PHYTOGEOGRAPHY, PROVENANCE AND SEDIMENT TRANSFER PATHWAYS IN THE PALEOCENE STRATA OF THE FAROE – SHETLAND REGION

Final Report for the Sindri Group

July 2004

Dr David W. Jolley
Department of Animal and Plant Sciences, University of Sheffield, Denny Building, Western Bank, Sheffield S10 2TN, UK Tel: +44 (0)114 222 3687; Fax: +44 (0)114 276 0159; e-mail: d.jolley@sheffield.ac.uk

Dr Andrew G. Whitham
CASP, West Building, 181a Huntingdon Road, Cambridge CB3 0DH UK; Tel: +44 (0)1223 277 586; Fax: +44 (0)1223 276 604; e-mail: andy.whitham@casp.cam.ac.uk

CONTENTS

	Page
1. INTRODUCTION	4
2. THE PALEOCENE POLLEN AND SPORE FLORA OF THE FAROE-SHETLAND BASIN	5
Introduction	5
General composition of the microflora	5
Mid succession communities	5
Early succession communities	6
Late succession communities	7
3. THE FLORA OF THE KETTLA MEMBER	8
Kettla Member heavy mineral assemblages	8
4. FLORAS OF THE PALEOCENE FAROE-SHETLAND AREA	10
Data set structure and interpretation	10
Stratigraphy of the 'Greenland Flora'	11
Heavy mineral evidence for a westerly source	11
5. COMPOSITION OF THE GREENLAND FLORA	12
6. COMPOSITION OF THE HERIDES-SHETLAND FLORA	17
Hebrides-Shetland sub dominant CA analysis	17
Hebrides-Shetland sub dominant cluster analysis	18
7. PALYNOFLORAL EVIDENCE FOR SEDIMENT SOURCE AREAS	19
HEBRIDES-SHETLAND	20
Sedimentary successions	20
Lava fields	21
Recycled palynomorphs	21
SOUTHERN EAST GREENLAND	23
Structural framework	23
Sedimentary units sampled	23
Greenland-evidence for the Paleocene flora	26
Christian IV Formation	26
Sediment Bjerge Formation	28
Origin of the Greenland Flora	31
8. PHYTOGEOGRAPHIC EVIDENCE FOR SEDIMENT TRANSFER PATHWAYS	32
Geographical distribution of the Greenland Flora – the westerly source	32
Geographical distribution of the Hebrides – Shetland floras - the easterly source	34
9. CONTROLS ON SEDIMENT TRANSFER	37

Importance of the Greenland stratigraphic record 37
Pulsing of westerly sediment source 37

10. REFERENCES

Data tables are provided as Exel files on the accompanying CD.

1. INTRODUCTION

Investigations into the distribution of heavy minerals (Morton et al., 2002) in the sediments of the Faroe – Shetland Basin have provided insights into sediment dispersal patterns in the area. A number of complimentary techniques can be used to identify the source of finer, argillaceous sediment. These techniques are less prominent in the published literature because they are of relatively new inception. Both detrital white mica age analysis and microfossil based phytogeography fall into this categeory.

This study concentrates on the contribution to our understanding of sedimentary provenance made by pollen and spores. Where available, the information derived is synthesised with data from heavy mineral and detrital white mica studies. These comparisons provide an extra dimension to the evidence derived from the palynological data, and allow cross checking of data from individual disciplines.

Plant pollen and spores are abundant in the Palaeogene sediments of the Faroe Shetland Basin (Jolley, 1997, Ellis et al., 2002). Terrestrially derived palynomorphs fall into the size range of 5-60um, and have hydrodynamic properties comparable to silt size sedimentary particles. Pollen and spores preserved in marine basins are derived from vegetation growing within catchment areas on the basin margins. Transportation of pollen and spores into a marine basin is dominantly by fluvial action. Once in the marine environment, this plant material will become part of the sediment in the coastal belt. However, in marine basins with salinity stratification, or major input from large fluvial systems, the pollen and spore load is transported for considerable distances offshore. This has been shown to occur in the North Sea Basin during the deposition of the Rogaland Group (Knox & Holloway, 1992), where pollen and spores are abundant (Schroder, 1992; Jolley, 1996). Similar restricted circulation marine conditions with considerable fluvial input, predominated in the northeastern Atlantic during the Paleocene and Early Eocene. This resulted in offshore transference of large volumes of pollen throughout this interval.

2. THE PALEOCENE POLLEN AND SPORE FLORA OF THE FAROE-SHETLAND BASIN

Introduction

The palynofloras recovered from the Late Paleocene sediments of the Flett Formation are of remarkable overall consistency across the northeast Atlantic (Jolley et al., 2002; Ellis et al., 2002). During this period, thermal uplift associated with North Atlantic Igneous Province (NAIP) activity led to emergence of parts of the northeastern Atlantic. Coupled with the amelioration of higher latitude climate associated with the Late Paleocene Thermal Maximum (LPTM) and succeeding interval (Winkler & Gawenda, 1999), this uplift allowed floral migration, resulting in closely similar coeval floras from eastern Greenland (Jolley & Whitham, 2004), the Faroe Islands (Lund, 1989; Ellis et al., 2002) and the Hebrides – Shetland region.

The current study concentrates on the older Paleocene sediments of the Sullom, Vaila and Lamba formations of the Faroe-Shetland Basin. This interval spans depositional sequences T10-T38 (Ebdon et al., 1995), although here we use a maximum flooding surface based subdivision (Figure 1) utilised by Jolley et al. (in press). The current data set is mostly dependent on boreholes, as little of this interval is exposed. Because of the history of hydrocarbon exploration in the Faroe-Shetland Basin, the wells presently within the public domain are situated in the UK zone. However, this skewed data set does allow a comprehensive overview of the floras that dominated the area now occupied by the Hebrides –Shetland shelf.

General composition of the microflora

Paleocene pollen and spore floras from wells along the strike of the Faroe - Shetland Basin are dominated by pine (Piniaceae) and dawn redwood pollen (*Glyptostrobus* or *Taxodium*). The Piniaceae pollen dominates in the intervals of highest relative sea level by virtue of its excellent hydrodynamic qualities and resistance to decay. The remainder of the pollen assemblages through the Vaila and Lamba formations are made up of mire community complexes.

