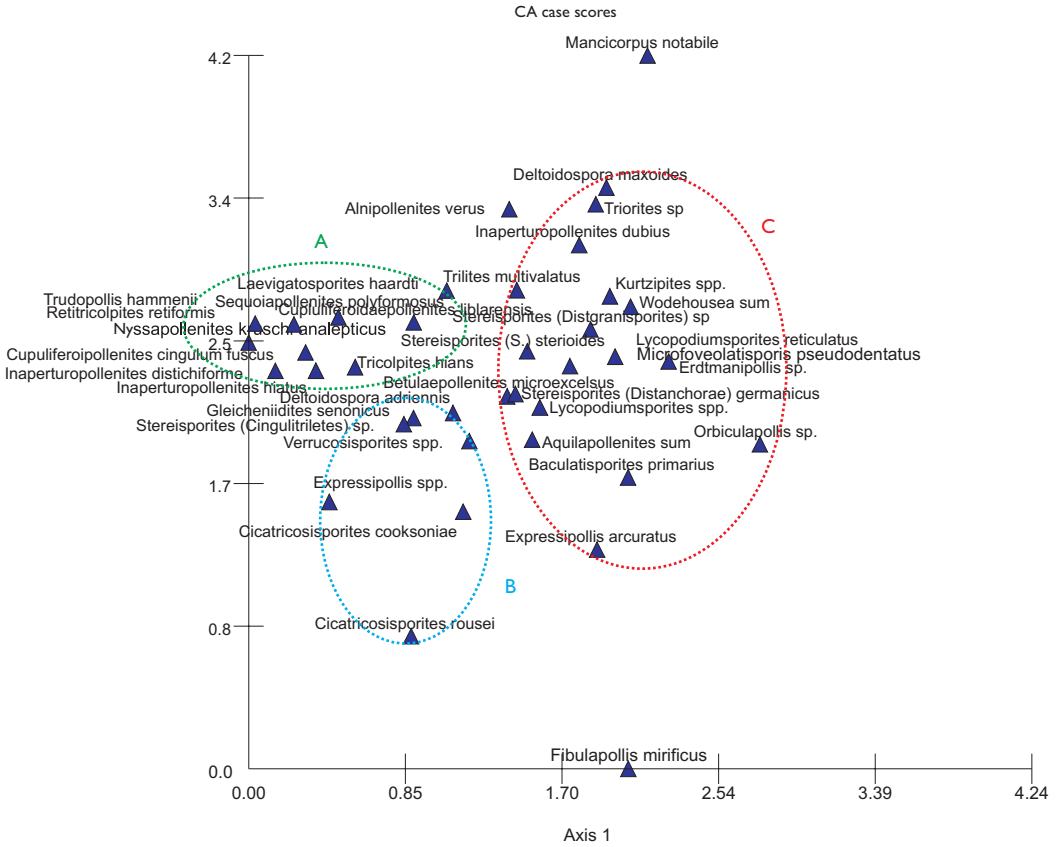



Figure 1: Map showing the distribution of known palynofloral sources in the NE Atlantic Late Campanian - Maastrichtian. Pale green arrow = Greenland derived Late Campanian flora; dark green arrow = Greenland derived Maastrichtian flora. Red arrows = Late Campanian - Maastrichtian Norway derived floras. Note that this is not an exhaustive map, only showing the extent of the currently available data set. Basemap after NPD.




Offshore Norway, Greenland Source, Maastrichtian
Group A: Late successional gymnosperm forest
Group B: Mid successional angiosperm accessory taxa
Group C: early successional bryophyte community




Offshore Norway, Norwegian source Maastrichtian floras
Group A: Late successional gymnosperm/angiosperm forest
Group B: Early successional fern community
Group C: Mid successional angiosperm community

Figure 2: Correspondence analysis plots of Maastrichtian palynofloras from offshore Norway. Note the greater diversity of the Norway-derived palynoflora. Details of the floral structure will be discussed below.

## DATA ANALYSIS

In this section of the report, we briefly describe by area, the sections which have been subjected to palynofloral or white mica analysis. Ecological analysis of the palynofloras has focussed on correspondence anlaysis and its derivative, detrended correspondence analysis. These analyses have beeen undertaken using MVSP software (Kovach, 2002). A discussion of the results and their implications forms the next section of the report.

### Geographical Society Island

Palynofloral analysis of 75 samples from Geographical Society Island, east Greenland, was undertaken to provide a reference point for the analysis of Late Cretaceous sediments in the Faroe-Shetland Basin (Figure 3 ). Analysis of the pollen/spore component of the palynofloras from the suite of samples from Geographical Society Island was undertaken to test for the existence of a western sedimentary source into the offshore Norway region during the Campanian.

The strata from which the samples were collected are the mudstone dominated Knudshoved Member and sandstone dominated units informally referred to the Leitch Bjerg Member, both belonging to the Home Foreland Formation (Kelly et al., 1998). These samples had been collected by CASP in 2003 (Whitham & Kelly, 2004), and had subsequently been analysed for their micropaleontological and dinocyst content (Kelly et al., 2004). Combined with macropalaeontological analysis, data from these studies confirmed a mid Campanian age for the sedimentary rocks.

Samples analysed for this study were taken from four exposures of Campanian sedimentary rocks on Geographical Society Island. Two of the sections W4334 and W4342 are up to 300m in thickness and comprise marine mudstones, sandstones and conglomerates. The remaining two sections, W4355 and W4356 are thinner, and duplicate parts of the more complete sections, but represent exposure from further north on the island.

#### Statistical analysis of Geographical Society Island palynofloras

Multivarite statistical analysis was carried out on the available data set to determine the degree of difference or similarity between the Geographical Society Island Campanian palynofloras and the Campanian and Maastrichtican palynofloras from offshore Norway wells. The following results were derived from this analysis, and illustrated at Figure 4.

Group A: Late successional gymnosperm/angiosperm forest

Aquilapollenites drumhellerensis
Cupuliferoipollenites cingulum fuscus
Deltoidospora adriennis
Inaperturopollenites hiatus
Lycopodiumsporites spp.
Nyssapollenites kruschi analepticus
Stereisporites (S.) sterioides

Group B: Early-mid successional angiosperm/fern community

Inaperturopollenites distichiforme
Inaperturopollenites dubius
Laevigatosporites haardti
Momipites spp
Tricolpites hians
Triporpopollenites/Paralnipollenites con

Group C: Early successional bryophyte fern community

Baculatisporites primaries
Betulaepollenites microexcelsus
Cupluliferoidaepollenites liblarensis
Echinosporis cycloids
Gleicheniidites senonicus
Mancicorpus notabile
Stereisporites (Cingulitriletes) sp.
Stereisporites (Distanchorae) germanicus
Stereisporites (Distanulisporis) spp.

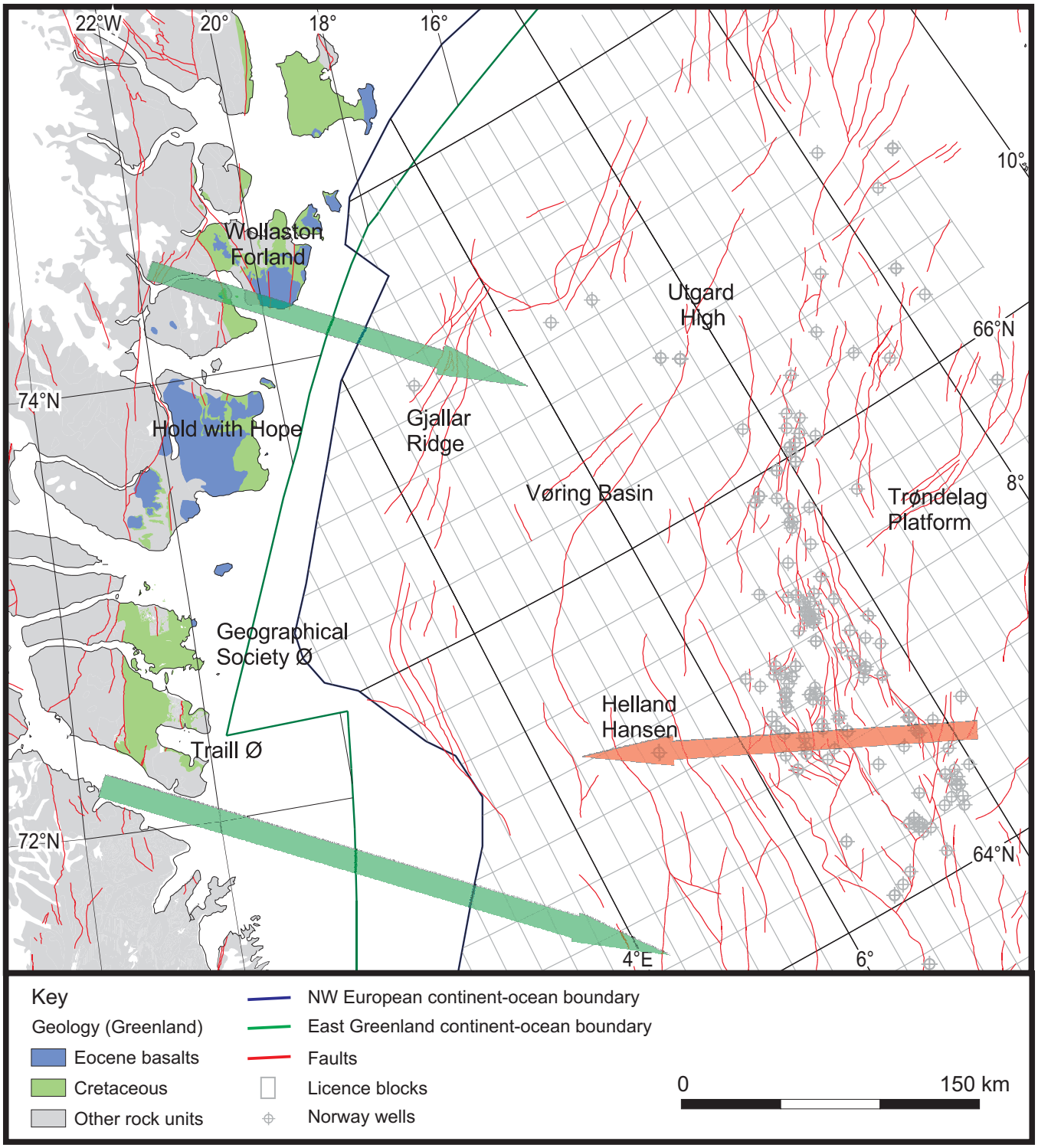
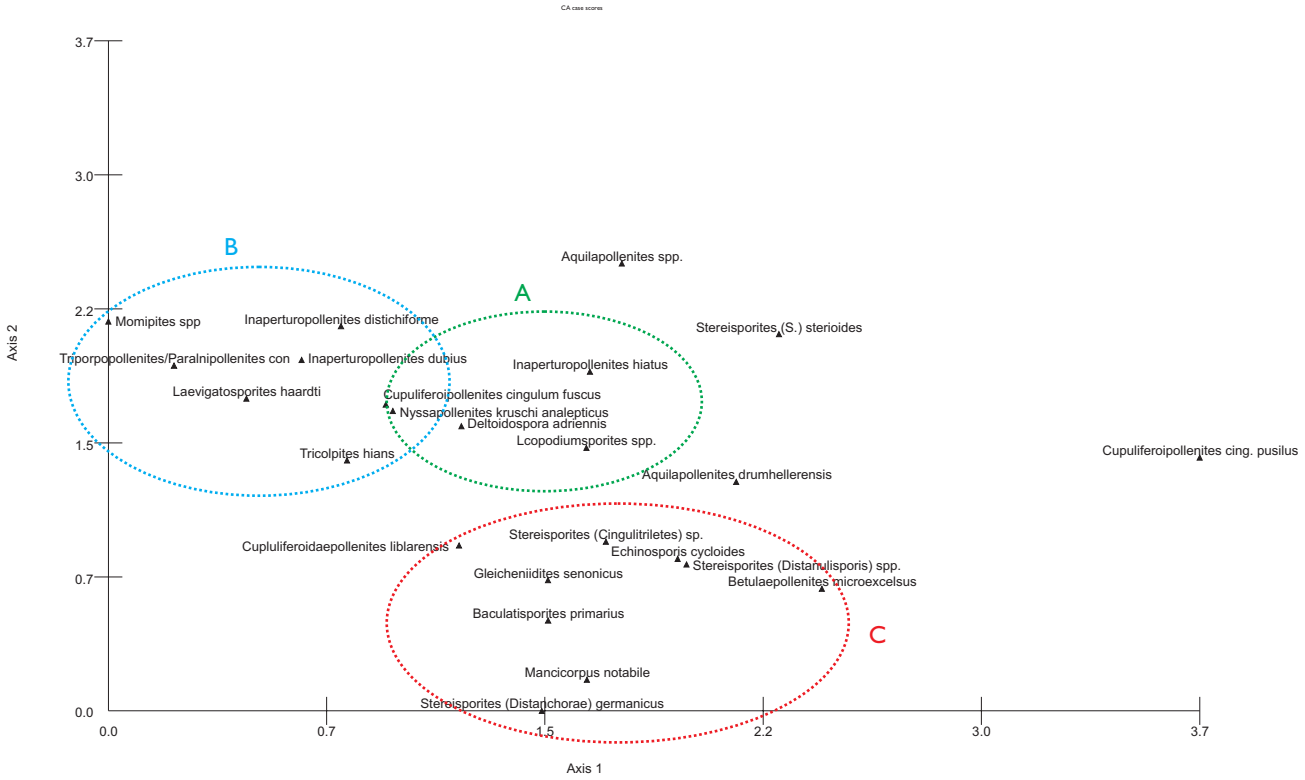



Figure 3: Reconstruction of the Norway-Greenland Sea region at the end of the Paleocene prior to the onset of seafloor spreading, after Cambridge Arctic Shelf Programme (CASP). Green and red arrows show known Late Campanian - Maastrichtian argillaceous sediment transfer vectors.




Geographical Society Island, Early Campanian.
Group A: Late successional gymnosperm/angiosperm forest
Group B: Early - Mid successional angiosperm/fern community
Group C: Early successional bryophyte/fern community

Figure 4: Correspondence analysis of palynofloral data from Geographical Society Island. Note the similarity in the structure of the groupings between this analysis and that returned for the Greenland sourced palynoflora in the offshore Norway wells of figure 2.

**Statistical Analysis of Kangerlussuaq Floras**

The Late Cretaceous stratigraphical geology of Kangerlussuaq has recently been clarified by Larsen et al., (2005), readers are referred to this report to Sindri for the lithostratigraphical nomenclature used here. In order to analyze the composition of Late Cretaceous floras in the Kangerlussuaq region of east Greenland, a number of samples were analysed, taken from field sections collected by CASP (Figures 6-12).

These sections, P2383 ,W4244 ,W4225 (Cenomanian Turonian) and W4275 (mid- late Cenomanian). These sections are taken from the Sorgenfri Formation (Larsen et al., 2005), which is separated from the overlying Christian IV Fm by an unconformity encompassing the Santonian to early Campanian interval. Further palynofloral data was utilised from sections covering the late Campanian to Maastrichtian interval (W4301, W4268/W4293,W4245 and W4282) within the Christian IV Fm of the same region.

Sorgenfri Fm Sections

The composite data set from the Sorgenfri Fn sections analysed exhibits a palynoflora of resticted diversity and abundance. It is dominated by both taxodiaceous pollen and saccate pollen, both derived from gymnosperms. CA analysis of this palynoflora identifies two main groupings with a succession of outliers, as with other analyses here, saccate pollen was excluded from the sum as a facies component (Boulter & Hubbard, 1984). The correspondence analysis groupings are (see also Figure 13):

Group A: Late Successional gymnosperm forest
*Cupuliferoipollenites cingulum fuscus*
*Echinatisporis spp.*
*Expressipollis spp.*
*Inaperturopollenites hiatus*
*Kurtzipites spp.*
*Pityosporites spp.*
*Stereisporites (S.) sterioides*
*Retitricolpites retiformis*

Group B: Early-mid successional fern-angiosperm community
*Aquilapollenites spp.*
*Concavissimisporites verrucosus*
*Deltoidospora adriennis*
*Lycopodiumsporites spp.*
*Tricolpites cf. hians*

Not grouped low frequency and sporadic taxa
*Caliallasporites turbatus*
*Cicatricosisporites cooksoniae*
*Cicatricosisporites rousei*
*Cicatricosisporites spp.*
*Complexipollis sibirica*
*Cycadopites spp.*
*Densoisporites perinatus*
*Expressipollis accuratus*
*Gleicheniidites senonicus*
*Inaperturopollenites distichiforme*
*Inaperturopollenites dubius*
*Klukisporites spp.*
*Lycopodiacidites spp.*
*Rugosporites bivessicualata*
*Stereisporites (Distanchoraesporites) germanicus*
*Stereisporites (Distgranisporis) 'granuloides*
*Triporpopol/Paralnipollenites confusus*
*Verrucosisporites spp.*

The presence of Cycad pollen in these assemblages is indicative of a frost free temperate climate.