Mid-succession communities

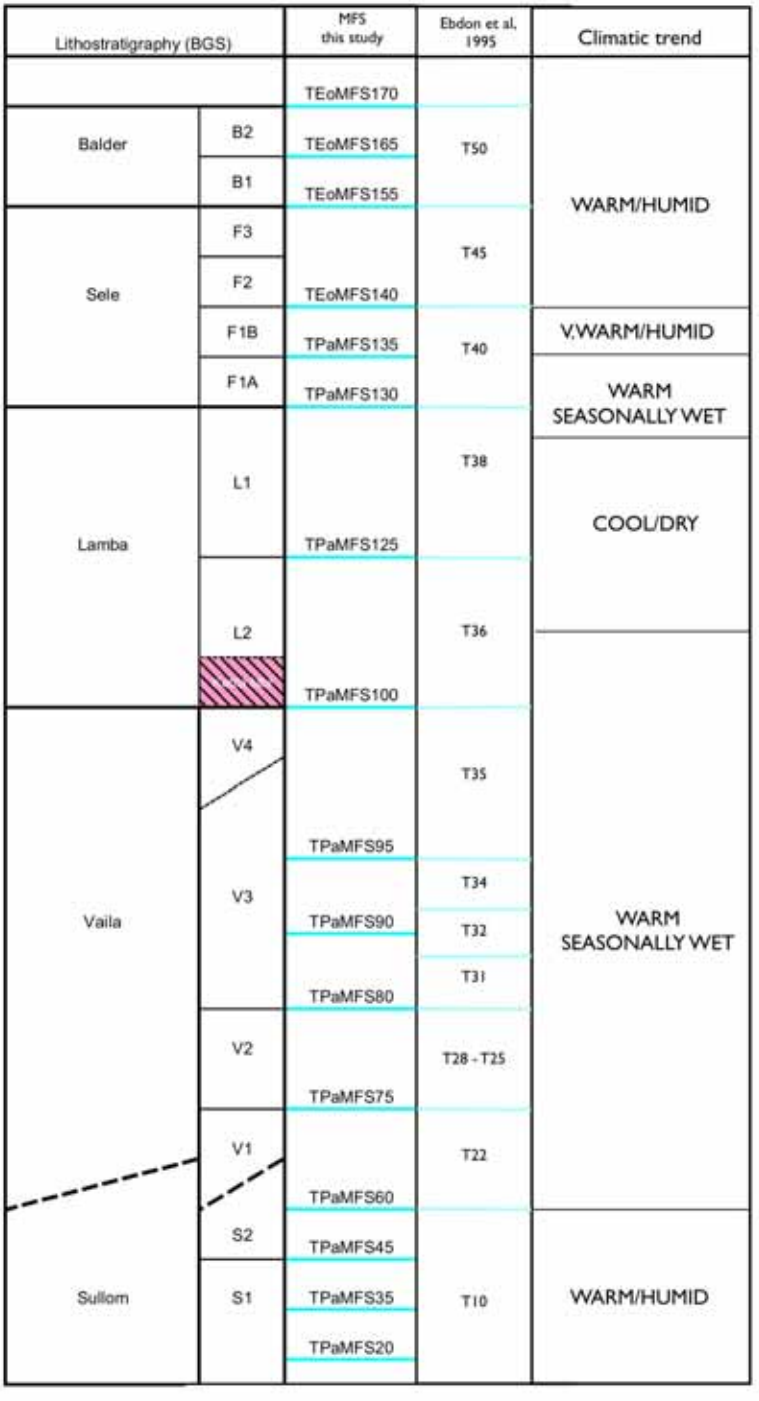


Figure 1. Maximum flooding surface based stratigraphical framework used in this study.

These mires form the mid and late successional phases of the vegetation community development.

- *Tricolpites* species (derived from plane tree types and relatives), are the dominant form in riparian vegetation. They may occur with *Monocolpopollenits tranquilus* (*Ginkgo*) in levee facies, or with the redwood *Sequoia*.
- *Momipites* species (Hickory relatives) are commonly associated with diverse mid-successional mire/floodplain communities. The ecology of fossil hickories indicates that they are well adapted to stable saturated mires in the early stages of formation. This flora was first identified on the east Shetland Platform by Jolley & Morton (1992). Here, *Momipites* species dominated the angiosperm component in a lowland peat mire. Similar Thanetian lowland floras where *Momipites* species dominate the angiosperm component have been recorded from the Thanet Sands and Ormesby Clay formations of southeastern England (Jolley, 1992; 1998).
- Dryer mid successional vegetation is characterised by Myricaceae (Myrtles) and *Liquidambar* types. These are often derived from uplifted areas.

Early succession communities

The precursor to these mid-successional communities are simple, and include taxa that persist into later successions

- Species of *Equisetum* (Mare's Tails) comprised the earliest colonist in the period. These plants are normally represented by macrofossils of *Equisetites*, the spores not being preserved. The example pictured on the right is from the stratigraphically younger Faroe Islands Lava Field
- *Laevigatosporties haardtii* forms a dominant part of early mire succession. High frequencies of *L. haardtii* (undifferentiated filicalean fern, but possibly attributable to the Blechnaceae or Thelypteridaceae) are indicative of recently disturbed or

submerged swamp or marsh areas (Collinson, 2002). This is evident from the example from the Faroe Islands Lava Field in Figure 2.

- Similarly, higher frequencies of *D. adriennis* (cyathaceaen tree ferns) and *Monocolpopollenites tranquilus* (*Ginkgo*) are characteristic of scrub vegetation in recently disturbed areas. These are commonly seen on floodplains and alluvial fans.

Late Succession communities

The late successional lowland vegetation at the Hebrides – Shetland margin was heavily dominated by dawn redwoods (Taxodiaceae). These, and in some cases the Juglandaceae (walnuts & hickories) dominated mid-successional communities in association with *Nyssa*-type angiosperms (Black Gums). The photograph on the right shows *Davidia,* a member of the same family as the black gum (Nyssa) common in Paleocene mid-late succession mires.

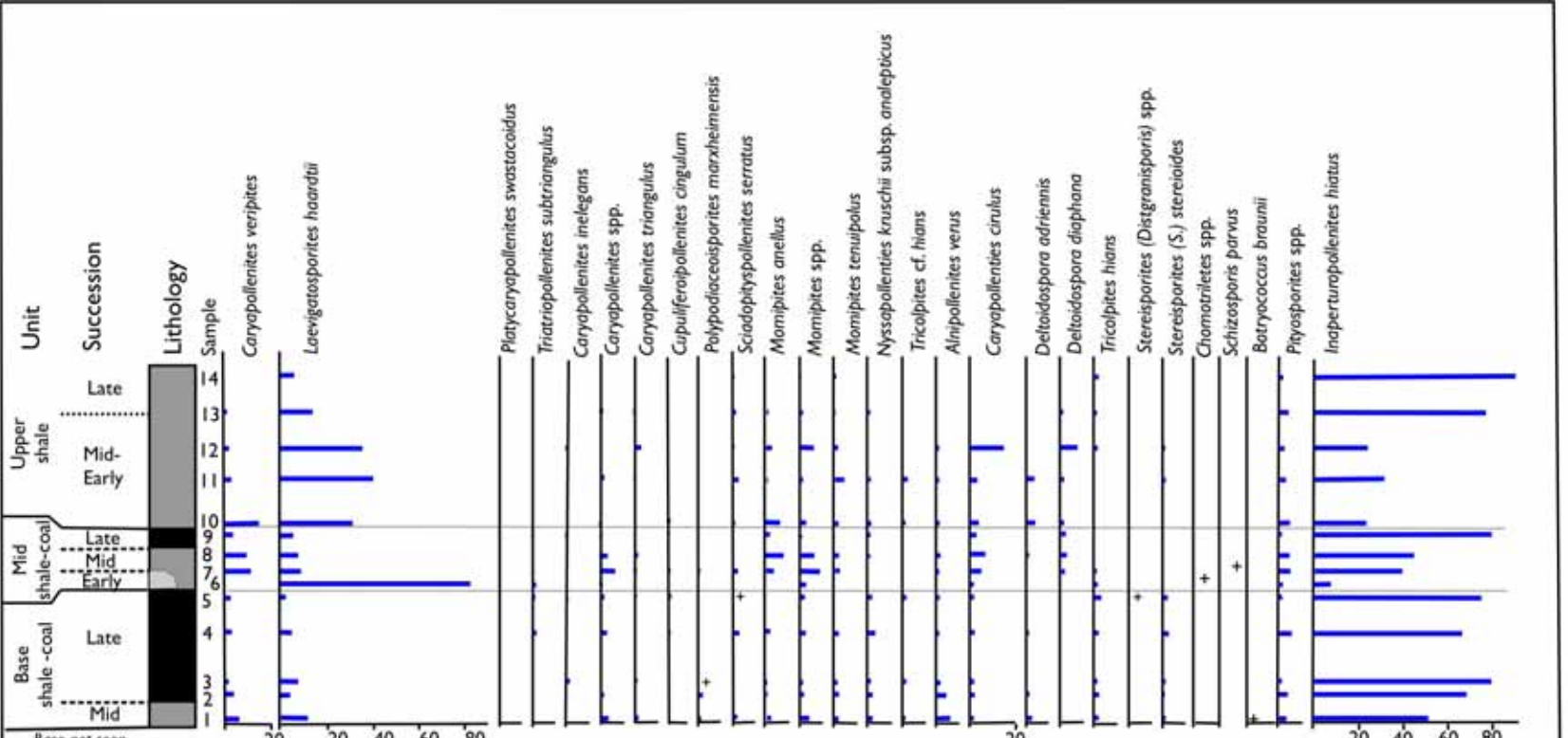


Figure 2. Clastic sedimentary sequence from the Faroe Islands, illustrating the transition from early to mid and late successional communities.