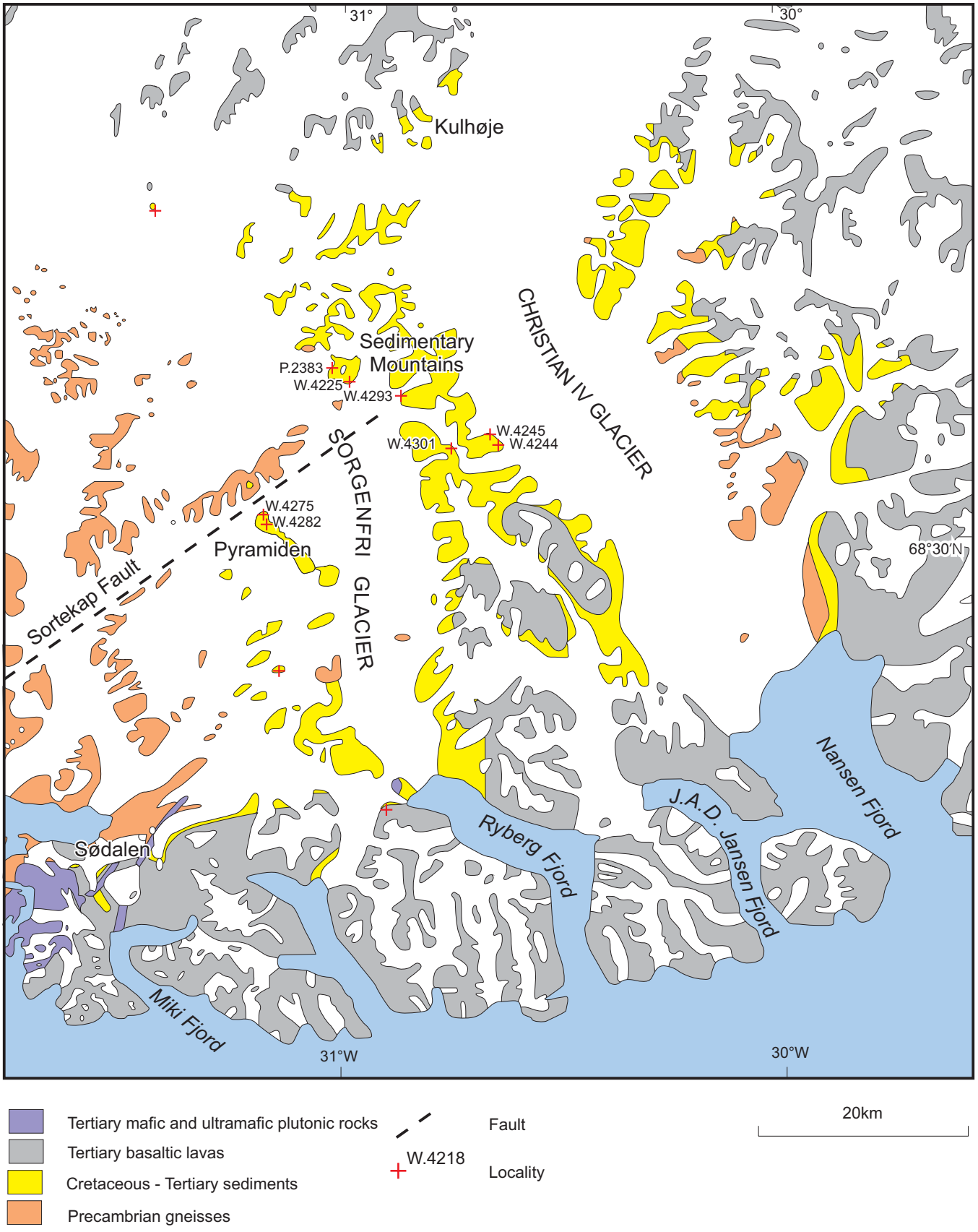



Figure 5: Geological map of the Kangerlussuaq region, eastern Greenland, showing the sample locations utilised in this study. Modified from CASP original.

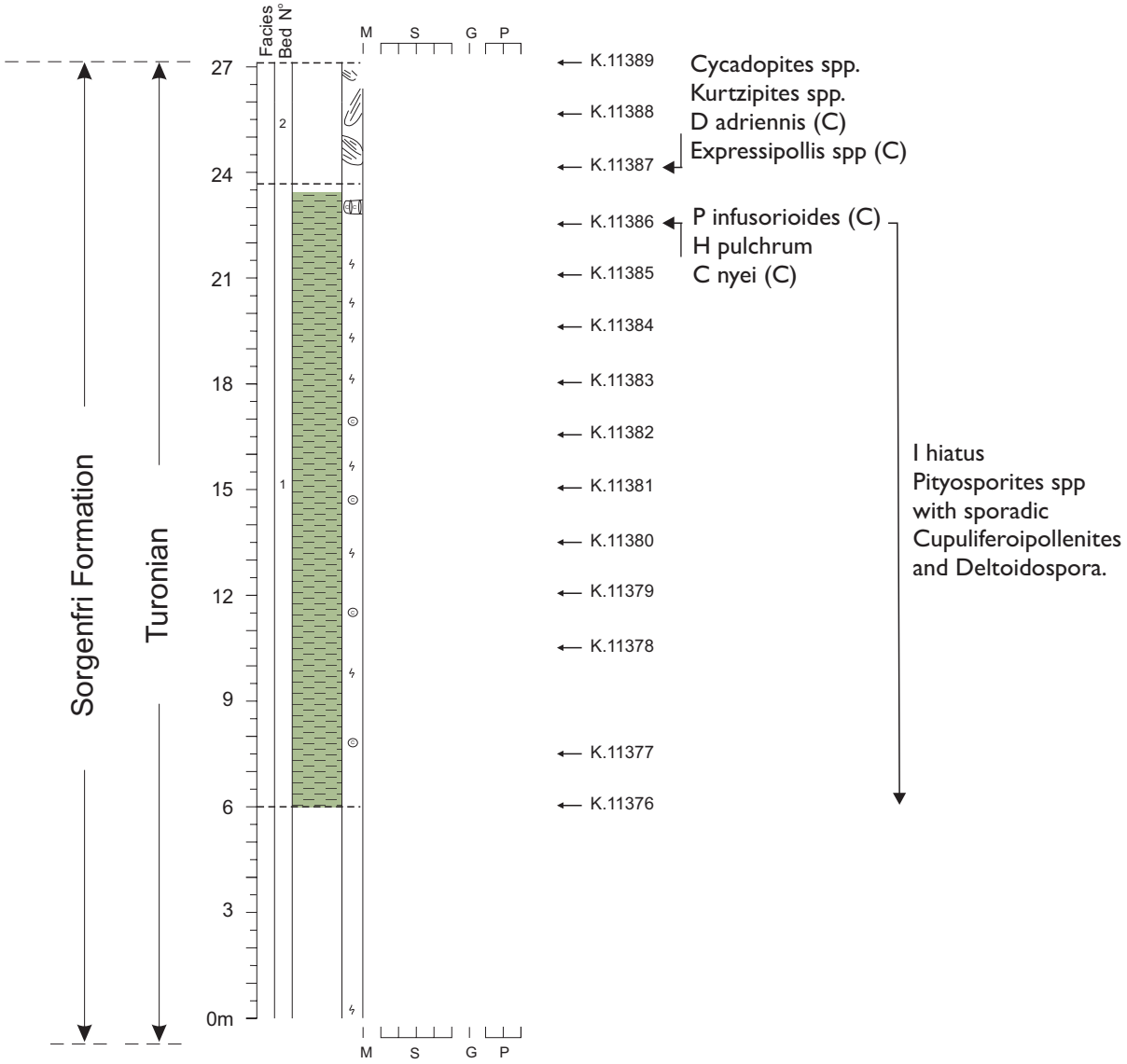
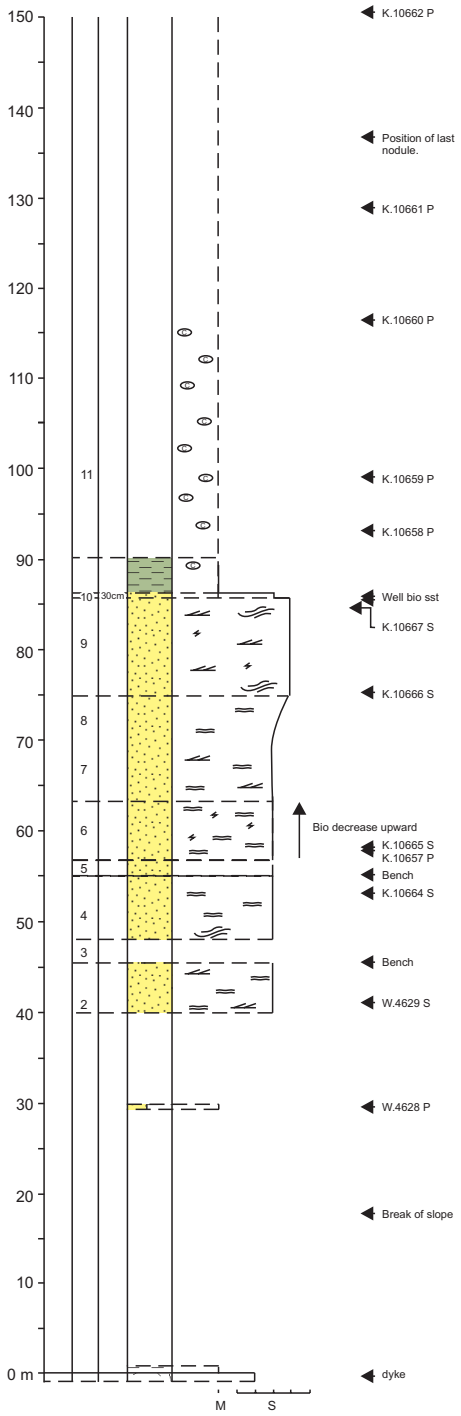


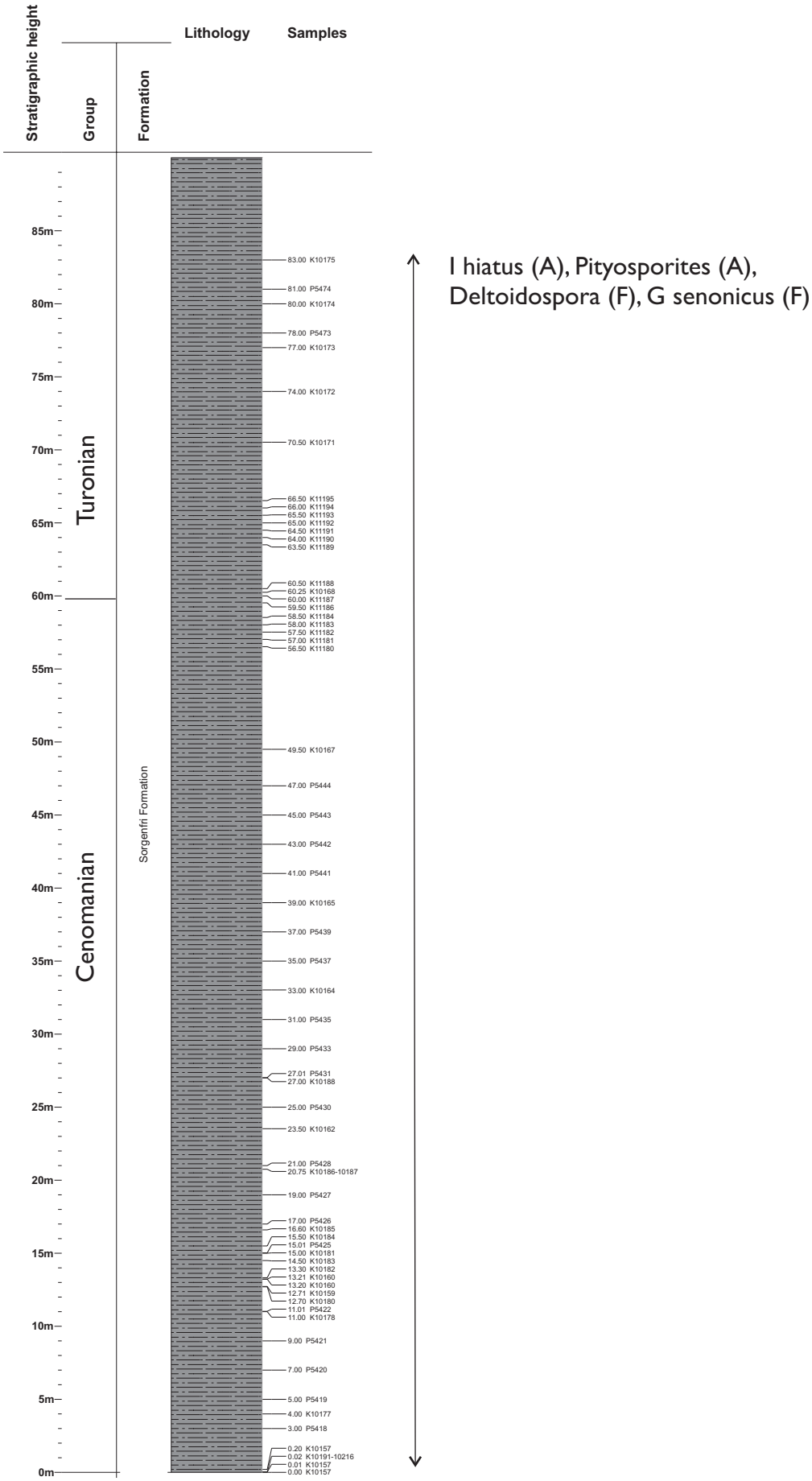

Figure 6: Locality P.2383, Sedimentary Mountains, N

The diversity of *Cicatricosisporites* species and the occurrence of other fern spores points to a humid climate, although the schizacean affinity of the *Cicatricosisporites* species suggests that there may have been a dry season. This palynoflora is indicative of warm temperate vegetation of the type suggested by the biome reconstructions of Chumakov et al. (1995). Stratigraphical plots of these groupings reveals little change over the Cenomanian- Turonian interval in the terrestial palynoflora. Frequencies of the early-mid successional group do occur, but are not of any apparent significance as they exhibit no long term trend.




Impoverished samples dominated by Pityosporites and 1 hiatus

Figure 7: Locality W4244, Kangerlussuaq




I hiatus (A), Pityosporites (A), Deltoidospora (F), G senonicus (F)

Figure 8: Location W4225

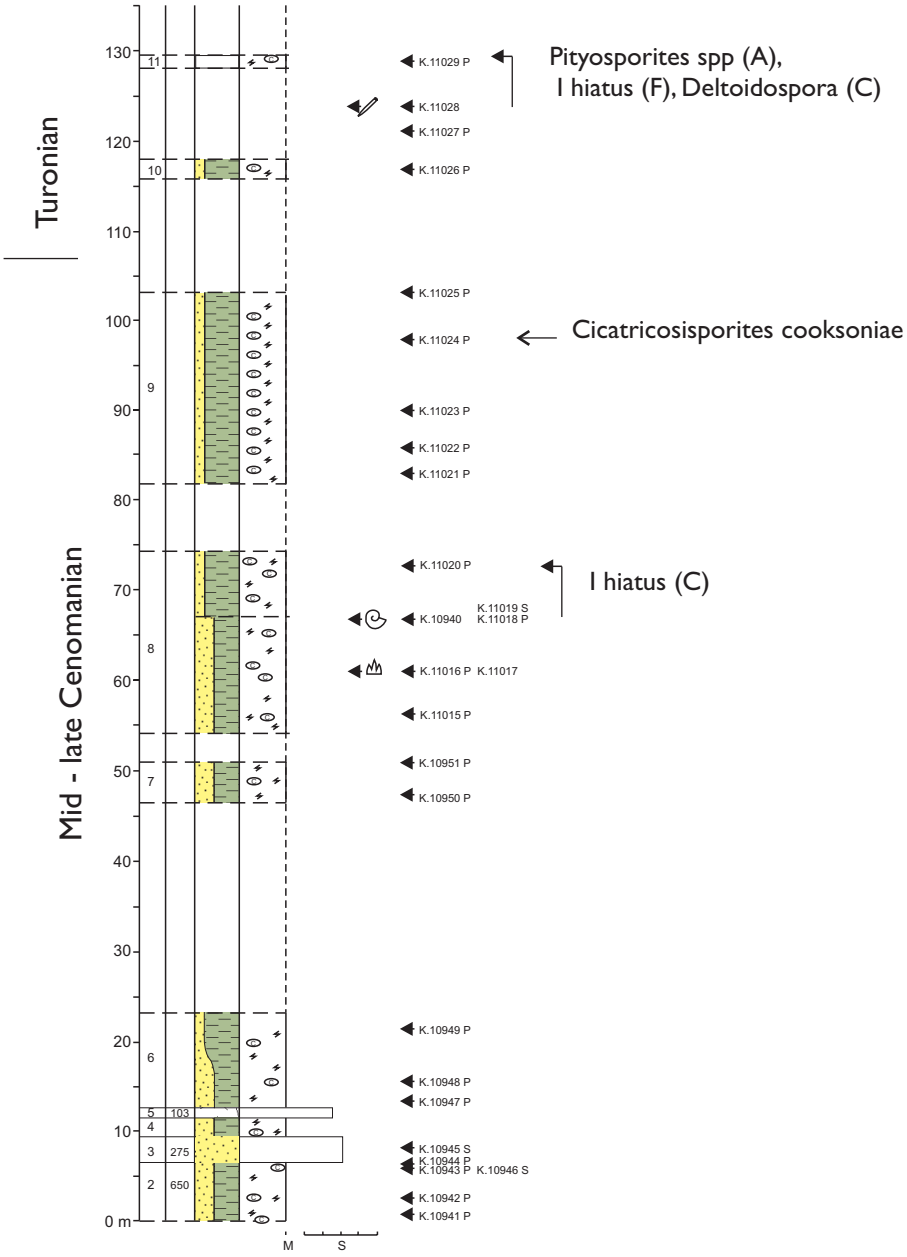



Figure 9: Location W.4275, Pyramiden, Kangerlussuaq

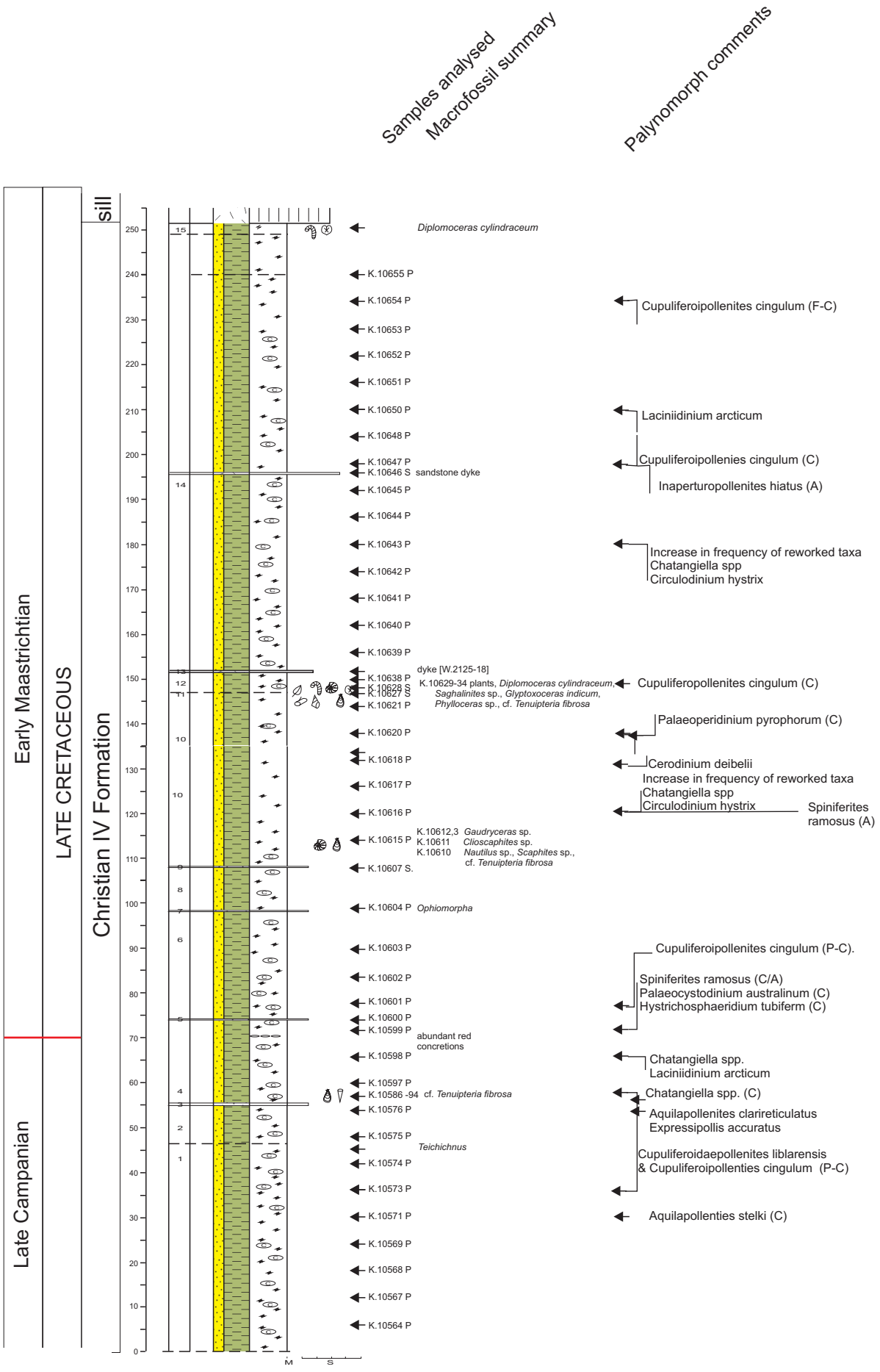



Figure 10: Location W4245, Sedimentary Mountains, Kangerlussuaq

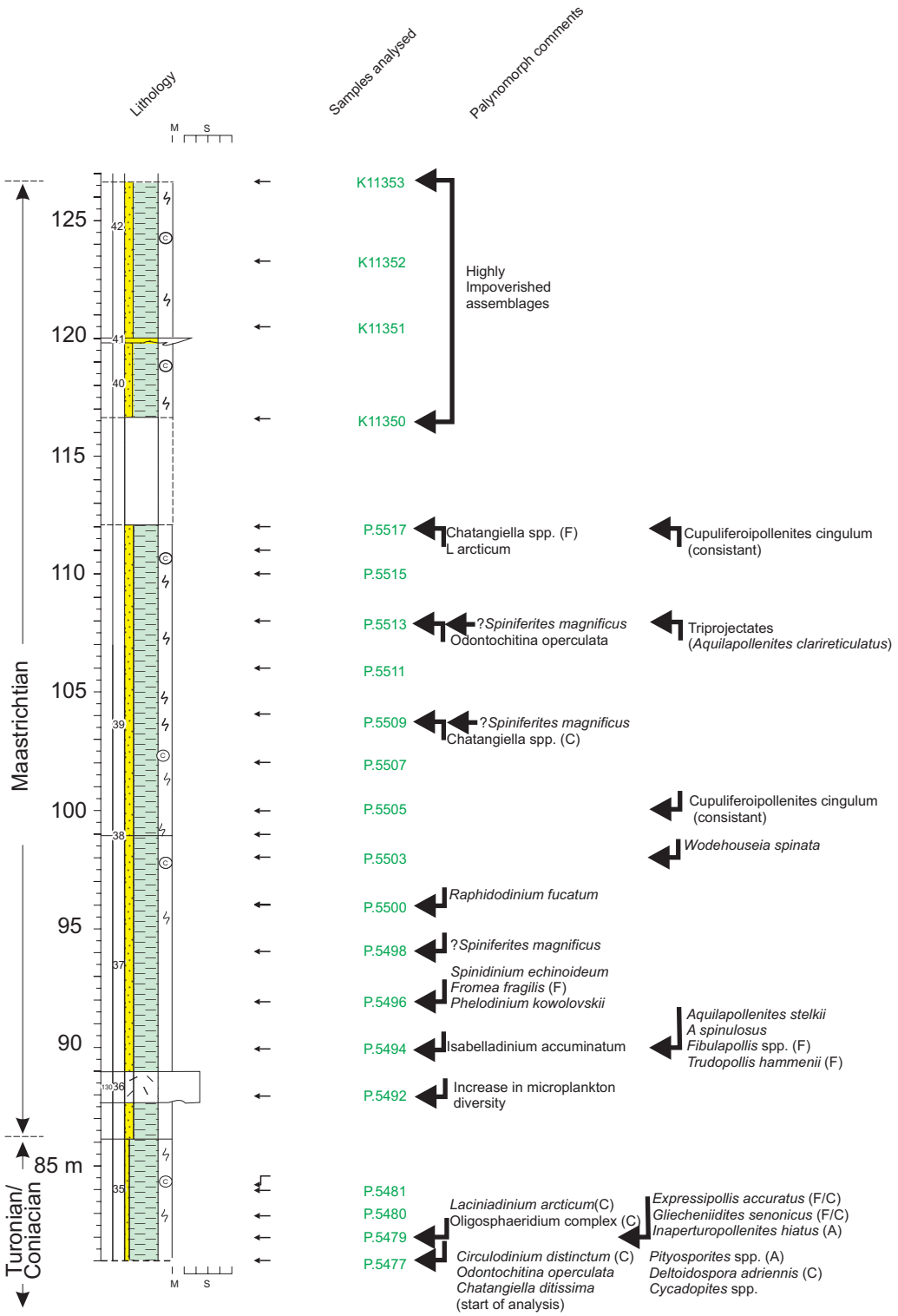



Figure 11: Location W.4268/W4293, Sedimentary Mountains, Kangerlussuaq.

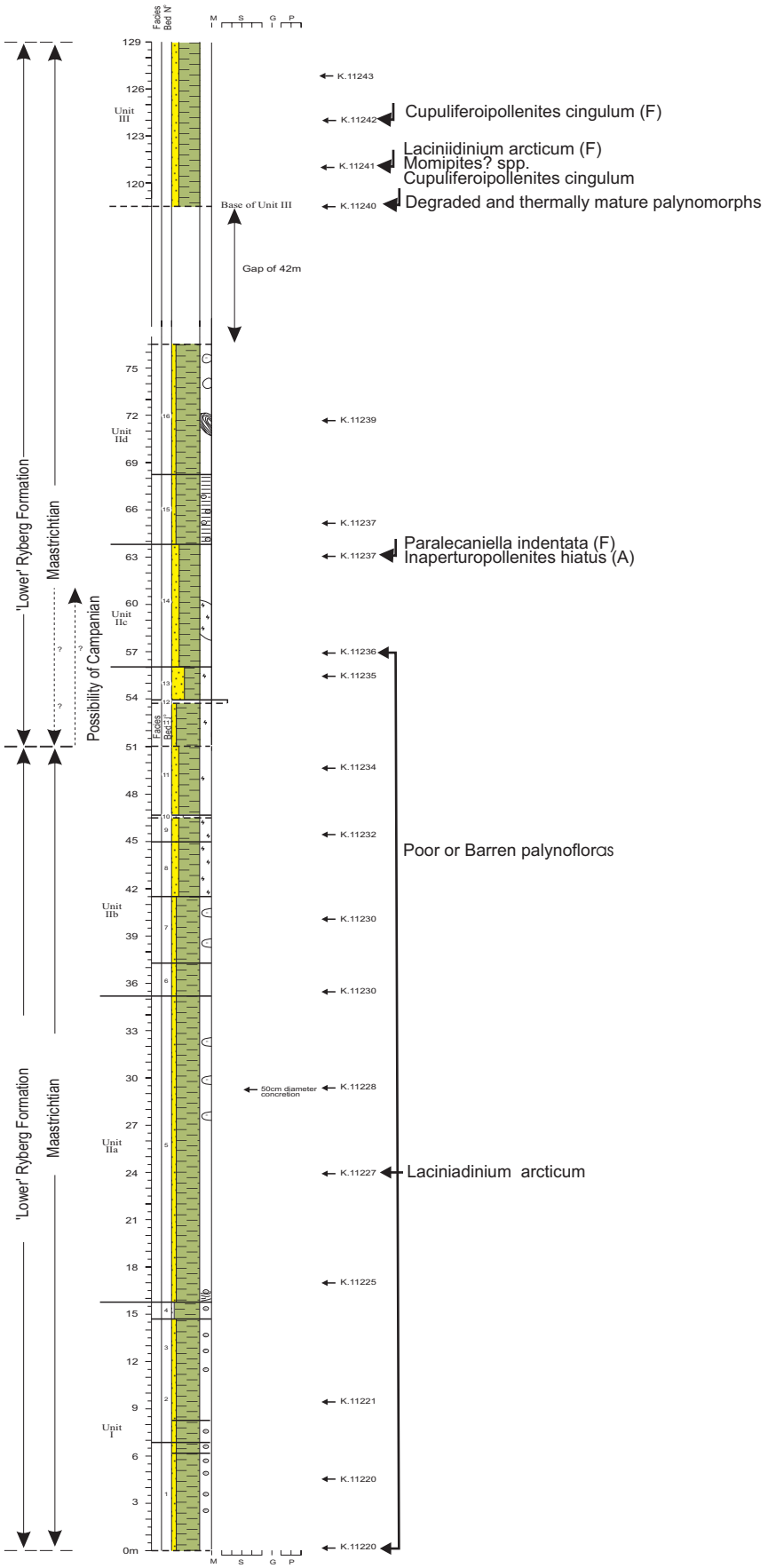



Figure 12: Location W4301, Sedimentary Mountains, Kangerlussuaq.

Similarly, correspondence analysis of palynofloral data from the Campanaian - Maastrichtian Christian IV Formation sediments has been undertaken. This has produced contrasting results that demonstrate the occurrence of three main groupings.

Christian IV Formation CA analysis (See Figure 13):

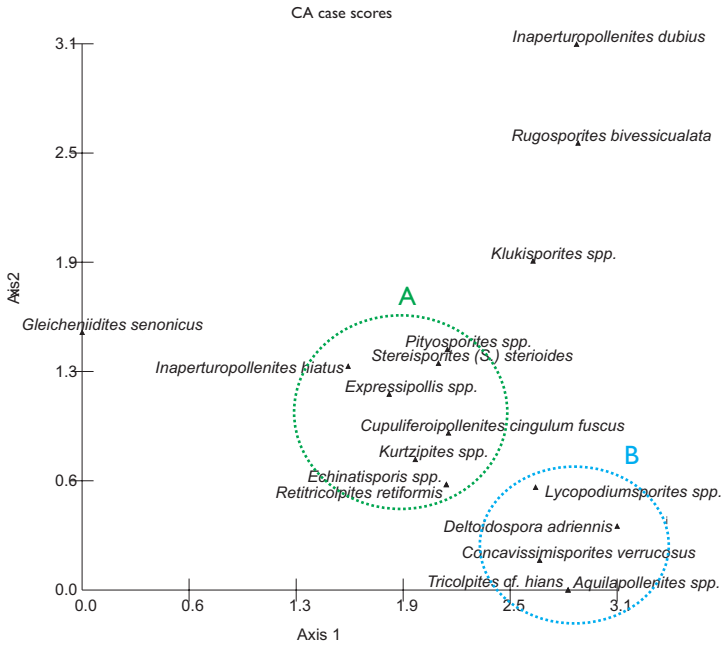
Group A: Late successional gymnosperm/angiosperm forest
*Inaperturopollenites hiatus*
*Cupuliferoidaepollenites liblarensis*
*Cupuliferoipollenites cingulum fuscus*
*Deltoidospora adriennis*
*Microfoveolatosporites pseudodentatus*
*Nyssapollenites kruschi analepticus*
*Plicapollis pseudoexcelsus*
*Stereisporites (S.) sterioides*

Group B = Early successional byrophyte community
*Expressipollis accuratus*
*Gleicheniidites senonicus*
*Sequoiapollenites polyformosus*
*Stereisporites (Cingulitriletes) spp.*
*Stereisporites (Distanc) germanicus*
*Stereisporites (Distverrusporis)* spp.
*Trilites tuberculiformis*
*Verrucosisporites* spp.
*Wodehouseia* spp.