3. THE FLORA OF THE KETTLA MEMBER

Prior to the initiation of this study, it had become apparent that the Kettla Member and underlying Vaila Formation Unit V4 sands of some Faroe-Shetland Basin wells contained floras which were unusual. Although the palynoflora continued to be dominated by gymnosperm pollen derived from pines and *Glyptostrobus*, the angiosperm component is not dominated by any one genus. Instead, this flora is typified by commonly occurring *Cupuliferoipollenites* and *Cupuliferoidaepollenties* (derived from chestnut-type plants of the Fagaceae), co-occurring with *Momipites* species. This flora is associated with the degraded volcanic ash and volcanogenic lithoclasts that characterise the Kettla Member. This is particularly well illustrated in the cored section of the Kettla Member in well 205/9-1(Figure 3). To date, the source of this volcanogenic sediment has not been identified, although Ellis et al, (2004) suggested a local source for similar volcaniclastics in a Corona Basin well. The unusual component of this palynoflora cannot have been derived from the eastern Hebrides-Shetland side of the basin. Here, the Kettla Member of wells in the centre and east of the basin lack the characteristic Fagaceae pollen. Instead, a source for this flora and at least some of the volcaniclastic sediments that contain it must be sought towards the west.

Kettla Member Heavy Mineral assemblages

The unusual nature of the palynoflora in the Kettla Member of 205/9-1 is mirrored by its detrital heavy mineral assemblage. This was reported by Jolley et al. (in press), demonstrating that the Kettla assemblage differs in two important respects compared with other Sullom, Vaila and Lamba Formation sandstones in the Foinaven and Flett sub-basins.

- The assemblage contains volcaniclastic components that indicate the source area included basic igneous rocks.
- The terrigenous clastic component of the assemblage has unusually low rutile:zircon ratios (RuZi, in the terminology of Morton & Hallsworth, 1994).

Sullom, Vaila and Lamba formation sandstones known to be derived from the Orkney-Shetland Platform to the east (Lamers & Carmichael, 1999) have higher

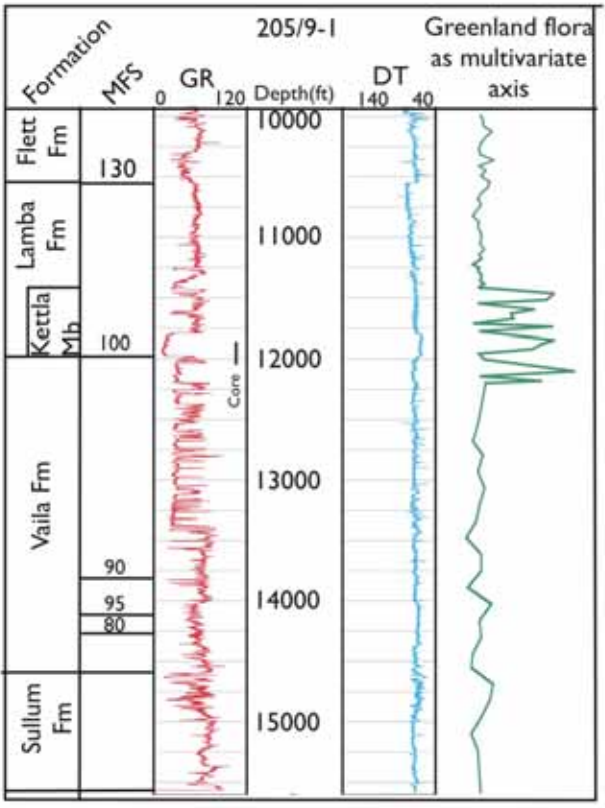


Figure 3. Statistical representation of the westerly sourced flora in the 205/9-1 well

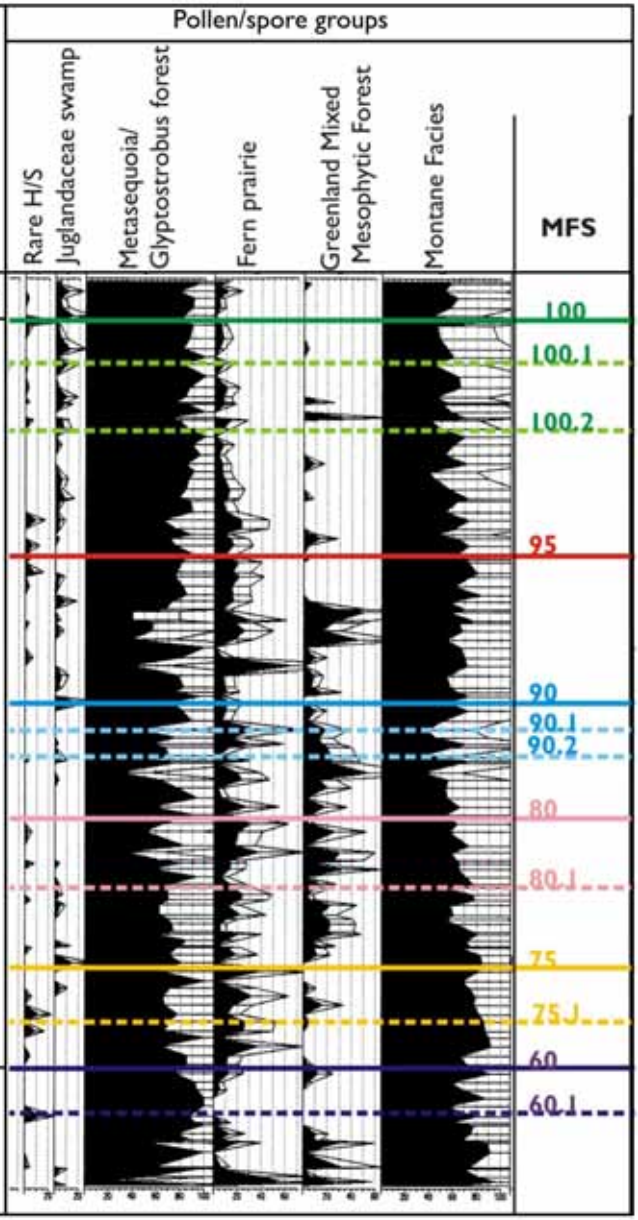


Figure 4. Caderived pollen community groupings for a Corona Basin Well. Note the influx of the Greenland Flora.

RuZi values, including those of the Foinaven sub-basin (Morton et al., 2002) and the Flett sub-basin (HM Research Associates unpublished data). The source area to the east (Orkney-Shetland Platform) therefore appears to have been unable to provide sediment with relatively low RuZi during the Palaeogene, suggesting that the low RuZi sediment in 205/9-1 must have had a western provenance.

4. FLORAS OF THE PALEOCENE FAROE-SHETLAND AREA

Data set structure and interpretation

The occurrence of the unusual component in the flora of the Kettla Member and Vaila Formation Unit 4 sands is repeated in other wells within the Faroe-Shetland Basin. To identify the stratigraphical and spatial distribution of this flora, it was necessary to examine the palynofloras from a number of wells along the strike of the basin. However, a key event in the recognition of the extent of the westerly sourced floral component was the drilling of wells in the south of the Corona Basin from 2002. These wells remain commercially sensitive, so data from the wells cannot be presented in this report. However, papers given at the Faroe Islands Exploration conference in 2004 and the data contained in Jolley et al., (in press), allows us to make some important observations.