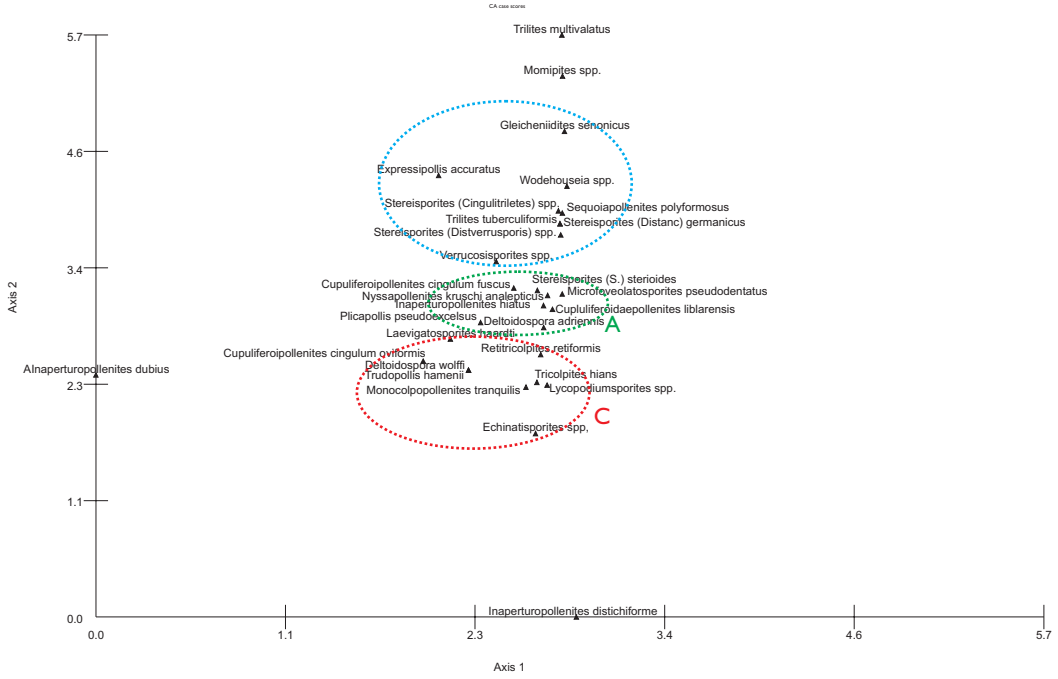
Group C = Early - mid successional angiosperm/fern community
*Cupuliferoipollenites cingulum oviformis*
*Deltoidospora wolffi*
*Echinatisporites* spp,
*Laevigatosporites haardt*ii
*Lycopodiumsporites* spp.
*Monocolpopollenites tranquilis*
*Retitricolpites retiformis*
*Tricolpites hians*
*Trudopollis hamenii*

Unattributed taxa
Inaperturopollenites distichiforme
Inaperturopollenites dubius
Momipites spp.
Trilites multivalatus

These groupings show some distinct differences to those derived from the older Sorgenfri Fm palynofloras. While the late and mid successional communities have overall similarity, there is a lack of thermophyllic species and normapolles pollen. The spore assemblage is also lacking in the schizacean component seen in the older palynofloras. However, the main difference arises from the bryophyte dominated early successional community, which is indicative of a cooler, wetter climatic regime. The stratigraphical and ecological implications of this change are discussed below




Kangerlussuaq Sorgenfri Fm field sections:
Group A = Late successional gymnosperm forest
Group B = Early successional fern-angiosperm




Kangerlussuaq, Christian IV Fm field samples
Group A: Late successional gymnosperm/angiosperm forest
Group B = Early successional byrophyte community
Group C = Early - mid successional angiosperm/fern community

Figure 13: Correspondence analysis plots for palynofloras derived from the Sorgenfri Fm Turonian - Coniacian (top) and from the Christian IV Fm Campanian -Maastrichtian (base). The structure of these palynofloras is discussed below, but note the occurrence of multiple *Stereisporites* bryophyte type spores in the Christian IV Fm assemblages.

## Statistical Analysis of West Greenland Floras

Because the data set available for East Greenland is restricted to specific geographical locations, a Santonian to early Campanian section penetrated by well 6354/4-1 drilled in west Greenland was incorporated into the study as a comparitor. This has allowed an improved model of paleofloral community structures and their component taxa to be developed for mid latitude Greenland. Well 6354/4-1 (also known as Quillieq-1) was drilled by Statoil at W54° 27'06.61" N63° 48' 48.03" within the Fylla East license, offshore central west Greenland, area to a depth of 2973m (Figure 14).

The petroleum geology of this prospect and the stratigraphical detail of this wel is considered in commercial reports available through GEUS (Ostby et al., 2001), and the biostratigraphy reported by Nøhr-Hansen et al (2001). Although the biostratigraphical subdivision of the well section presented by these authors was used in this study, it was focussed on marine taxa of dinoflagellates, foraminifera and nannofossils. To define plant communities for comparison with eastern Greenland floras, we analysed the terrestrial component of the Selandian to Campanian interval of the well.

Ditch cuttings samples from this well yielded an interesting and surprising palynoflora. This flora is dominated by gymnosperm pollen, and peteridophyte spores, with pollen derived from angiosperms forming only a small fraction of the assemblages recovered. The characteristic feature of this palynoflora is the abundance and diversity of the bryophyte spore component, which includes species which are currently not described. It will be demonstrated here that this bryophyte component is both stratigraphically significant, and represents an endemic west Greenland floral grouping.

Analysis of the pollen and spore flora from these marine sediments of the 6354/4-1 well was undertaken by correspondence analysis. Tthe CA analysis again defined clear groupings which have ecological significance.

Group A: Taxodiaceae-fern forest
*Inaperturopollenites hiatus*
*Complexipollis spp.*
*Deltoidospora adriennis*
*Echinosporis cycloides*
*Gleicheniidites senonicus*
*Laevigatosporites haardti*
*Lycopodiumsporites spp.*
*Nyssapollenites kruschi subsp. analepticus*
*Stereisporites (Cingulitriletes) sp.*
*Stereisporites (Distgranisporis) spp*
*Triporpopollenites/Paralnipollenites confusus*

Group B: Mid succession community I
*Inaperturopollenites dubius*
*Camerozonosporites insignis*
*Cupuliferoipollenites cingulum subsp. fuscus*
*Extratriporopollenites parmatus*
*Retitricolpites retiformis*
*Stereisporites (Distanulisporis) spp.*
*Stereisporites (S.) stereioides*

Group C: Bryophyte early successional community
*Lygodiumsporites sp*
*Stereisporites (Cingulitriletes) 'spinatus'*
*Stereisporites (Cingulitriletes) 'giganteus'*
*Stereisporites (Distgranisporis) anulatus*
*Trudopollis hemiperfectus*

Group D: Mid successional 222
*Inaperturopollenites distichiforme*
*Cicatricosisporites rousei*
*Expressipollis accuratus*
*Stereisporites (Distanchoraesporis) germanicus*

Group M: Upland
*Pityosporites spp.*

Unclassified
*Dictyophylidites harisii*
*Nudopollis thiergartii*
*Nyssapollenites spp.*

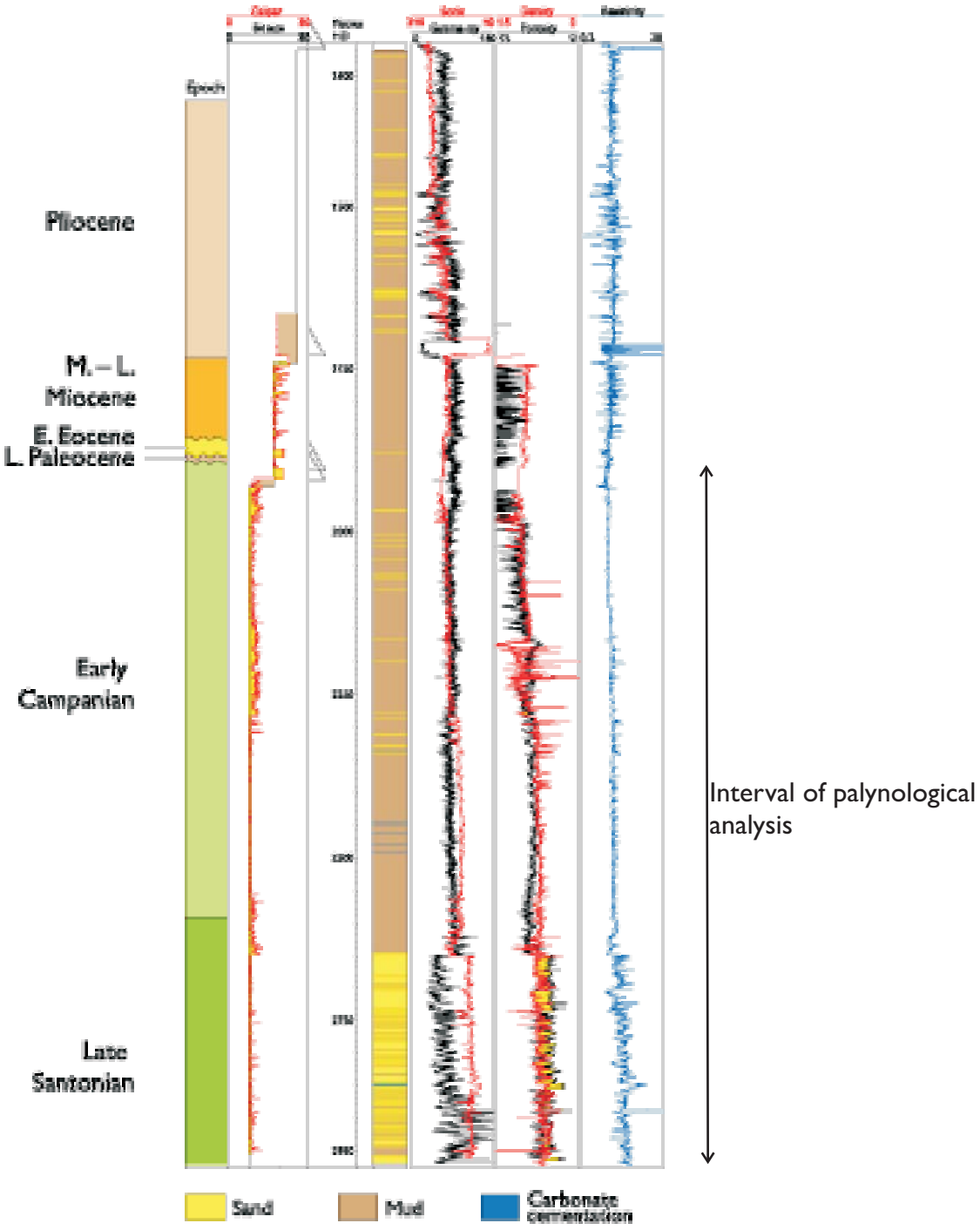
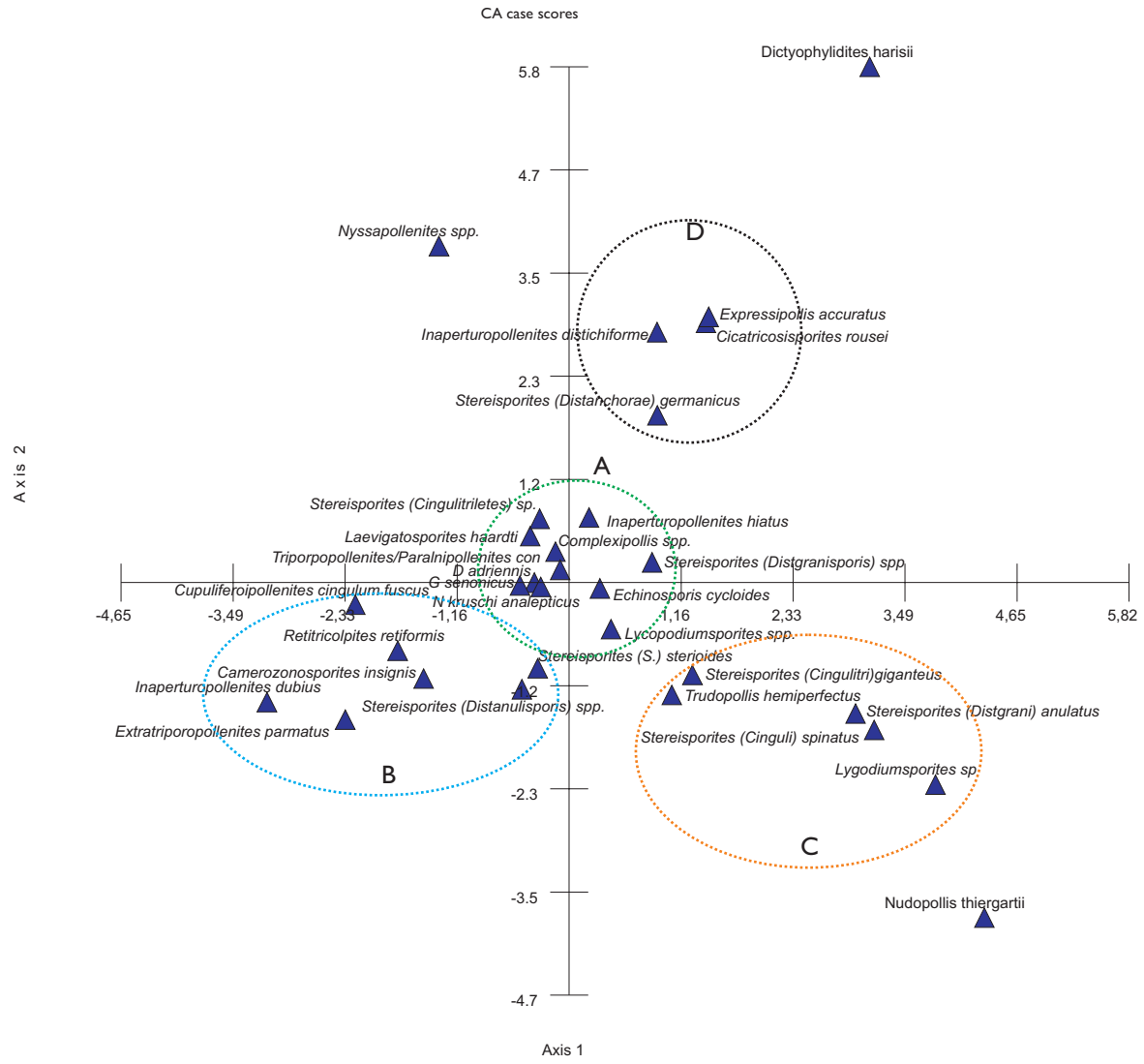



Figure 14: Lithological, stratigraphical and electric logs for the 6354/41, after GEUS (2001)




Group A: Taxodiaceae-fern forest community
Group B: Mid successional 1
Group C: Bryophyte early successional
Group D: Mid successional 2
Saccate coniferous pollen was removed from the sum prior to analysis.

Figure 15: Correspondence analysis plot of palynofloras from 6354/4-1, Fylla prospect, west Greenland. When compared to the Sorgenfri Fm and Christian IV Fm palynoflora CA analyses (Figure 13) it will be noted that this analysis identified two mid successional groups, this is a result of the data set spanning the Santonian to Campanian interval where palynofloras exhibit a marked change. Group D is most similar to the mid successional floras identified for the Sorgenfri Fm assembalges, while Group B is comparable to those determined from the Christian IV Fm data set. The stratigraphical and ecological inferences drawn from these data are discussed below.

## Faroe-Shetland Basin

Having analysed the composition of the terriginous palynoflora from Greenland, and discussed the rather more diverse flora derived from Norway, this section reports the analysis of Late Cretaceous palynofloras from the Faroe-Shetland Basin. The results of the palynofloral analysis are presented below, under individual well headings.

### Statistical Analysis of Well 213/23-1 Palynofloras

This well was drilled on the edge of the Corona Ridge (Figure 16) on the UK side of the Faroe Shetland Basin, penetrating a thick sequence of mudstones between the base of the Paleocene (3099m) to the top of the Cenomanian at 3489m. The well completed in basement below 4342m. The following Late Cretaceous sequence was identified:

| | |
|---|---|
| Late Paleocene: | 2987m - 3099m |
| Unconformity | |
| Campanian | 3099m - 3126m |
| Coniacian | 3126m - 3250m |
| Turonian | 3250m - 3489m |
| Cenomanian | 3489m - 3578m |

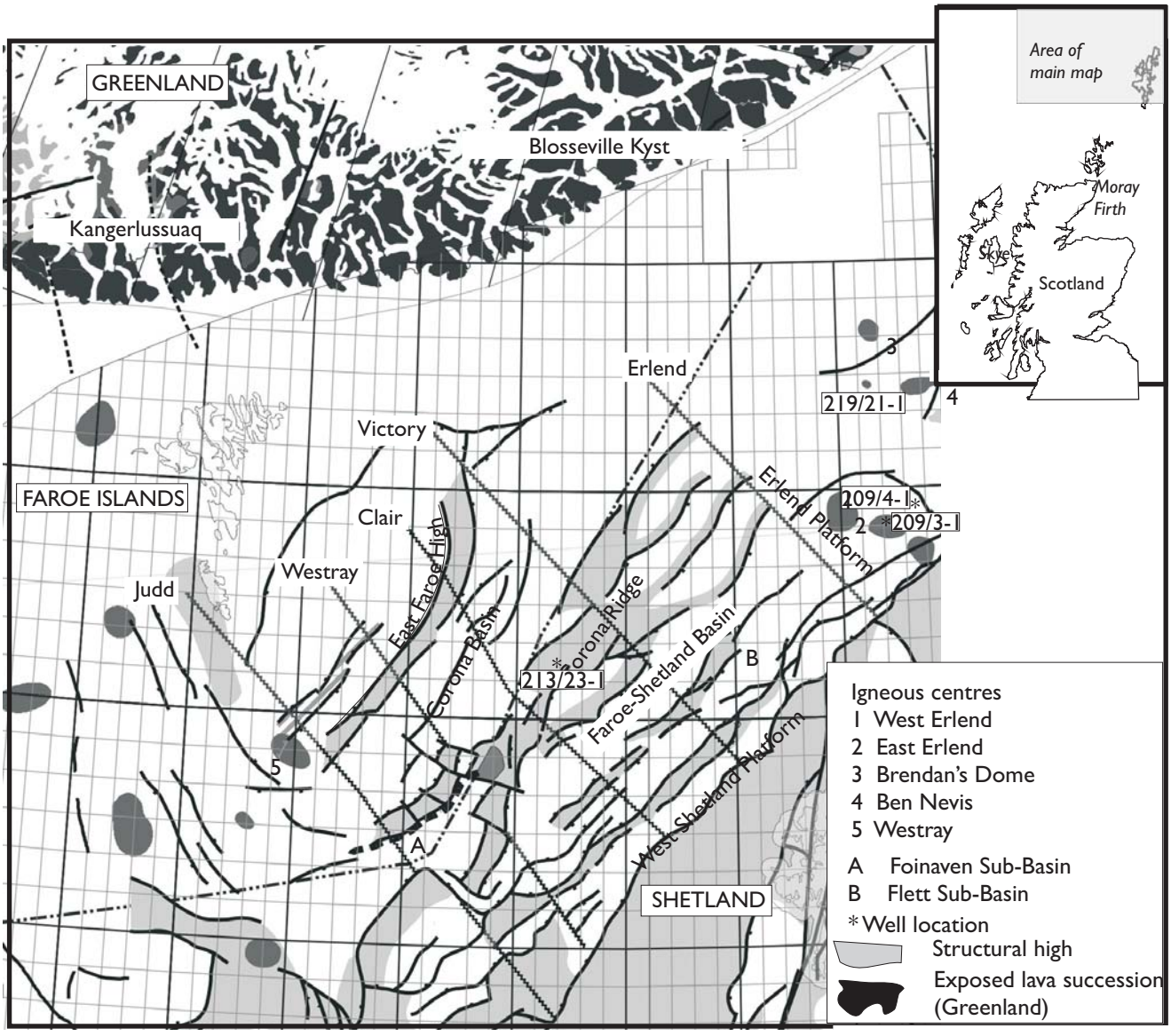



Figure 16: Location map of Faroe-Shetland basin wells analysed for this study

Correspondence analysis of the Late Cretaceous palynofloras from well 213/23-1yeilded a three-fold division (Figure 17):

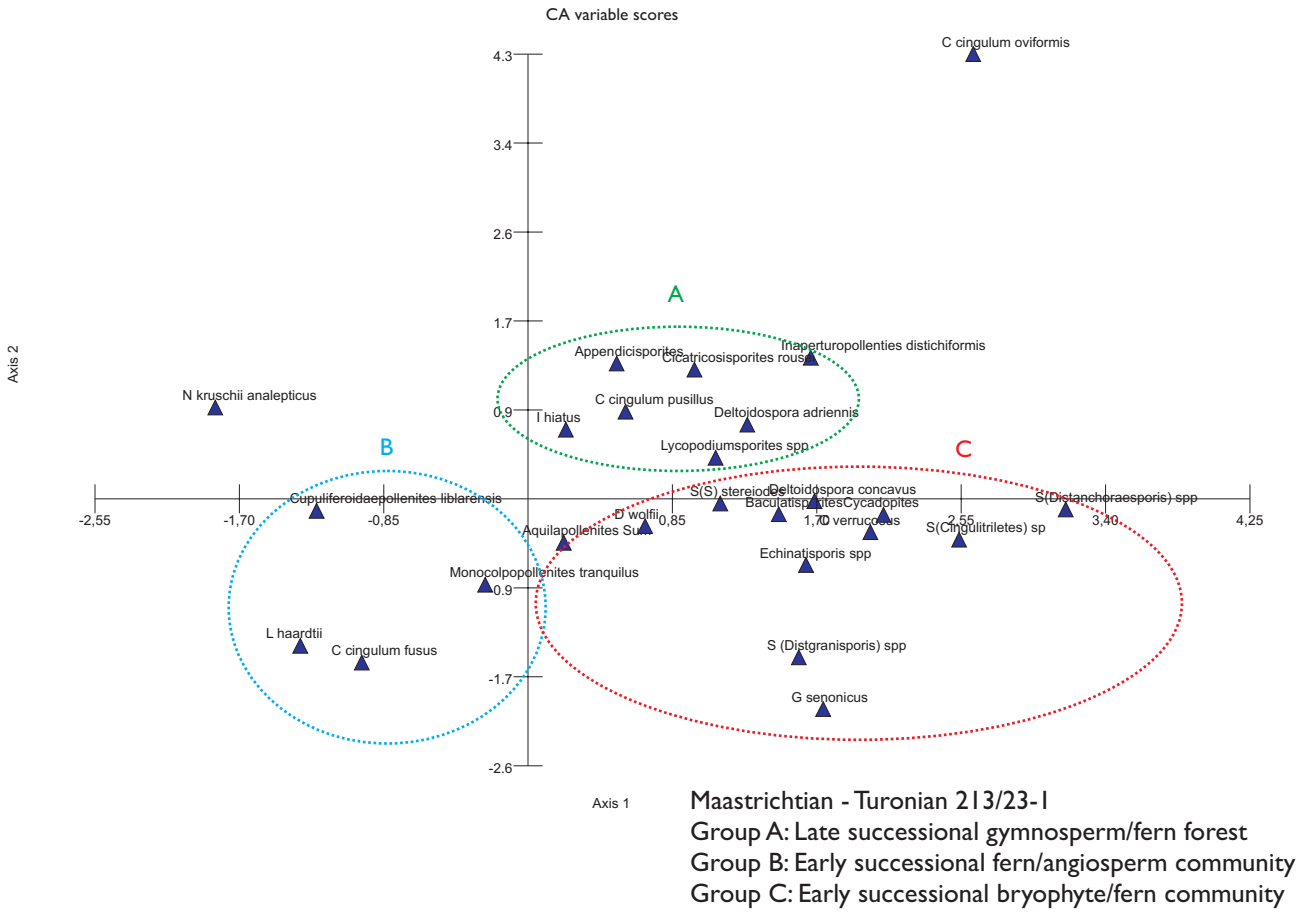
Group A: Late successional gymnosperm/fern forest
*Inaperturopollenites ditichiforme*
*Inaperturopollentiee hiatus*
*Apendicisporties spp.*
*Cicatricosisporites rousei*
*Cupuliferoipollenties cingulum pusillus*
*Deltoidospora adriennis*
*Lycopodiumsporites spp.*

Group B: Early successional fern/angiosperm community
*Cupuliferoipollenites cingulum pusillus*
*Cupuliferoidaepollenties liblarensis*
*Laevigatosporites haardtii*
*Monocolpopollenties tranquilus*
*Aquilapollenties sum*

Group C: Early successional bryophyte/fern community
*Baculatisporites spp.*
*Concavissimisporites verrucosus*
*Cycadopites spp.*
*Deltoidospora concavus*
*Deltoidospora wolfii*
*Echinatisporis spp.*
*Gleicheniidites senonicus*
*Stereisporites (Cingulitriletes) spp,*
*(Stereisporites (Distgranisporis) spp.*
*Stereisporites (Distanchoraesporis) spp.*
*Stereisporites (Stereisporites) sereioides*

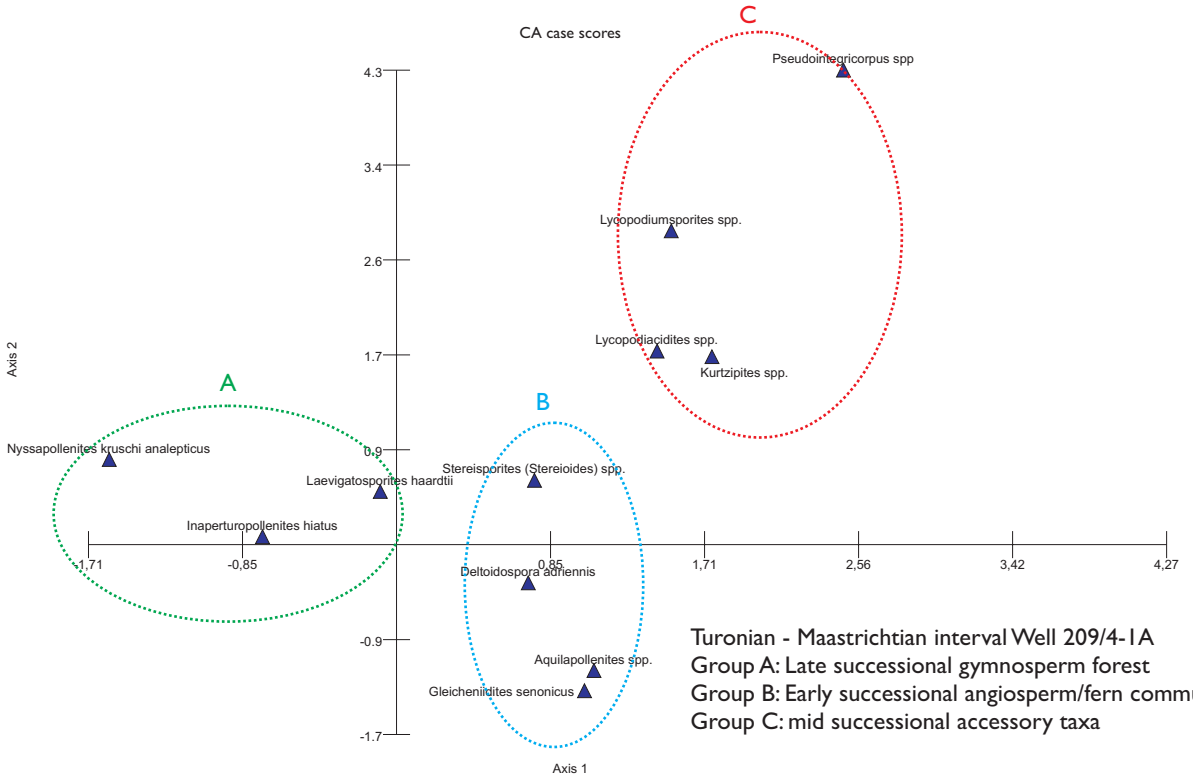
Unattributed
*Cupuliferoipollenites cingulum oviformis*
*Nyssapollenites kruschii analepticus*

This well section is one of the longest stratigraphical intervlas studied, spanning the period from Turonian to Maastrichtian. Although the palynofloras of the Maastrichtian are somewhat impoverished, particularly in thes upper section, recovery increases downhole, allowing the identification of a bryophyte based early successional community, similar to that seen in the Campanian-Maastrichtian of eastern Greenland.




Maastrichtian - Turonian 213/23-1
Group A: Late successional gymnosperm/fern forest
Group B: Early successional fern/angiosperm community
Group C: Early successional bryophyte/fern community

Figure 17: Correspondence analysis of terrestral palynofloras from 213/23-1




Turonian - Maastrichtian interval Well 209/4-1A
Group A: Late successional gymnosperm forest
Group B: Early successional angiosperm/fern community
Group C: mid successional accessory taxa

Figure 18: Correspondence analysis of terrestrial palynofloras from well 204/9-1A.

**Statistical Analysis of Well 204/9-1A Floras**

This well was drilled in 1984 on the north flank of the Erlend volcanic complex. After drilling through Paleocene volcanic rocks, the well penetrated Maastrichtian strata at 3120m (10130' ), with Cretaceous sedimentary rocks being encountered to TD.

| | |
|---|---|
| Maastrichtian | 3120m - 3246m |
| *Unconformity* | |
| Early Campanian | 3246m - 3367m |
| *Unconformity* | |
| Coniacian | 3367m - 3810m |
| Middle to Late Turonian | 3810m - 4049m (TD) |

Correspondence analysis of the palynofloras recovered from this interval derives three groups(see Figure 18):

Group A: Late successional gymnosperm forest
*Inaperturopollenites hiatus*
*Laevigatosporites haardtii*
*Nyssapollenites kruschi analepticus*

Group B Early successional gymnosperm forest
*Aquilapollenites spp.*
*Deltoidospora adriennis*
*Gleicheniidites senonicus*
*Stereisporites (Stereioides) spp.*

Group C: Mid successional fern/angiosperm community
*Kurtzipites spp.*
*Lycopodiacidites spp*
*Lycopodiumsporites spp.*
*Pseudointegricorpus spp*

Group C is, in part, a stratigraphical grouping caused by the high levels of *Pseudointegricorpus* and *Kurtzipites* species in the Campanian. The triprojectates grouped under the genus *Aquilapollenties*, should most probably be attributed to this group, but they are found commonly in the Coniacian and Turonian section, possibly augmented by cavings from the overlying interval. The late successional forest, Group A, is one composed of Taxodiaceae-Nyssaceae and accessory polypodiaceous ferns and is closely similar to those seen in other localities. The early successional angioserm fern community is dominated by ferns (*Deltoidospora* and *Gleicehenііdites*) which characterise much of Late Cretaceous floodplain temperate vegetation. This grouping is particularly well represented in the Turonian - Coniacian interval for reasons discussed below.

**Statisical Analysis of Well 219/21-1 Floras**

This is the most recently drilled of the studied wells, being drilled on the Ben Nevis prospect to the south east of the Brendan's Dome igneous complex (Figure 16). The stratigraphical subdivision of the section is largely based upon the operator's end of well report, as the palynofloras recovered are in many cases impoverished. In this study, the microplankton palynoflora was only of significant stratigraphical value in the older part of the Cretaceous interval, much of the Campanian - Maastrichtian section yielding only terrestrial palynofloras.

| | |
|---|---|
| Late Maastrichtian | 1985m - 2069m |
| Early Maastrichtian | 2069m - 2139m |
| Maastrichtian/Campanaian | 2139m - 2154m |
| Campanian | 2154m - 2319m |
| ?Santonian | 2319m - 2404m |

Correspondence analysis of the palynofloras recovered from the Late Cretaceous interval derives a poorly defined result. This is in part attributable to the barren or impoverished nature of many of the samples.

What is derived from this analysis can be interpreted as one single group comprising

*Inaperturopollenitess hiatus*
*Deltoidospora adriennis*
*Cupuliferoipollenites cingulum fusus*
*Stereisporites (S.) Sterioides*

The two triprojectate genera, *Mancicorpus* and *Aquilapollenties* are recorded as outliers from this main grouping, and possibly represent secondary vegetation (Figure 19)

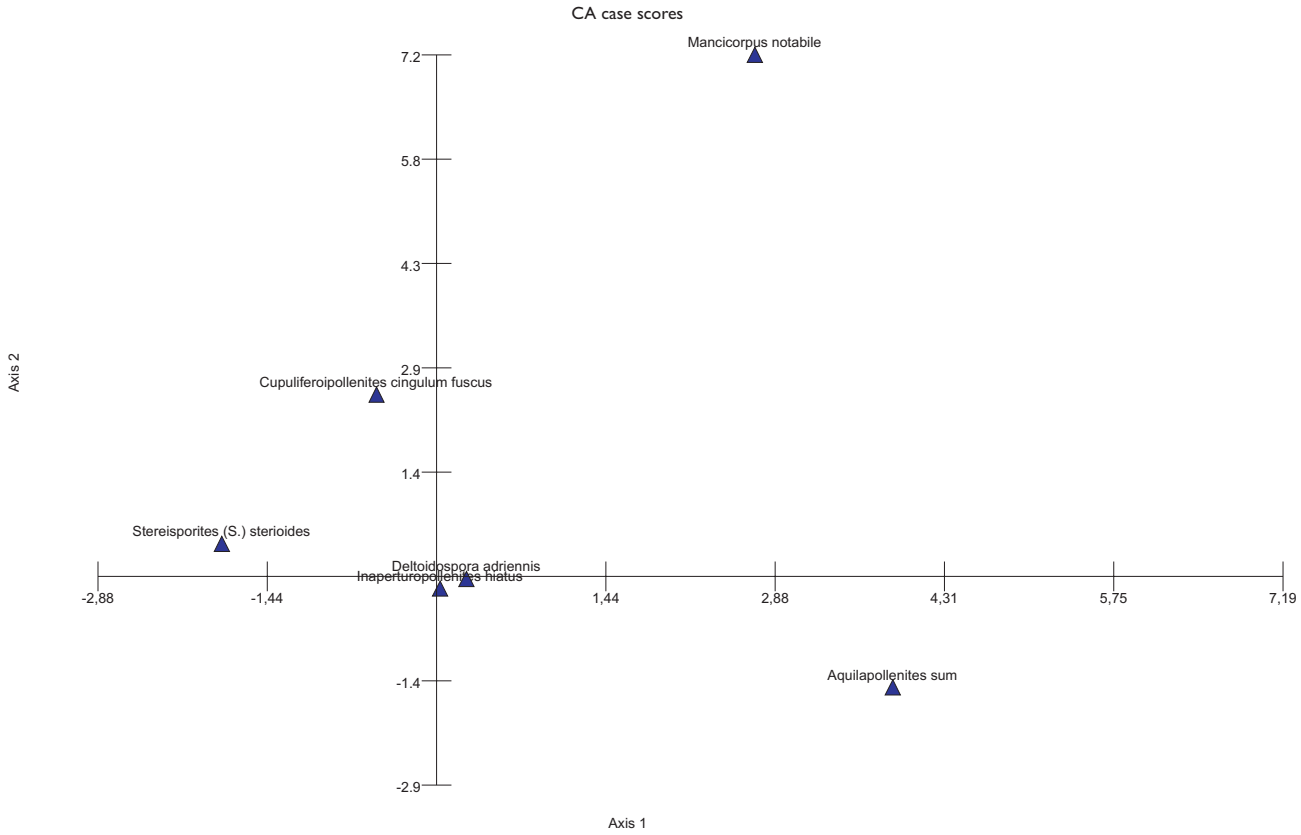



Figure 19: Correspondence analysis of Late Cretaceous terrestrial palynofloras from well 219/21-1.