For this study, the resource available was dominantly primary analytical data prepared by the investigators. Additional palynological and micropaleontological data was available for use in the study from regional studies undertaken for Sindri partners by stratigraphical contractors. Unfortunately, because the palynological data is prepared using a relatively large sieve size, the isolation and recognition of insitu pollen and spore taxa is poor. Reliance must therefore be placed only on the primary analytical data produced for this study.

Data quality is also an important issue when attempting to acquire data on small-sized pollen taxa. Most of the offshore sample material available is in the form of ditch cuttings. This type of sample has disadvantages and advantages. The nature of ditch cuttings means that sediments in the sample are from a range of depths, some of which may constitute cavings from uphole, uncased section. Quality is higher in unwashed cuttings than in washed and dried stored cuttings. The advantage of cuttings to this kind of study is that they provide a 'blur' of data from an interval. Core and sidewall core samples will only provide 'snapshot' insights into the flora, which for taphanomic reasons may not be representative of the whole interval.

While it would in theory be possible to recognise the occurrences of the westerly sourced 'Greenland Flora' (Jolley et al, in press) in the basin by the occurrence of common *Cupuliferoipollenites* and *Cupuliferoidaepollenites* species, a statistical technique can also be adopted. Because of the higher quality of the data set in the Corona Basin

wells, analysis of the whole data set from individual wells can be undertaken using correspondence analysis (CA). This is a powerful statistical tool used by ecologists. It enables complex multivariate data sets to be simplified into a number of data axes. Where the data set is of favourable composition, the majority of the data variation can be included in the first two axes. These axes can then be plotted as x:y scatter graphs, allowing a visual presentation of clustering of species, or samples within a section. Clusters of species in this context are representative of co-occurring taxa. These groups of taxa may share an ecological affinity. The palynofloras of the Sullom, Vaila and Lamba formations are well suited to CA, as they lack evolutionary variation. This prevents an evolutionary overprint from masking ecology-based trends in the data set.

Adoption of CA as a determinant of the presence and composition of the 'Greenland Flora' allows the identification of taxa whose occurrence suggests that it forms part of the floral structure. It also allows identification of a group of taxa which occur in both the 'Greenland Flora' and that derived from the Hebrides – Shetland area.

Stratigraphical occurrences of the 'Greenland Flora'

Within these data, two other stratigraphical intervals have yielded influxes of the westerly derived flora, with a third interval probable. Greenland Flora components have been identified in the Sullom Formation, beneath TPaMFS60 (within sequence T10 of Ebdon et al, 1995). A strong pulse is also seen in the TPaMFS95-sub TPaMFS90 interval (the sequence T31-T34 interval of Ebdon et al. 1995) of the Vaila Formation. A further pulse may exist between TPaMFS80 and TPaMFS 70, but further analysis is necessary to demonstrate this conclusively (Figure 4).

Heavy Mineral evidence for a westerly source

By comparison with the Kettla Member in 205/9-1, low RuZi values may be used as an indicator for the presence of westerly-derived sandstones. On this basis, a strong western influence can be identified in the sub TPaMFS90 interval, closely coincident with the influx of the Greenland Flora (Figure 4). There is also evidence for low-RuZi heavy mineral suites in the Sullom Formation. However, complete coincidence between westerly sourced heavy mineral suites and the occurrences of the Greenland Flora are

not expected. While the heavy mineral suite reflects the distribution of sand grade sediments within the Faroe-Shetland Basin, the lighter pollen flora reflects transportation of argillaceous sediment.

5. COMPOSITION OF THE GREENLAND FLORA

Definition of the westerly floral component in the pollen assemblages of the Faroe Shetland and Corona basins has been achieved using CA. To illustrate the process, the statistical analysis of a well from the Corona Basin is detailed below. The stratigraphical section includes the Sullom, Vaila and Lamba formations. Using the CA technique outlined above, it is possible to simplify the data into a series of ecological groupings.

I. Hebrides – Shetland mid-succession mire community

Spore/pollen taxon	Botanical affinity
Alnipollenites verus	*Alnus (Alder)*
Aquilapollenites spinulosus	*Unknonwn Cretaceous relict taxon*
Baculatisporites primaries	*Osmunda, Osmundaceae (tree ferns)*
Cicatricosisporites rousei	*Schizaceae, (ferns)*
Dicellaesporites spp.	*Fungi*
Intratriporopollenites pseudoinstructus	*Tilia,Tiliaceae, (lime)*
Laevigatosporites haardtii	Polypodiaceae fern – possibly related to Cretaceous *Berissia*
Momipites anellus	*Engelhardtia,* Juglandaceae (hickory)
Momipites cf. anellus	*Engelhardtia,* Juglandaceae (hickory)
Momipites cf. tenuipolus	*Engelhardtia,* Juglandaceae (hickory)
Momipites strictus	*Engelhardtia,* Juglandaceae (hickory)
Momipites tenuipolis	*Engelhardtia,* Juglandaceae (hickory)
Platycaryapollenites platycaryoides	*Platycarya*, Juglandaceae (hickory)
Plicapollis pseudoexcelsus	Normapolles, possibly protojuglandaceae
Retitricolpites angululuminosus	Platanaceae
Retitricolpites retiformis	Platanaceae
Rhoipites microreticulatus	Rhus
Sciadopityspollenites spp.	Sciadopitys, Taxodiaceae
Stereisporites (Cingulitriletes) spp.	Bryophyte moss
Stereisporites (Distanc) germanicus	Bryophyte moss
Stereisporites (Distverrusporis) spp.	Bryophyte moss
Tetracellaesporites spp.	Fungi
Torisporis toroides	Gleiceniaceae?
Tricolpites cf. *hians*	Platanaceae or Cercidiphylaceae

Triporopollenites robustus	*Myricaceae, (Myrtles)*

This grouping contains many taxa which are known to have favoured wet lowland mires. They are normally associated with mid succession floras. It also contains floodplain taxa and ferns (cf. *Berissia*) which form part of the early succesional vegetation in the development of mires in the region.

2. Fern scrub community

Spore/pollen taxon	Botanical affinity
Deltoidospora adriennis	Cyathea type tree ferns
Deltoidospora maxoides	Pteridaceae, ?*Achrosicum* (mire fern)
Gleicheniidites senonicus	*Gliechenia* (fern)
Intratriporopollenites microreticulatus	Tiliaceae*, Tilia (lime)*
Microsporonites spp.	Fungi
Momipites coryloides	Juglandaceae*, Engelhardtia (hickory)*
Pompeckjoidaepollenites subhercynicus	Unknown Normapolles taxon
Rhoipites ficifolius	*Viburnum, Viburnaceae*
Sequoiapollenites polyformosus	*Sequoia,* Taxodiaceae (redwood)
Stereisporites (S.) sterioides	*Bryophyte moss*
Subtriporopollenites anulatus anulatus	Unknown Normapolles taxon
Triatriopollenites triangulus	*Myrica, Myricaeae, (myrtle)*
Trudopollis hamenii	Unknown Normapolles taxon, refered to 'protojuglandaceae'

This is a subsidiary grouping to the mid-successional mire, and contains more ferns and fewer swamp angiosperm taxa. Some of the taxa in this group are associated with dryer soils. Others are associated with environmental disturbance, often seen in alluvial fans and floodplains

The volume of pollen production from these two pollen and spore communities is high, suggesting that they occupied an extensive swamp area on the fringes of the Hebrides to Shetland Islands area. This lowland swamp forest area must have been extensive, with the mid-successional mire forming much of the vegetation. In the intertidal zone however, *Glyptostrobus*-type trees would have dominated in a littoral mangrove analogy

community. While the fern scrub group is indicative that dryer areas existed in the swamp, the mid-successional mire contains taxa from a riparian margin community. With so much of the Hebrides to Shetland shelf mantled by swamp vegetation, runoff from the Scottish landmass must have been concentrated into major river systems cutting through the lowland swamp forests. Changes in base level and tectonic shifts would have influenced the courses taken by these large drainage systems and may account for compositional changes in easterly sourced heavy mineral suites reported in the Paleocene of the Foinaven – Shiehallion area (Morton et al., 2002).