This section is divided into two parts, one concerning stratigraphical variation in the palynofloras from around the north-east Atlantic, the second examining the inter-regional variation within these floras.

## Stratigraphical Variation

Results from the correspondence analysis have demonstrated variation in the composition of some of the Late Cretaceous palynofloras analysed here. This is demonstrated in single sections which span the Turonian to Maastrichtian interval.

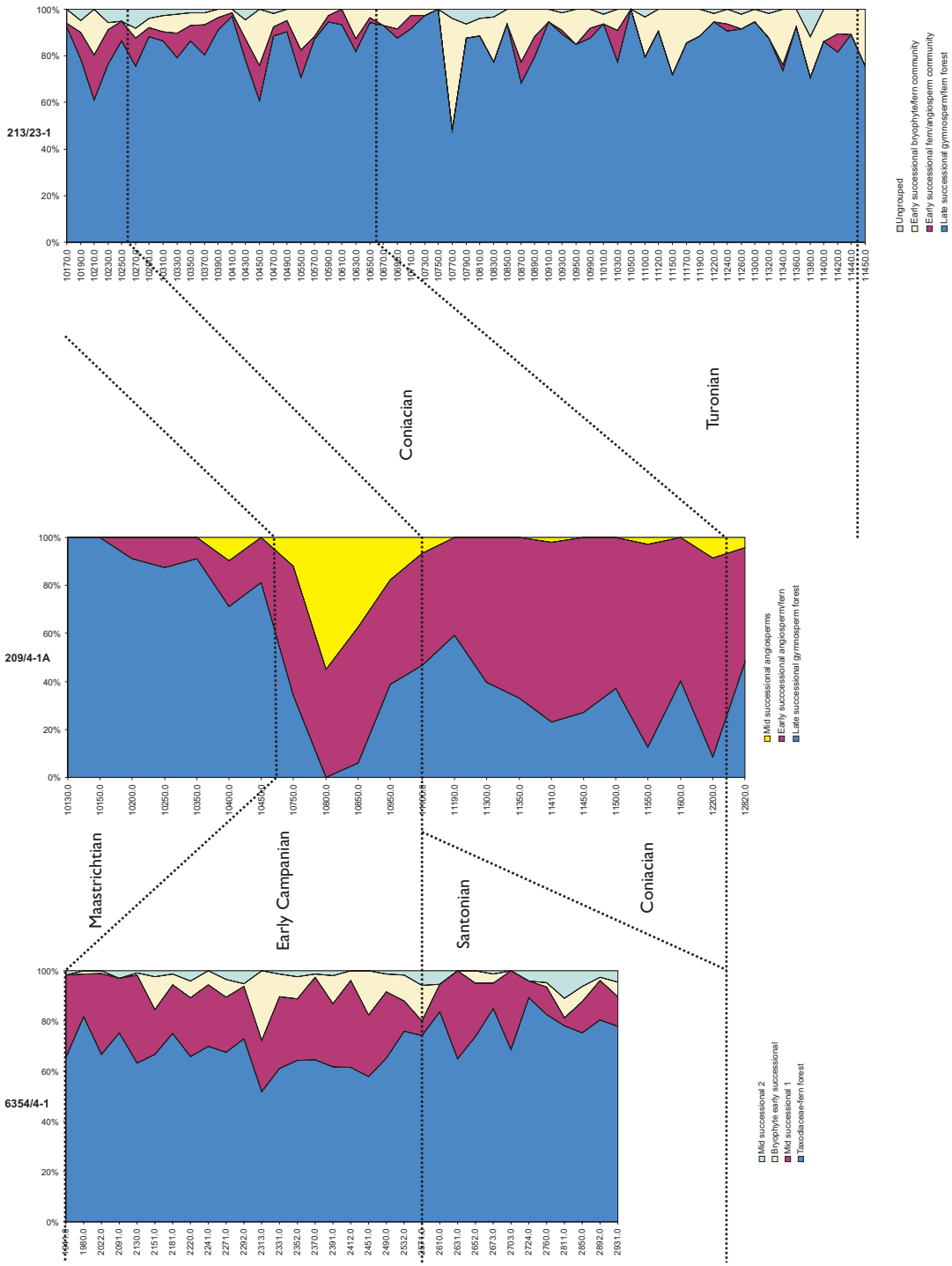



Figure 20: Correlation panel of wells 6354/4-1 (West Greenland), 209/4-1A (Erlend Complex) and 213/23-1 (Corona Ridge), showing the normalised stratigraphical distribution of the major ecological groupings identified in the palynofloras. Saccate coniferous pollen has not been plotted because of the distortion in the variation of other groups that is caused by its inclusion.

Within well 6354/4-1 it is evident that there is a fundamental difference between the Santonian and Campanian palynofloras. The abundance of early and mid successional communities increases upsection, implying that there is increasing disturbance to plant community structure through the latest part of the Santonian and in the Early Campanian. This is supported by the high frequency of such communities in the records from the Campanian of Geographical Society Island and Kangerlussuaq in east Greenland. A similar pattern is observed in 213/23-1 where the early successional fern/angiosperm community increases into the Campanian. This shift in composition is most pronounced in well 209/4-1A where an influx of triprojectate pollen within the base of the Campanian results in increased proportions of secondary vegetation communities.

Most probably occurring within the base of the Campanian is a second, connected change in the composition of the palynofloral communities recorded here. This is most marked in 6354/4-1, but is also evident between the Kangerlussuaq data sets from the older Sorgenfri Fm and the younger Christian IV Fm. This change comprises a marked increase in the abundance of bryophyte spores (*Stereisporites* species), their frequency allowing the recognition of bryophyte dominated communities. Within Greenland, this change is consistent, but there are remarkable differences in the proportions and species of bryophytes from the west to the east. The westerly section seen in well 6354/4-1 contains a diverse suite of bryophyte spores, including some undescribed taxa, taxa which do not occur in the Kangerlussuaq or Geographical Society Island. The Campanian vegetation represented by this palynoflora is one dominated by gymnosperms with associated ferns and some angiosperm taxa. The majority of the early successional vegetation was composed of bryophytes, suggesting that a comparison with modern day Taiga (Figure 21).

Figure 21: Modern Taiga vegetation, south of the Brooks Range mountains, Alaska. The vegetation in the background is formed of black spruce (*Picea nigra*), whilst the foreground area is recovering from one of the frequent forest fires and is covered by alders (*Alnus*), willows (*Salix*) and birches (*Betula*). The herbaceous angiosperms that dominate the foreground had not evolved to this form in the Late Cretaceous, their place being taken by ferns and bryophytes.

This Taiga type vegetation replaced the Santonian and older vegetation that contains early and mid successional communities dominated by ferns. These ferns are relatives of a range of modern cool to warm temperate families, and some that imply the potential for seasonal dry periods (Schizaceae). In addition to these ferns are early angiosperms belonging to the Normapolles group, and frost sensitive taxa such as cycads. These plants grew in association with a redwood/swamp cypress dominated forest vegetation.

This kind of vegetation, in which angiosperms occur within the late early successional and mid successional communities, is seen in the Santonian section of 6354/4-1, the Sorgenfri Formation of Kangerlussuaq and in the Turonian - Coniacian interval of the Faroe-Shetland Basin wells. The late successional vegetation has no direct parallel today, but the temperate fern dominated mid successional vegetation is still evident in areas where scrubby angiosperms have not displaced them (Figure 22)

Figure 22: Something of the appearance of riparian fern dominated vegetation in the Turonian - Santonian can be gained from this assemblage of *Dicksonia* (background) and *Azolla* (a floating water fern).

Such a fundamental change in community structure provides a valuable ecological and stratigraphical marker event, but to assess the importance of this event, it is necessary to identify the cause. In this case, there is already significant evidence pointing towards changes in post-Coniacian plant community structure being attributable to climate deterioration after the mid Cretaceous optimum. Data supporting this is largely derived from plant macrofossils, utilizing the coarse-scale mapping of climatically sensitive plant and lithological data (Spicer & Parrish, 1990; Chumakov et al., 1995). The mean annual temperature (MAT) data produced from analysis of plant macrofossil assemblages (Spicer & Parrish, 1990) indicates a fall of 8°C between the mid Coniacian and mid Campanian for floras from Alaska. The data presented here is from the same biome and climatic belt as the Alaskan data of Spicer & Parrish, and is therefore directly comparable. Such a fall in MAT would be sufficient to change the vegetation structure from a temperate gymnosperm-fern-angiosperm forest to a conifer and bryophyte dominated Taiga (Wolfe, 1981). These data presented here demonstrate, for the first time, that this cooling caused a significant change in the regional vegetation by the start of the Campanian.

By examination of Figure 19, it will be noted that the representation of the bryophyte community declines to the end of the Campanian in well 6354/4-1. There is a further change in the palynoflora that is not immediately apparent from this figure, that is one of increasing abundance of the genus *Cupuliferoipollenties* in the early Campanian above 2130m.

*Cupuliferoipollenites* becomes the dominant taxon in the Mid successional 1 grouping, an increase in abundance also seen in the coeval Christian IV Fm data set from Kangerlussuaq. This is of phytogeographical significance, as this genus becomes one of the characteristic features of the transported 'Greenland Flora' recorded in westerly sourced sediments from the Paleocene Faroe-Shetland Basin (Jolley et al., 2005, Jolley & Morton, 2007). Such an increased representation of *Cupuliferoipollenties* occurs at the expense of bryophyte spores, these changes suggesting that the palynoflora represents the gradual warming of the climate during the Maastrichtian. These data support the conclusion of Jolley & Whitham, (2004), that the origins of northeast Atlantic Paleocene phytogography lie in the Campanian - Maastrichtian.

**Inter Regional Variation**

This variation will be considered in two stratigraphical intervals, Campanian - Maastrichtian and Turonian - Santonian.

Campanian - Maastrichtian

It is worth reiterating the differences stated earlier between the Maastrichtian-Campanian floras of Norway and Greenland

The principle floras are:

1. A Norway derived flora which is of high diversity, with a diverse triprojectate pollen suite including species not seen in Greenland sediments. It includes diverse Normapolles pollen and accompanying Lauraceae (laurel) types. The diversity of this flora decreases to the north, reflecting a decline in land surface temperature.
2. A westerly, Greenland flora. This is seen in offshore wells, and in the field samples. There is a moderate diversity of triprojectate pollen, and little or no Normapolles pollen. These taxa are accompanied by common specimens of *Cupuliferoipollenites* and *Cupuliferoidaepollenites* species (chestnut types). These taxa, only occurring in very low frequencies in the Norway sourced flora, are characteristic of the Paleocene 'Greenland Flora'.

So how do these two floras differ from that of the Faroe-Shetland area?

In a previous Sindri study, Larsen et al., (2005) presented an environmental reconstruction of the Faroe-Shetland region during the Campanian. Because of high relative sea levels and limited extension of the Late Cretaceous NE Atlantic basin, coarser clastic sediment became ponded on the shallow marine shelf to the northwest, now forming eastern Greenland. These authors suggest that the evidence of silicified chalk deposits as far north as Skye (Mortimore et al., 2001,) indicates that chalk deposition once extended over much of the Scottish mainland, implying minimal sediment supply from the basins eastern flank. Larsen et al., (2005) surmise that the large thicknesses of Campanian - Maastrichtian mudrocks found in the Faore - Shetland Basin must have been sourced from Greenland to the northwest, with limited arenaceous input from an emergent Shetland Islands area, and from the core of the highland Scottish mainland not submerged by the high relative sea level.

In considering the Larsen et al., (op. cit.) model, it is important to give consideration to the preservation of ?Campanian - Maastrichtian shallow marine quartz arenites on the mainland adjacent to the isle of Mull. Locally termed the Loch Aline Sandstone, these sediments are preserved above the Griburn Chalk on Mull itself and reported as 'desert sandstones' by Bailey et al. (1924). These deposits suggest that the shallow region from the Hebridies to the Shetlands may have been a sediment starved shallow marine arenaceous shelf, rather than a carbonate platform. However, sediment supply from this environment into the deeper basin would have been negligable.

Testing this model of sediment transport is straightforward using the palynofloral data set contained in this study. If the majority of Faroe-Shetland Basin mudrocks are sourced from Greenland, this will be evident from a close affinity between floras derived from Faroe - Shetland wells, and those from Kangerlussuaq. Accordingly, a data set was assembled from the Campanian - Maastrichtian samples from Kangerlussuaq, and wells 213/23-1 (Corona Ridge) and 209/4-1A (Erlend Complex). This data set was subjected to correspondence analysis (Figure 23), which identified a close similarity between the palynofloras of Kangerlussuaq and those of 213/23-1. Well 219/21-1 is unfortunately barren of palynomorphs in the Campanian - Maastrichtian interval, but well 209/4-1A displays a clearly different palynofloral composition.

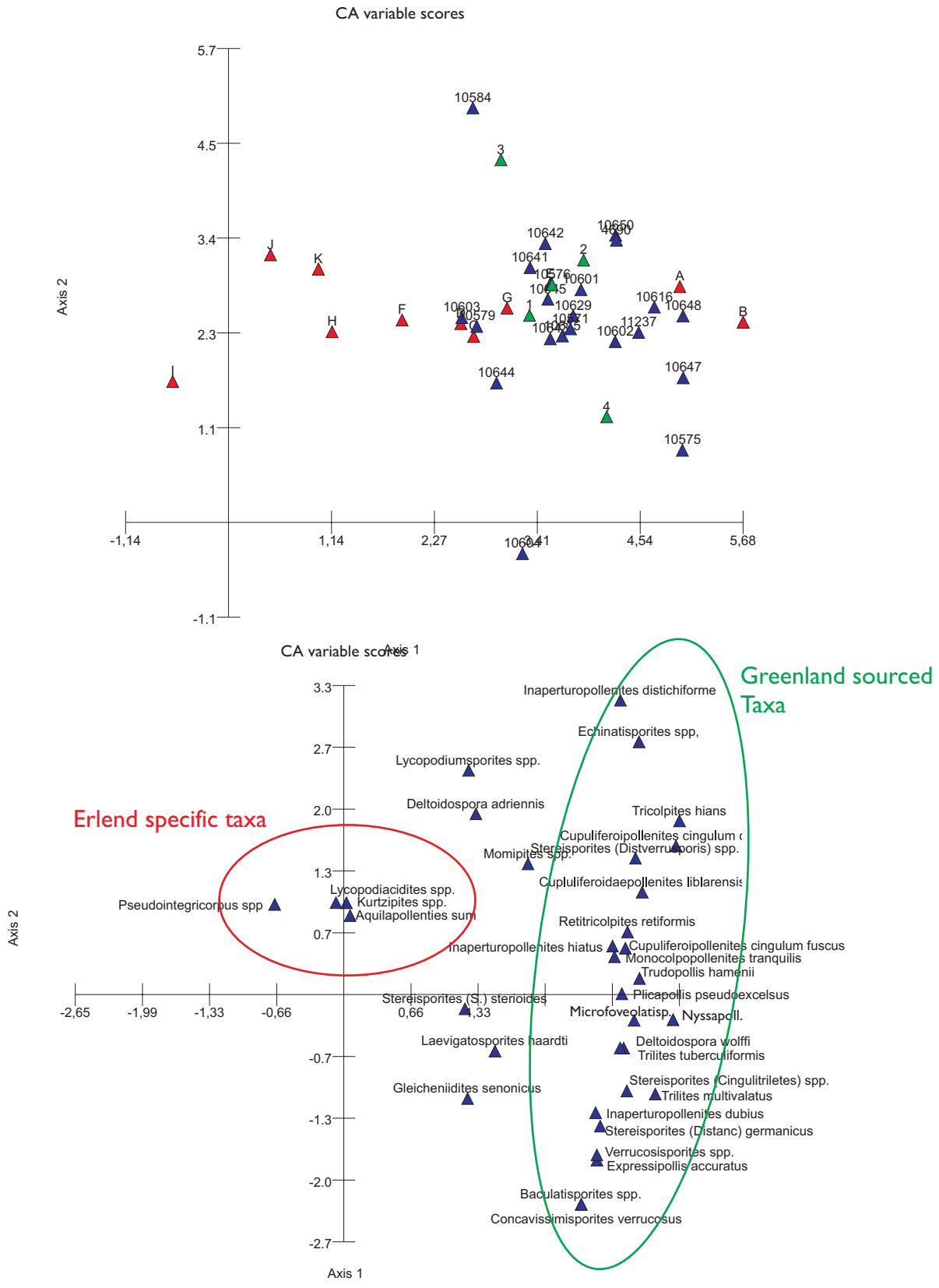



Figure 23: Detrended correspondence analysis plots of samples (top) and species (bottom) from the selective data set for the Campanian - Maastrichtian palynofloras of Kangerlussuaq and the Faroe-Shetland Basin. Note that samples from well 213/23-1(green triangles) plot with the Kangerlussuaq samples (blue triangles). Samples from 209/4-1A (red triangles) plot in a completely separate field. In the species DCA plot below, species characteristic of the Erlend area wells plot away from shared and Kangerlussuaq/Faroe Shetland Basin samples.

This difference in composition is reflected in the community analysis (Figure 20), the species composition (Figure 23) and the sample similarity (Figure 23), providing clear evidence for a different argillaceous sediment source for the Erlend area during the Campanian - Maastricthtian period. To test this result, data gathered by Jolley & Bell (2002) from the centre of the Erlend Complex in well 209/9-1 was examined, and the data derived from Campanian siliciclastic sediments extracted into the table below, taxa with single specimen occurrences and saccates being excluded.

| Depth(m) | 1508.0 | 1661.0 | 1664.0 |
|---|---|---|---|
| *Aquilapollenites* sum | 2 | 23 | 28 |
| *Deltoidospora adriennis* | 0 | 1 | 2 |
| *Inaperturopollenites hiatus* | 14 | 23 | 8 |
| *Kurtzipites* spp. | 0 | 2 | 3 |
| *Laevigatosporites haardtii* | 3 | 9 | 5 |
| *Monocolpopollenites tranquilis* | 0 | 2 | 0 |
| *Nyssapollenites kruschi analepticus* | 2 | 5 | 3 |
| *Stereisporites (Stereisporites) steroides* | 0 | 2 | 2 |
| *Stereisporites (D.) germanicus* | 0 | 0 | 2 |
| *Pseudointegricorpus* spp. | 1 | 6 | 7 |

Well 209/9-1 additional extracted palynology data. Single occurrences and *Pityosporites* are excluded from these data.

These data show a close similarity to that derived from well 209/4-1A to the north, suggesting that this triprojectate-dominated palynoflora was characteristic of a sediment source derived from the north of the Shetland area during the Campanian - Maastrichtian.

Turonian - Santonian

A similar approach to that adopted for analysis of phytogepgraphic provincialsim was adopted for analysis of data gathered from the Turonian - Santonian interval. Although older, this interval is thought to have been deposited under similar marine conditions to that of the Campanian - Maastrichtian interval studied above. Relative sea levels at this time were high, with mudstone deposition mantling the Faroe Shetland Basin, resulting in Greenland sourced muds being deposited across the area. Later a major regression forced an unconformity at the margins of the basin, spanning the Santonian to Early Campanian. This unconformity has been used to separate the Turonian to Santonian data set from the Campanian-Maastrichtian data.
Results from the CA treatment of the combined data set are presented at Figure 24, and demonstrate a clear separation between samples from well 209/4-1A and those from all the other study data included. This is supported by the species CA scatter plot which shows a clear separation of the triprojectate rich flora of 209/4-1A from the dominantly gymnosperm-fern flora of the other sites. Although the nature of the ditch cuttings samples in 209/4-1A means that there may be some element of cavings in this well from the overlying interval, there remains the possibility that the mudrocks present in the Turonian-Coniacian of this well are derived from a Shetland source area.
Unfortunately, other wells drilled in this region do not provide a means of testing the Shetland source in 209/4-1A, because they TD in younger strata. Because of this, it is necessary to assign some caution to the observations of Turonian-Santonian sediment derivation, regarding a Shetland source as possible in the Erlend area.

## DETRITAL MUSCOVITE ANALYSIS

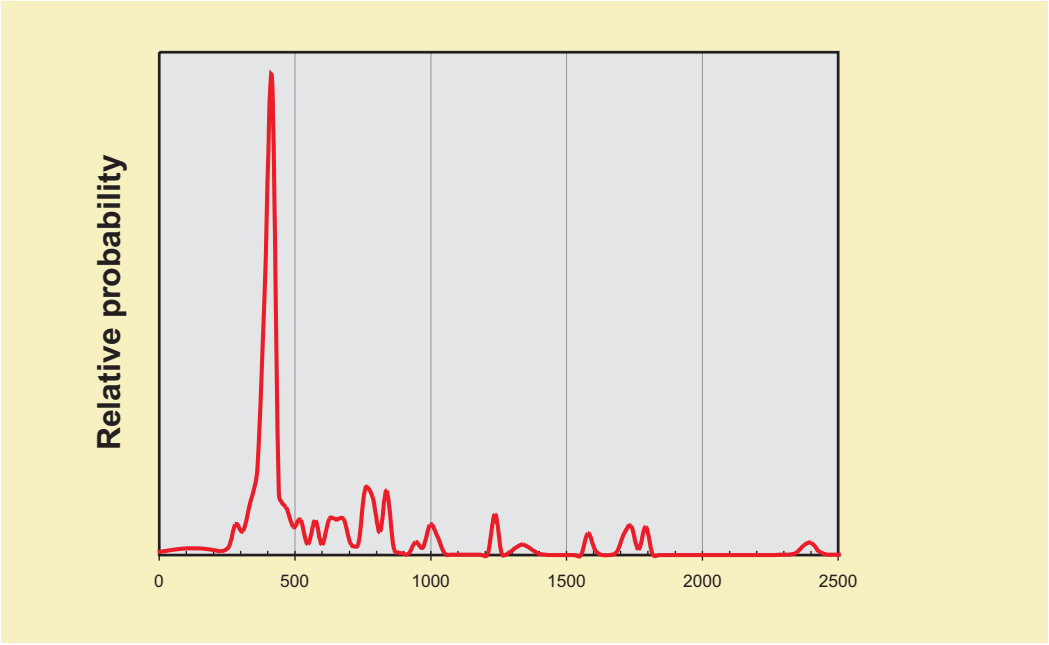
### Analytical Techniques

Detrital muscovite grains were separated from ditch cuttings of sandstones and siltstones by crushing and hand picking under a binocular microscope. For samples from well 219/23-1 well, around 25-50 clean white mica grains, generally greater than 250 microns diameter were picked and cleaned ultrasonically in methanol and de-ionised water prior to packaging in aluminium foil. For the Kangerlussuaq samples, as many samples were extracted as possible from the cuttings prior to cleaning, however in many cases, samples were consolidated in order to create sufficient sample. All samples were irradiated in the McMaster (Canada) reactor for 50 hrs and the neutron flux was monitored using GA1550 biotite standard (98.79±0.96 Ma, (Renne *et al.*, 1998)). On return, the micas were loaded into 2 mm diameter holes an aluminium platen such that individual grains could be targeted. Argon isotopes data were obtained on individual detrital muscovite grains by total fusion of individual grains using a spectron 902TQ CW Nd-YAG laser focussed through a customised Leica microscope. Gasses released by laser fusion were cleaned by two Zr-Al getters for five minutes prior to automatic inlet into an MAP 215-50 noble gas mass spectrometer, where all masses from 35 to 41 were measured. Analyses of $^{36}Ar$ to $^{40}Ar$ were corrected for blanks measured either side of two consecutive samples analyses, 37Ar decay and neutron-induced interference reactions. Argon isotope data for individual grains are shown in Appendix 2, table 1 and table 2.

### Laserprobe $^{40}Ar/^{39}Ar$ results

The ages of 69 detrital white micas were measured in Cenomanian/Turonian sediments from Kangerlussuaq, and 125 detrital white micas were analysed from sediments recovered from a well in the Ben Nevis area of the Faroe-Shetland Basin (219/21-1). Individual ages from Kangerlussuaq ranged from 307-2391Ma, while those from the Faroe-Shetland area ranged from 894-980Ma.

Samples from Cenomanian/Turonian in Kangerlussuaq are shown in Figure 25. The most striking feature is the mode (425Ma) in caledonian mica ages with a tail of older ages ranging up to 2391Ma. This is very similar to other detrital mica signatures in Cretaceous sediments from southern Greenland, and the Faroe-Shetland basin.



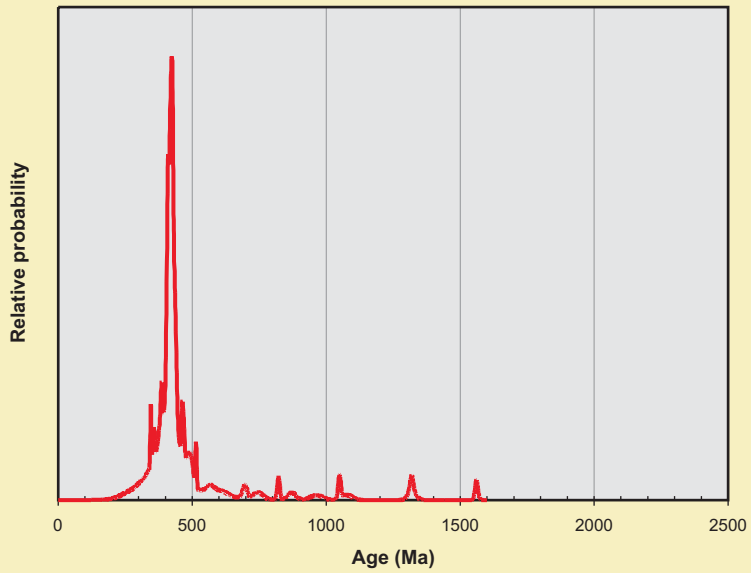
An earlier study focussed on Paleogene sediments in Kangerlussuaq but with some Cretaceous sediments, showed strong variations in similar aged sediments. Figure 26c shows Cenomanian/Turonian sediments from the previous study with an identical pattern to that seen in the present work. Figure 26b shows a probablility distribution plot for Campanian/Maastrictian sediments and a remarkable lack of Proterozoic micas. Figure 26a shows the age distribution in Paleogene sediments which show a pattern similar to the Cenomanian/Turonian pattern.

White micas separated from sediments of the Ben Nevis area of the Faroe Shetland basin (ditch cuttings from 219/21-1) exhibit a very different and anomalous age pattern. In contrast to all other samples analysed from the Faroe Shetland basin and Kangerlussuaq, this suite of samples yielded no caledonian micas (circa 400-450Ma). These samples yielded a narrow range of ages 894-980Ma, with a mode at 930 Ma (Figure 27a) and similar age range within each sample (Figure 27b). In addition to the anomalous age structure the white micas in this sampale suite were generally large (up to 1mm diameter, unaltered and undeformed) compared with Kangerlussuaq (generally less than 500 microns diameter, sometimes showing signs of peripheral alteration, and deformed). We investigated drilling muds used during the process in this particular well and discovered that mica had been used as a component of a 'Millica' loss circulation material during the drilling, but we have not been able to acquire a sample to test, and we are pursuing this issue. The micas extracted and measured from well 219/21-1are likely to be a contamination and do not yield geological information. In order to investigate what Ben Nevis well might have yielded we refer to Cretaceous samples from the basin analysed in a previous Open University study. See table below,

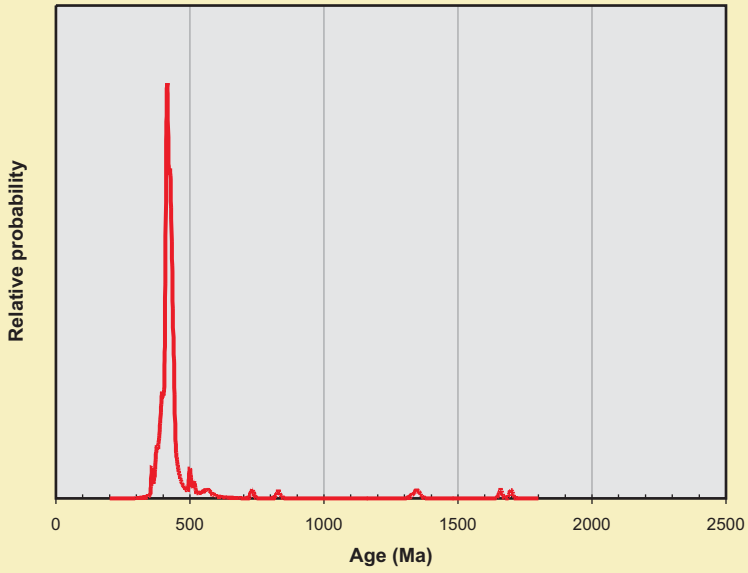
| Sample | Well | Depth(feet) | Age | Lithology |
|---|---|---|---|---|
| P5403 | 205/10-3 (4) | 8456.5 | Top Maastrichtian | Mud |
| P5406 | 214/27-1 (4) | 16491.75 | Upper Maastrichtian | Mud |
| P5408 | 219/20-1 (2) | 12347.5 | Campanian | Mud |
| P5409 | 219/20-1 (6) | 15982.0 | Cenomanian-Turonian | Mud |

Figure 28 shows the results from two Cenomanian/Turonian samples which indicate a similar age distribution to the samples analysed here. In addition, upper Maastrichtian samples yield the dominantly caledonian signal seen in Kangerlussuaq. This pattern reflects the dominant supply of this area via supply pathways during the Campanian/Mastrichtian). In contrast Paleogene samples in the Faroe Shetland basin contain a much higher proportion of Proterozoic micas, and are less dominated by caledonian micas, a feature we can track using matching reworked palynomorphs and indicates polyphase recycling of Carboniferous sediments from rift flanks (unpublished data and Jolley & Morton, 2007).

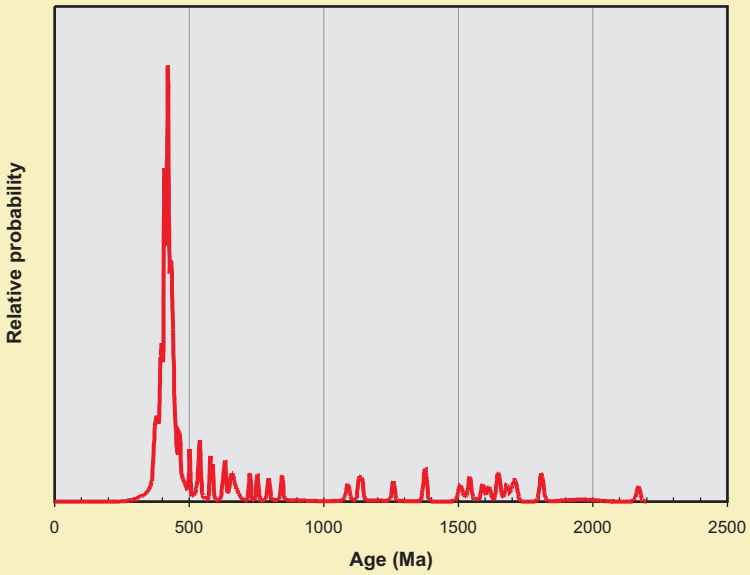
Although there are fewer Cenomanian/Turonian and Campanian/Maastrictian samples from the basin, the changing pattern is clearly identical to that seen in Kangerlussuaq. The implication of this similarity is that argillaceous sediment deposition in this part of the Faroe Shetland basin has the same provenance as that in Kangerlussuaq. The evidence from white mica age populations corroborates conclusions based on foral provenance and indicates similar provenance for both arenaceous and argillaceous sediments. Further, the dominant caledonian peak in all samples (mode around 425Ma) indicates that the origin of the micas was not Kangerlussuaq which lies west of the caledonian front and was not affected by the caledonian orogeny. Micas eroded from basement rocks in Kangerlussuaq yield proterozoic detrital micas and yet most detrital mica samples from Cretaceous sediments in Kangelussuaq and the Faroe Shetland basin yield dominantly caledonian ages. Micas and pollen and spores behave similarly in water and may thus have travelled similar distances, much further than heavy minerals. This may indicate ultimate sources in the caledonian mountains to the east, or in reworked caledonian molasse hidden beneath the ice.