3. Common elements

Spore/pollen taxon	Botanical affinity
Cupuliferoipollenites cingulum subsp *pusillus*	*Castanea, Fagaceae (chestnut types)*
Momipites spp.	Juglandaceae, *Engelhardtia (hickory)*
Nyssapollenites kruschi subsp *analepticus*	*Nyssa, (Black Gum)*
Polyatriopollenites stellatus	*Juglandaceae (?*
Triatriopollenites subtriangulus	Myricaceae, *Myrica*
Cupuliferoideaepollenites liblarensis subsp. *fallax*	*Castanea,* Fagaceae (chestnut types)
Deltoidospora wolffi	Cyatheaceae, *Cyathea, fern*
Intratriporopollenites ceciliensis	*Tilia,* Tiliaceae
Lycopodiumsporites spp.	*Lycopodiaceae*, moss
Microthallites spp.	Fungi
Momipites dilatus	Juglandaceae, *Engelhardtia (hickory)*
Monocolpopollenites tranquilis	*Ginkgo,*
Nyssapollenites kruschi subsp *accessories*	*Nyssa, (Black Gum)*
Pesavis tagluensis	Fungi
Pterocaryapollenites spp.	*Pterocarya* (pecan)
Tricolpites hians	*Platanaceae,* plane types
Trilites tuberculiformis	Lygodiaceae, *Lygodium,* fern
Trivestibulopollenites palaeobetuloides	Birch type, *Betulaceae*
Verrucatosporites secundus	Polypodiaceae, fern

This group of taxa occur in combination with the Hebrides-Shetland and Greenland communities. They are dominated by species that occur in intervals where both

Greenland and Hebrides-Shetland floras are represented. Others are derived from the west in very low frequency.

4. Greenland Flora: Mixed mesophytic forest

Spore/pollen taxon	Botanical affinity
Baculatisporites nanus	*Osmunda, royal fern*
Cicatricosisporites dorogensis	*Schizaceae (fern)*
Cupluliferoidaepollenites liblarensis subsp. *liblarensis*	*Castanea, Fagaceae (chestnut types)*
Cupuliferoipollenites cingulum subsp.*fuscus*	*Castanea, Fagaceae (chestnut types)*
Cupuliferoipollenites cingulum subsp. *oviformis*	*Castanea, Fagaceae (chestnut types)*
Cyrillacaeapollenties megaexactus	*Castanea, Fagaceae (chestnut types)*
Intratriporopollenites instructus	Tiliaceae, *Tilia,* (lime)
Mulicellaesporites spp.	Fungi
Pseudoplicapollis serenus	Normapolles pollen
Quercoidites microhenrici	Oak, *Fagaceae*
Stereisporites (Distanulisporis) spp.	Moss
Tetracolpites 'psilatus'	?Fagaceae
Tetracolpites reticulates	?Fagaceae
Trilites multivalatus	Lygodiaceae (fern)
Triporopollenites corlyloides	Myricaceae, *Myrica* type

Although the three intervals characterised by the Greenland Flora span a period of several million years, there is no fundamental difference in association composition between them. The diagnostic taxa of the Greenland Flora are long ranging, and recorded throughout the Palaeogene of Northwest Europe. Despite this, a number of unusual species have been identified. Rare occurrences of *Pseudoplicapollis* species, a genus not recorded in UK Thanetian sediments, are recorded in the TPaMFS90-sub TPaMFS95 interval in the most westerly wells.

6. COMPOSITION OF THE HEBRIDES – SHETLAND FLORA

From the CA results given for the Corona Basin well in the preceeding section, the diversity of floral components derived from the east of the basin is apparent. Empirical inspection of the data produced by the study indicated that this Hebrides – Shetland Sullom to Vaila formation flora exhibited geographical variation in its composition. This variation was particularly noticeable in wells along the strike of the Faroe-Shetland Basin. Because analysis of this variation could contribute to our knowledge of sedimentary sources on the Shetland Platform, statistical analysis of part of these floras was undertaken. This analysis concentrated on the sub-dominant taxa in the assemblages recorded, excluding the dominant genera *Pityosporites* and *Inaperturopollenites*.

Hebrides-Shetland flora sub dominant CA analysis

The first test employed was CA based on the dataset of sub-dominant taxa. The results tabulated below show 64% of the variation in the first two axes. This provides a high degree of confidence, allowing the use of the first two axes as a means of plotting the simplified data. Analysis is provided for both the variables (taxa) and cases (wells), the resultant graph demonstrating which of these have the closest relationship in the data matrix

	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0,484	0,313	0,184	0,122
Percentage	39,347	25,386	14,934	9,869
Cum. Percentage	39,347	64,733	79,667	89,537

CA variable scores

	Axis 1	Axis 2	Axis 3	Axis 4
Alnipollenites verus	1,685	-0,323	0,256	0,129
T. cf hians	0,258	1,368	0,489	-0,502
L haardtii	-0,152	0,184	-0,082	0,177
M. tenuipolus	-0,412	0,203	-0,209	0,291
N kruschii	0,746	-0,002	-0,248	-0,494
S polyformosus	-0,341	0,66	-0,184	-0,212
T hians	-0,735	-0,766	0,323	-0,307
D adriennis	0,656	-0,457	0,492	0,194
M anellus	0,447	-0,43	-1,171	0,255
Liquidambarpollenites stigmosus	2,106	-0,278	2,244	1,579
Momipites spp.	2,129	-0,655	0,174	0,238
Retitricolpites retiformis	2,152	-1,033	-1,896	-1,103

CA case scores

	Axis 1	Axis 2	Axis 3	Axis 4
204/19A-3	-0,021	1,938	0,339	-0,87
208/17-1	-0,723	-0,892	0,507	-0,423
204/20-3	-0,269	0,235	-0,201	-0,545
214/28-1	-1,026	-1,713	1,325	-1,179
205/14-1	-0,428	0,183	-0,764	1,643
205/9-1	-0,733	-0,193	-0,691	0,779
219-27-1	0,796	0,342	0,418	-0,089
220-26-1	2,106	-0,278	2,244	1,579
218-28-2	2,152	-1,033	-1,896	-1,103

Hebrides-Shetland flora sub-dominant cluster analysis

This statistical test helps to indicate which wells share the closest similarity in both the sub-dominant flora, and the distribution of the species within the wells. The resultant dissimilarity is displayed as Euclidean distance in the graphs (Figures 5, 6).

Node	Group 1	Group 2	Dissimil.
1	*Alnipollenites verus*	*Momipites spp.*	4,123
2	*Liquidambarpollenites stigmosus*	*Retitricolpites retiformis*	4,243
3	Node 1	Node 2	4,814
4	Node 3	*S polyformosus*	7,031
5	Node 4	*M anellus*	7,412
6	Node 5	*D adriennis*	8,453
7	Node 6	*N kruschii*	14,514
8	L haardtii	*M. tenuipolus*	15,297
9	Node 7	*T. cf hians*	20,461
10	Node 8	*T hians*	32,325
11	Node 9	Node 10	35,14

Node	Group 1	Group 2	Dissimil.	Objects in group
1	219-27-1	220-26-1	7,937	2
2	208/17-1	214/28-1	10,344	2
3	Node 1	218-28-2	10,833	3
4	205/14-1	205/9-1	14,697	2
5	204/20-3	Node 4	18,553	3
6	Node 2	Node 5	22,827	5
7	Node 6	Node 3	25,39	8
8	204/19A-3	Node 7	26,78	9

Similarity of dataset between wells:

Both the denderogram and CA plot produced from the data show the close linkages between the wells south of the Brendan's Dome area (218/28-2, 220/26-1 and 219.27-1), wells in the south of the area, including Schiehallion (205/9-1, 205/14-1 and 204/20-3) and wells in the centre of the basin (214/28-1 and 214/28-1). The Foinaven well, 204/29A-3 is demonstrated (Figures 7, 8) to be of different composition to the other three areas.