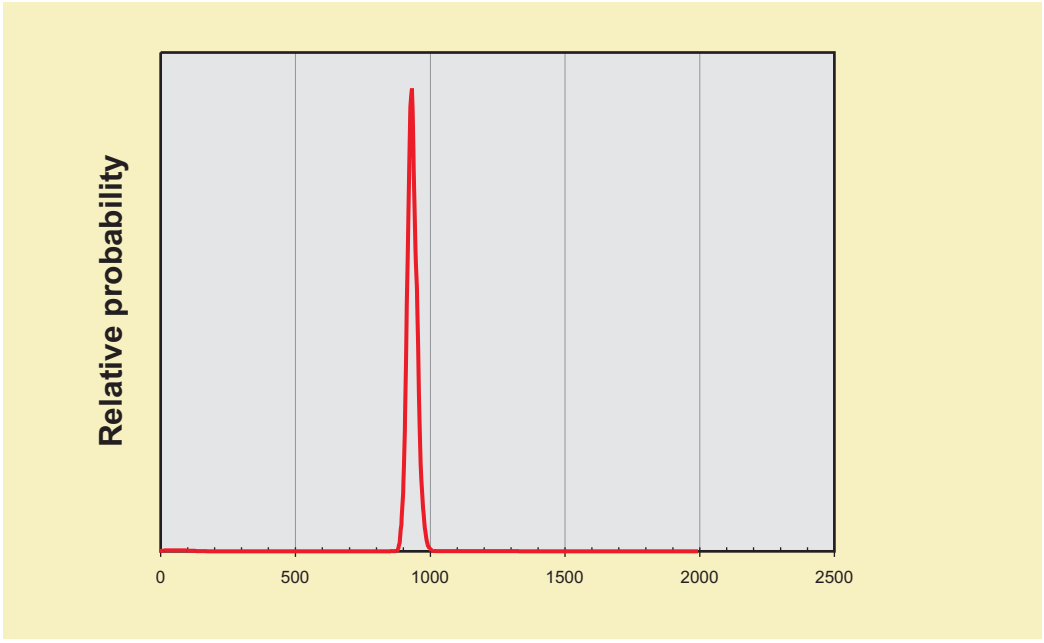

(a) Paleogene sediments



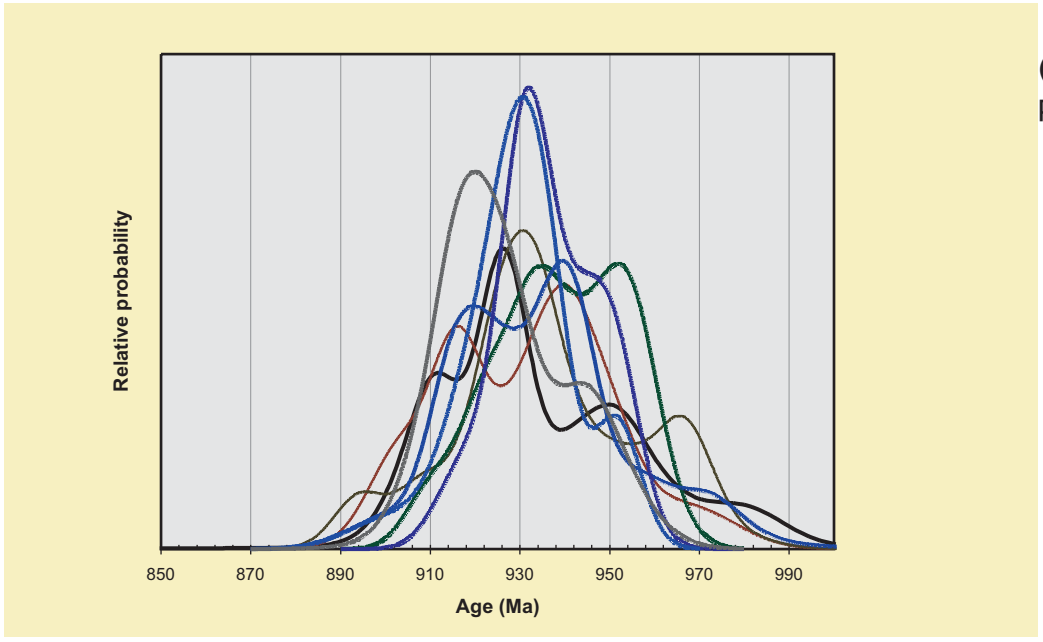

(b) Campanian/Maastrictian sediments.




(c) Cenomanian/Turonian sediments




(a) Whole sample suite




(b) Individual samples plotted separately

Figure 27. Probability plots of white micas extracted from ditch cuttings from well 219/21-1 in the Ben Nevis area. The age range for individual samples is similar to the variation of the entire suite indicating no variation between samples within the suite.

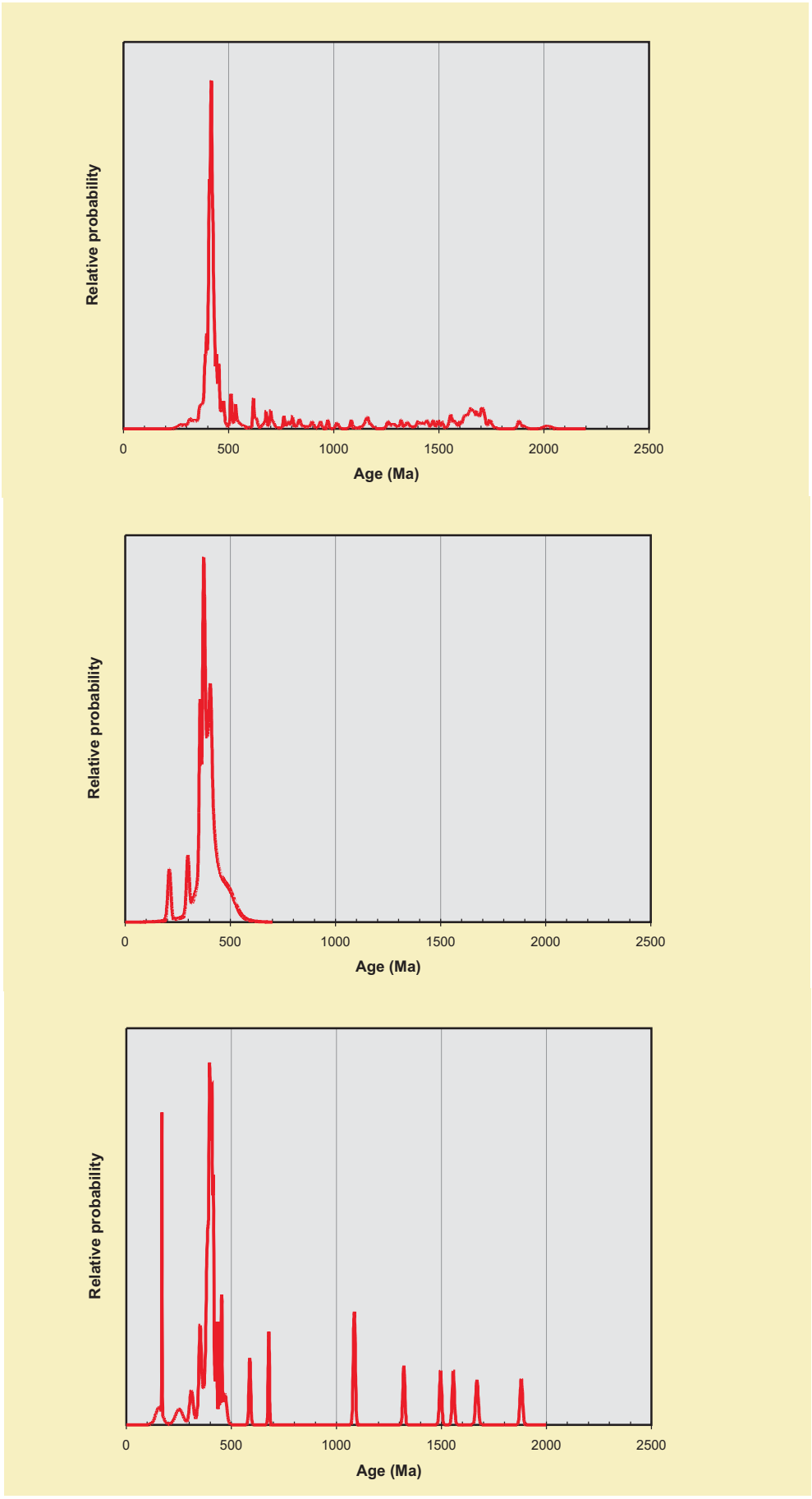



Figure 28. Three probability plots from the Faroe Shetland basin. Although the number of samples from Cenomanian/Turonian and Campanian/Maastrictian sediments are limited, the pattern is clearly identical to that seen in Kangerlussuaq (Figure 26).

## CONCLUSIONS

Within the Campanian Maastrichtian palynofloras recovered in this study, there are three major types which represent different source vegetation (Figure 29). These can be defined using multivariate statistics, but are also evident from empirical inspection of the data set. They comprise:

**A Norwegian flora**, which is highly diverse and contains similarities to palynofloras recorded from other Northern European sites (Chalnova et al., 1981). Characteristic of this is the combination of triprojectate and Normapolles group pollen with pollen of laurel types.

**A Greenland flora**, which contains a moderately diverse triprojectate assemblage, and has a moderately diverse suite of bryophyte spores. Younger parts of the interval show an increasing dominance of *Cupuliferoipollenites* species. This indicates that the origins of the Paleocene Greenland flora (Jolley et al., 2005) are within the Campanian.
Within Greenland, our data indicates that west Greenland was wetter than the eastern side.

**A Scottish flora,** which is characterised by an abundant and diverse triprojectate flora. The remainder of the assemblage is composed of bryophyte spores, fern spores and gymnosperm pollen, and is not highly diverse. Despite being further to the south, it lacks the thermophyllic laurel and Normapolles elements of the Greenland flora. This may reflect isolation and endemic floral community evolution during the Late Cretaceous. Other records of this flora are scarce, but it is recorded as reworking in the sub-basaltic basal Paleogene sediments of Mull (Simpson, 1962, Jolley et al., 2002)

Data for the older Turonian-Santonian interval is less equivocal, but indicates that the Campanian Maastrichtian argillaceous sediment transfer model applies here also. Because of the similarity to the later period in the terms of mudstone deposition in a marine basin during a period of high relative sea level, this conclusion is intuitive. It is not possible to demonstrate the presence of a distinctive Norwegian flora during this period, because sediments of this age from offshore Norway have not been examined.

Analysis of the pollen and spore flora suggests that major changes in composition occur in response to climatic variation. Significant cooling is demonstrated to have occurred in terrestrial environments at the end of the Santonian, with subsequent warming occurring in the upper Campanian. This provides a stratigraphy for pollen and spore assemblages in the region, although currently it does not compare with the resolution available from other micropaleontological data.

By combining this study with that reported by Jolley et al., (2005) and Jolley & Morton (2007), a complete phytogeography and argillaceous sediment transport history can be developed for the Turonian to Paleocene (to top Sequence T38) can be utilised.

In the region of the Faroe Islands a sediment bypass system developed in Santonian - Early Campanian (Larsen et al., 2005). The new data gathered here indicates that westerly sediment transfer into the Faroe-Shetland Basin dominated the Late Cretaceous period. Although the lack of borehole coverage means that direct evidence is not available, sequences of Cenomanian - Coniacian and Late Campanian - Maastrichtian mudrocks could be expected to occur under the Faroe Islands. There remains the possibility that westerly sourced clastic sediments of Santonian - early Campanian age may occur in this area. These are more likely to host arenaceous beds by virtue of them being deposited during a period of low relative sea levels.

Detrital mica age evidence indicates similar sediment pathways as palynological evidence and a Greenland sediment source in the Faroe-Shetland Basin. However, the ultimate source of silicate grains in argillaceous and arenaceous sediments must have been dominated by the Caledonian fold belt, or sediments derived from these rocks (e.g. Carboniferous, Jurassic).

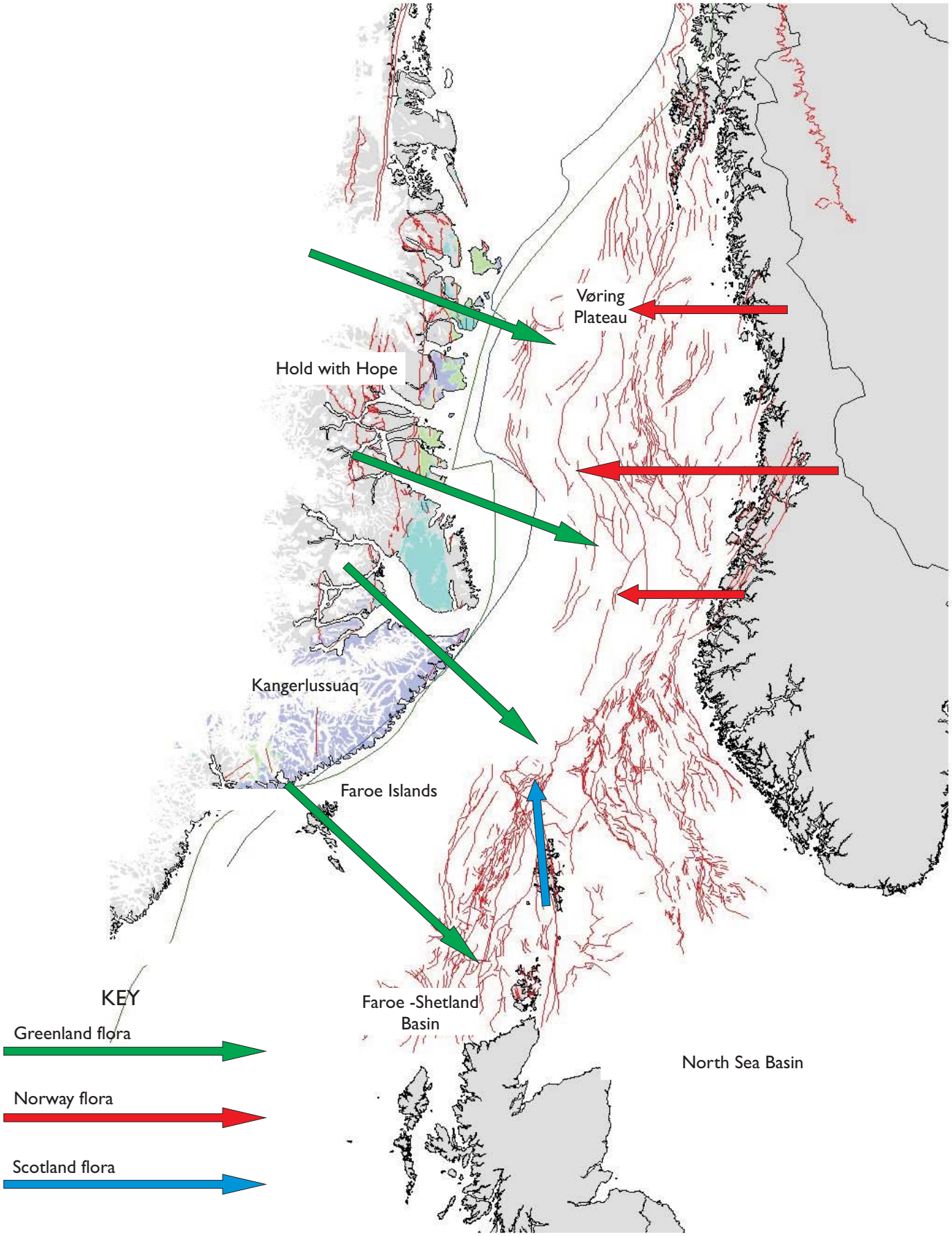



Figure 29: Map showing reconstructed argillaceous sediment supply pathways during the Campanian - Maastrichtian. Evidence suggests that a similar pattern of sediment distribution occurred during the older, Turonian - Santonian interval in the region between Kangerlussuaq and the Shetland Islands.

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