Similarity of dataset between taxa:

Similarly, both the CA and dendrogram for the distribution of the sub-dominant species show that there are separate co-occurring groups in the dataset. These groups form the basis of the ecological analysis presented here (Figures 5, 6).

In summary, the Hebrides-Shetland flora is divisible into four ecological/geographical groups:

- A 'northern flora' seen in well between the Erlend Volcanic Complex and Brendan's Dome Volcanic complex
- A 'central flora' seen in the area south of the Erlend Volcanic Complex as far as the Clair Transfer Zone.
- A 'southern flora' seen from the Clair Transfer Zone area as far south as the Schiehallion field.
- A Foinaven flora, seen in a Foinaven field well.

These are coeval Vaila Formation floras, whose compositional variation reflects source differences on the Shetland Platform.

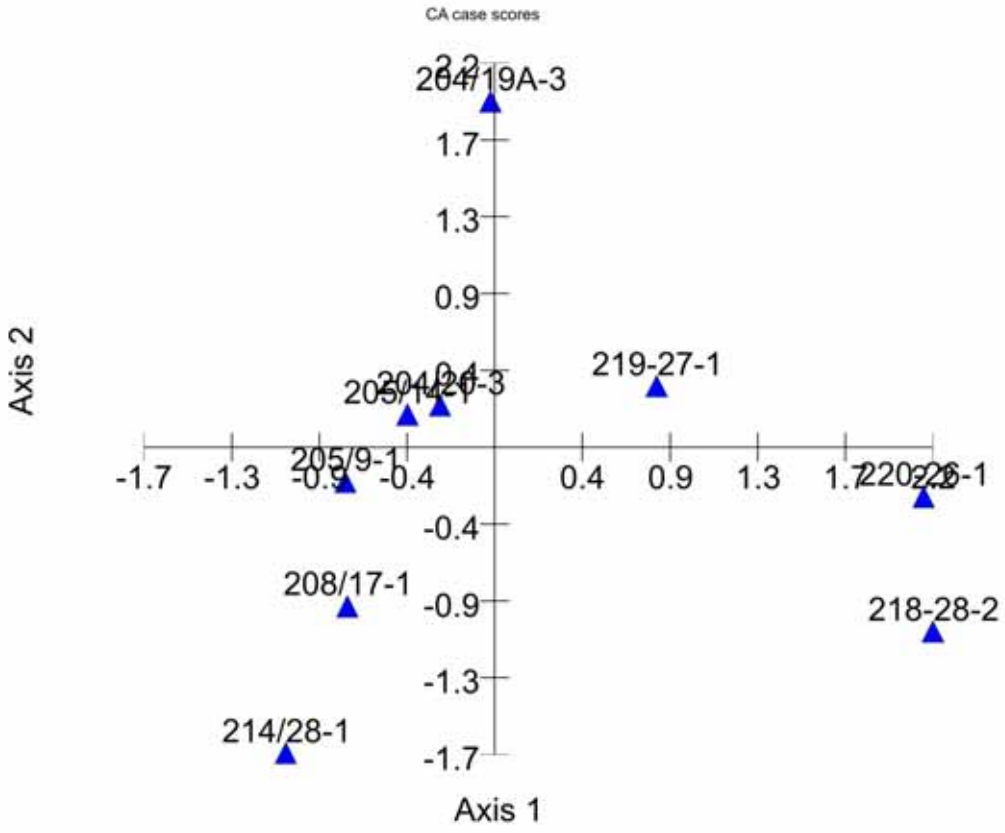


Figure 5. CA analysis plot of similarity between wells

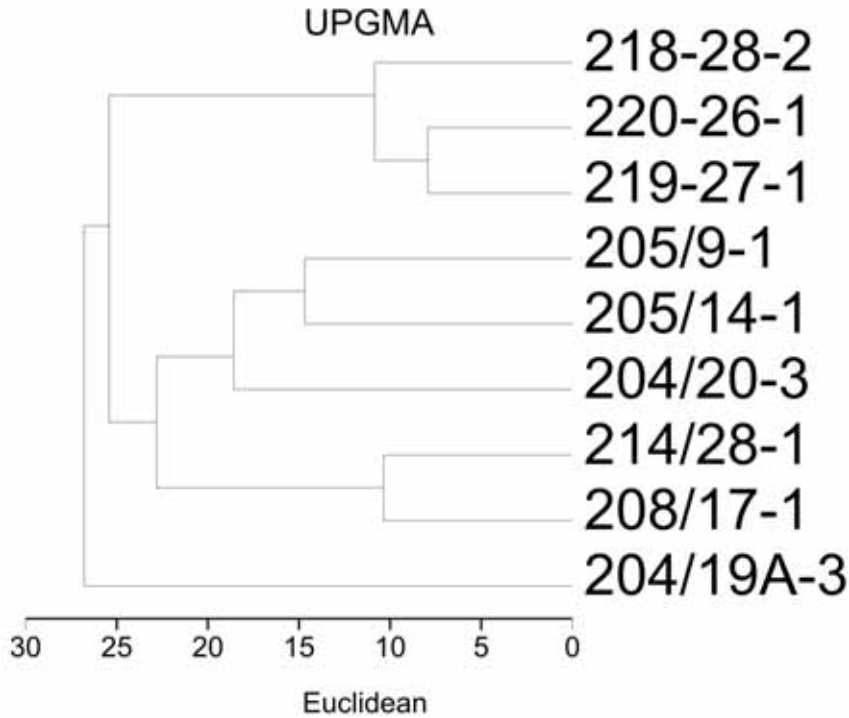


Figure 6. Dendrogram illustrating results of cluster analysis between wells.

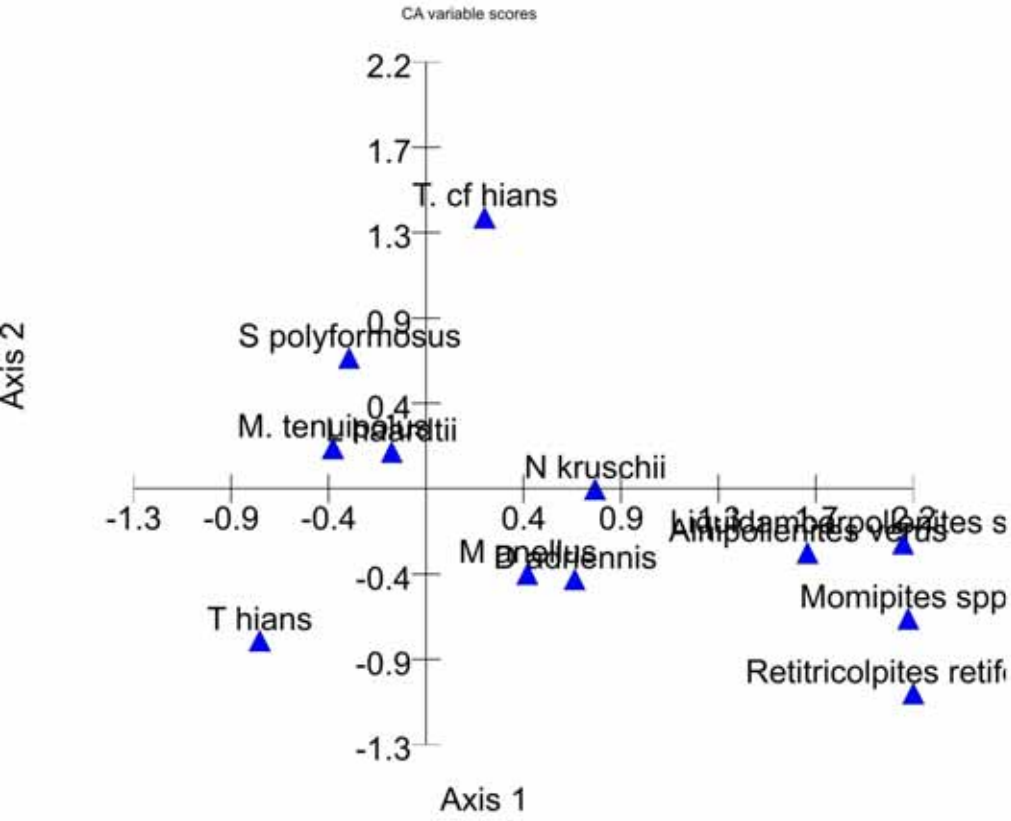


Figure 7. CA analysis plot showing similarity between species

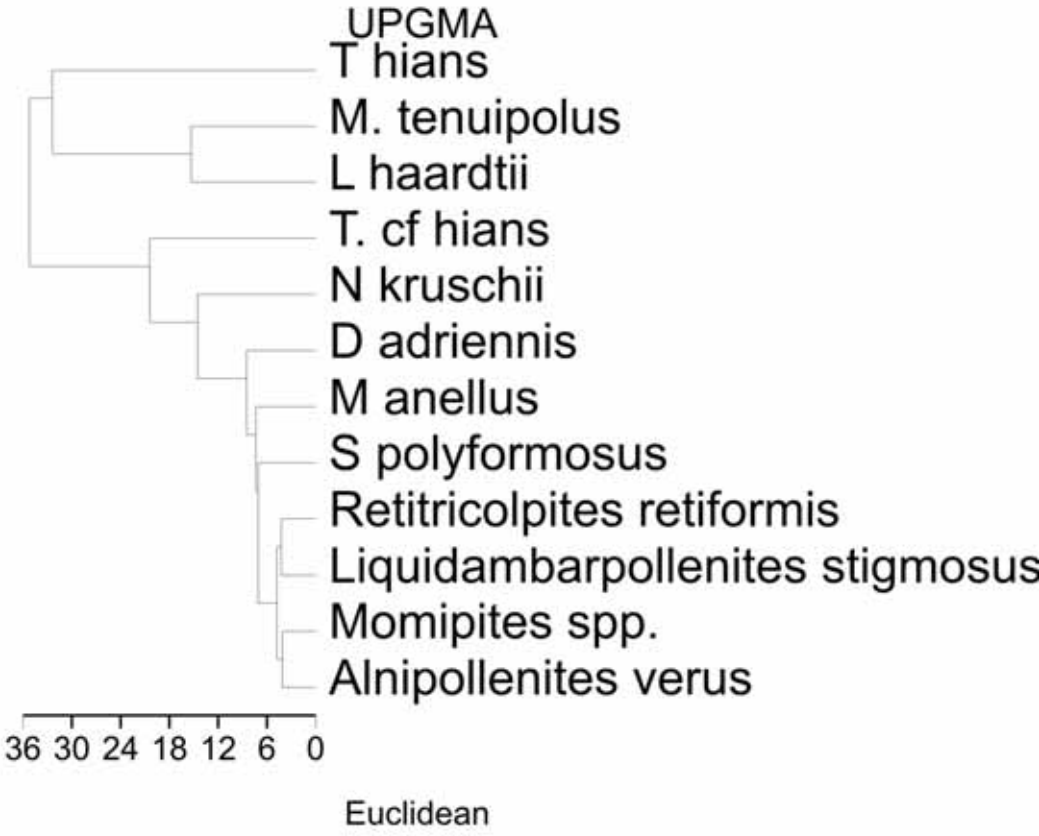


Figure 8. Dendrogram showing similarity between specieis in cluster analysis

7. PALYNOFLORAL EVIDENCE FROM SEDIMENT SOURCE AREAS

HEBRIDES – SHETLAND

It is important to compare both the westerly derived Greenland Flora and the Hebridies Shetland floras to pollen spectra derived from sediments in the projected source area. This phase of the investigation is made complex by the nature of the sedimentary record on the shelf margins. In the case of the Hebrides – Shetland terrace, there are two potential sources of relevant information, shallow boreholes and outcrop associated with lava fields. To ensure a degree of taxaonomic comparablility, it is necessary to restrict these to floras which are known to be Paleocene.

Sedimentary successions

Paleocene sedimentary records on the Shetland Platform are limited. There are no outcrops, and the basins drilled in the British Geological Survey (BGS) coring programe are of younger age (Evans et al., 1991: Hitchen et al., 1995). A comparable section deposited in a terrestrial environment was reported in BGS borehole 82/15 in the Inner Moray Firth Basin (Jolley & Morton, 1992). Here, a lignite is overlain by a thin bed of tuff. Geochemical analyses of the tuff (Jolley & Morton, 1992) indicate that it is of comparable composition to the Fairy Bridge Basalts of Skye and to the Balmoral Tuffite of the Andrew Formation, North Sea Basin (Knox & Holloway, 1992). The flora in the underlying lignite was deposited on a lowland coastal mire. The taxa comprising this flora change upsection. The oldest sample contains a mid-succession *Glyptostrobus-Engelhardtia* type mire in which *Momipites anellus* is 24% of the palynoflora. In the succeeding samples, *Laevigatosporites haardtii* increases in dominance to over 40%. This primary colonising fern indicates that the section is experiencing increasing environmental stress, possibly as a result of relative sea level rise and flooding of the mire site.

The dominance of *Momipites anellus* in the lignite from BGS borehole 82/15 is directly comparable with the presence of this taxon as one of the sub-dominant species in the Hebrides – Shetland southern flora. Reference to the location of the Inner Moray Firth

Basin borehole with respect to the location of the southern flora confirms a potential source in the West Orkney Basin – Inner Moray Firth zone.

Lava Fields

The lava fields of the Hebrides are 1º of latitude further south than the southern end of the Faroe – Shetland Basin. Despite this geographical dissimilarity, a comparison with some of the low altitude floras from these lava fields is informative. Many of the intra-lava sediments in this region are of Eocene age, and cannot be directly compared with the floras studied here. However, the Skye Lava Field is of comparable age, at least on biostratigraphical grounds. It contains a number of floras deposited in lowland environments which can provide useful comparison. In particular, the clastic facies of Glen Osdale, and the coal beds at Tungdal River and Allt Mor Carbostbeg (see Jolley, 1997 for location details) in western Skye provide a useful insight.

These sites show dominance by Taxodiaceae pollen, and contribution from Pines growing outside the immediate area of deposition. The sub-dominant taxa include the early successional *Laevigatosporites haardtii*. The remainder of the sub-dominant flora comprises *Momipites tenuipolus* (*Englelhardtia* type), *Tricolpites hians* (plane types) and bryophyte spores. The Allt Mor Carbostbeg site shows a later succesional flora, which includes a greater dominance of taxodiaceous pollen and common occurrences of *Nyssapollenites kruschi* and *Sequoiapollenites polyformosus*.

Although from a complex mosaic of environments, these sections show similar palynofloras to those seen in the Faroe- Shetland Basin. Despite the similarity in overall composition, they compare best with the Hebridies-Shetland northern flora. This suggests that the Skye Lava Field area did not contribute sediment to the southern end of the study area. Instead, it suggests that a similar kind of flora was present in the northern part of the west Shetland Platform. The occurrence of this flora may not be attributable to volcanic disturbance, but to a degree of environmental instability.

Recycled Palynomorphs

Reworked palynomorphs are common in the Paleocene sections that have been examined for this study. They originate as components of clast reworking of older formations. In the absence of oxidative weathering, they can survive within the

sedimentary system to become a component of newly deposited strata. As they are part of the sedimentary system that supplies a given geographical area, the age of the recycled palynomorphs can reflect the source area geology. In the majority of the offshore sections analysed, there is ubiquitous and often common reworking of Mesozoic taxa. Intervals within the Mesozoic that are known to produce abundant palynofloras, often well represented by reworking. These include Toarcian marine floras, Bajocian – Bathonian terriginous floras and Oxfordian-Kimmeridgian marine floras. Early Cretaceous floras are also well represented, and in contrast to more southerly latitudes, the clastic Late Cretaceous yields recycled taxa.

Recycling of Permian – Triassic palynomorphs is sometimes difficult to determine in assemblages, due to the sparsity of the parent terriginous floras. Many of the studied sections contain sporadic recycled Permo-Triassic taxa. However, a greater concentration of these taxa is recorded in the Vaila Formation of the Foinaven – Scheihallion Fields implying a different source component for this area.

Recycling of Carboniferous palynomorphs is both geographically and stratigraphically restricted in the studied sections. These provide a useful tool in defining sediment provenance and transport pathways which is complimentary to the data on insitu palynolomorphs presented here. The derivation of the Carboniferous spores concerned (mainly the highly abundant taxa *Lycospora pusilla* and *Densosporites annulatus*) is restricted by the stratigraphical range of these taxa. Assemblages containing these species would be expected from Namurian to Westphalian sediments. Although sediments of this age have not been reported from north of Inninmore Bay, Morven, late Devonian – Visean sediments have been reported from the west Shetland Platform (Stoker et al., 1993). More recently, the release of well 213/23-1 has demonstrated the occurrence of thick Namurian non-marine sediments on the Corona Ridge. The distribution of the recycled Carboniferous spores is contained between the Clair Transfer Zone and the Erlend Centre. Further details of this distribution are synthesised with the insitu palynomorph data below.

SOUTHERN EAST GREENLAND

A 900 m thick unit of Cretaceous-Tertiary sedimentary strata is found beneath the 6 km thick plateau basalt succession in Kangerlussuaq (Larsen et al., 1996; Whitham et al., 2004: Larsen, et al., 2004). A new lithostratigraphic scheme for this unit of sediments is currently being worked on as part of another project funded by SINDRI (Stratigraphy in volcanic basins of the North Atlantic – implications for basin evolution and petroleum assessment offshore of the Faroe Islands). The samples analysed and presented in this study are described in the context of this new lithostratigraphic scheme which consist of five new formations and eight new members (Figure 9).

The samples that have been analysed as part of this study are taken from the Christian IV Formation, the Sediment Bjerge Formation and the Vandfaldsdalen Formation.

Structural framework

Deposition of the Aptian-Early Eocene succession was influenced by two intervals of rifting prior to the onset of seafloor spreading in the North Atlantic. The first occurred in the Mid-Albian and is indicated by normal growth faults and the development of local angular unconformities (Morton and Whitham, 2004). Faults active at this time appear to have a SW-NE orientation (Figure 10). The second occurred some time after the Late Maastrichtian and before the Eocene. This period of extension involved a large-scale fault with SE-NW orientation located in the Christian IV Glacier (Larsen & Whitham, in press). This fault may have been a conduit for sediment to the Faroe-Shetland Basin to the southeast. A final period of extension post-dates the extrusion of the plateau-basalts and involves reactivation of the SW-NE orientated fault-set. The prominent Sortekap Fault is part of this set of faults.

Sedimentary units sampled

Christian IV Formation: This unit could be as much as 500 m thick, and rests disconformably on Turonian-Coniacian mudstones belonging to the Sorgenfri Formation. The thickest continuous section is at W4245 on the west side of the Christian IV Glacier where the unit is in excess of 250m thick. The succession is dominated by well-bioturbated sandy mudstones, with rare beds of unbioturbated sandstone up to 80 cm

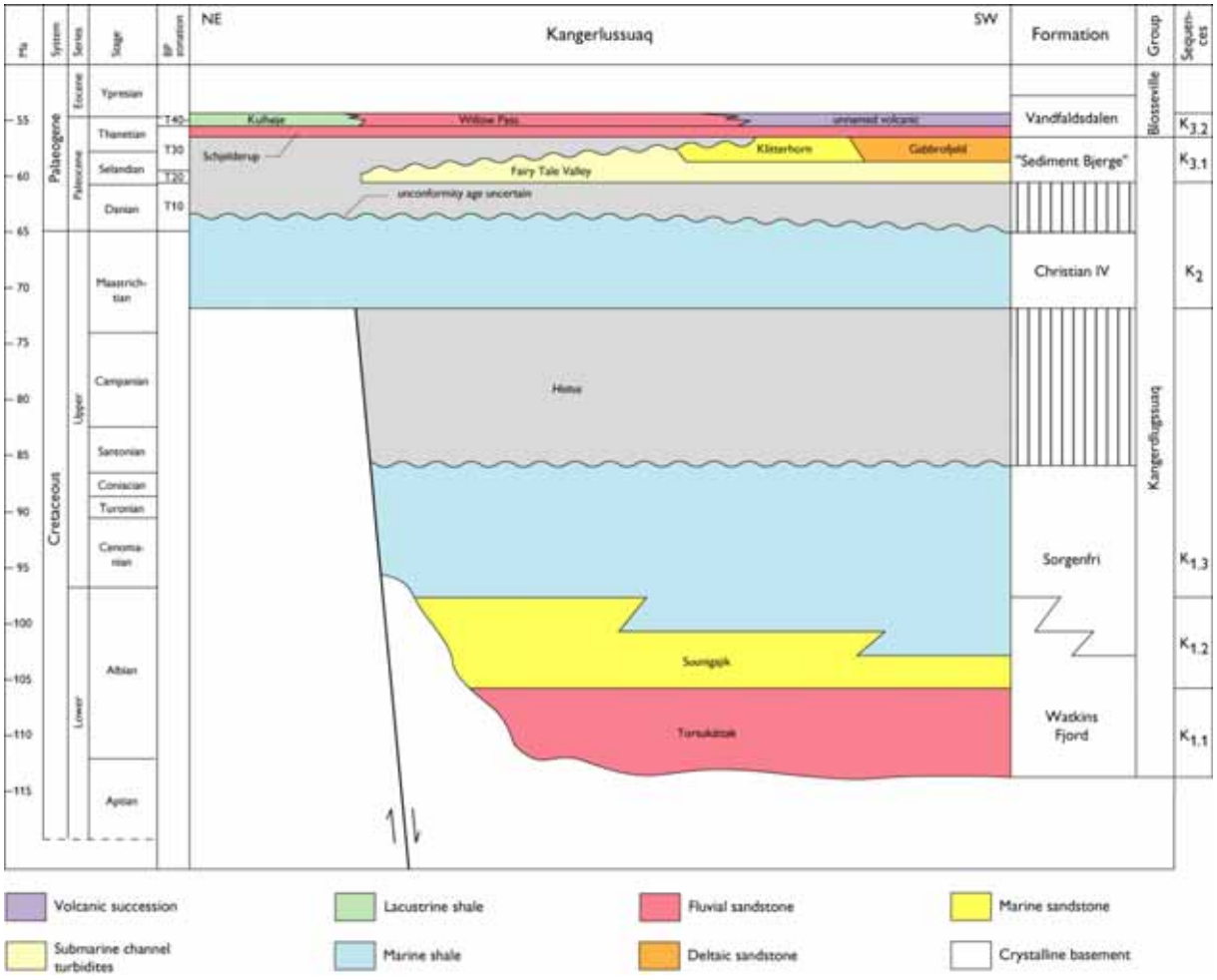


Figure 9. New lithostratigraphical scheme for Kangerlussuaq, from Larsen et al., 2004.

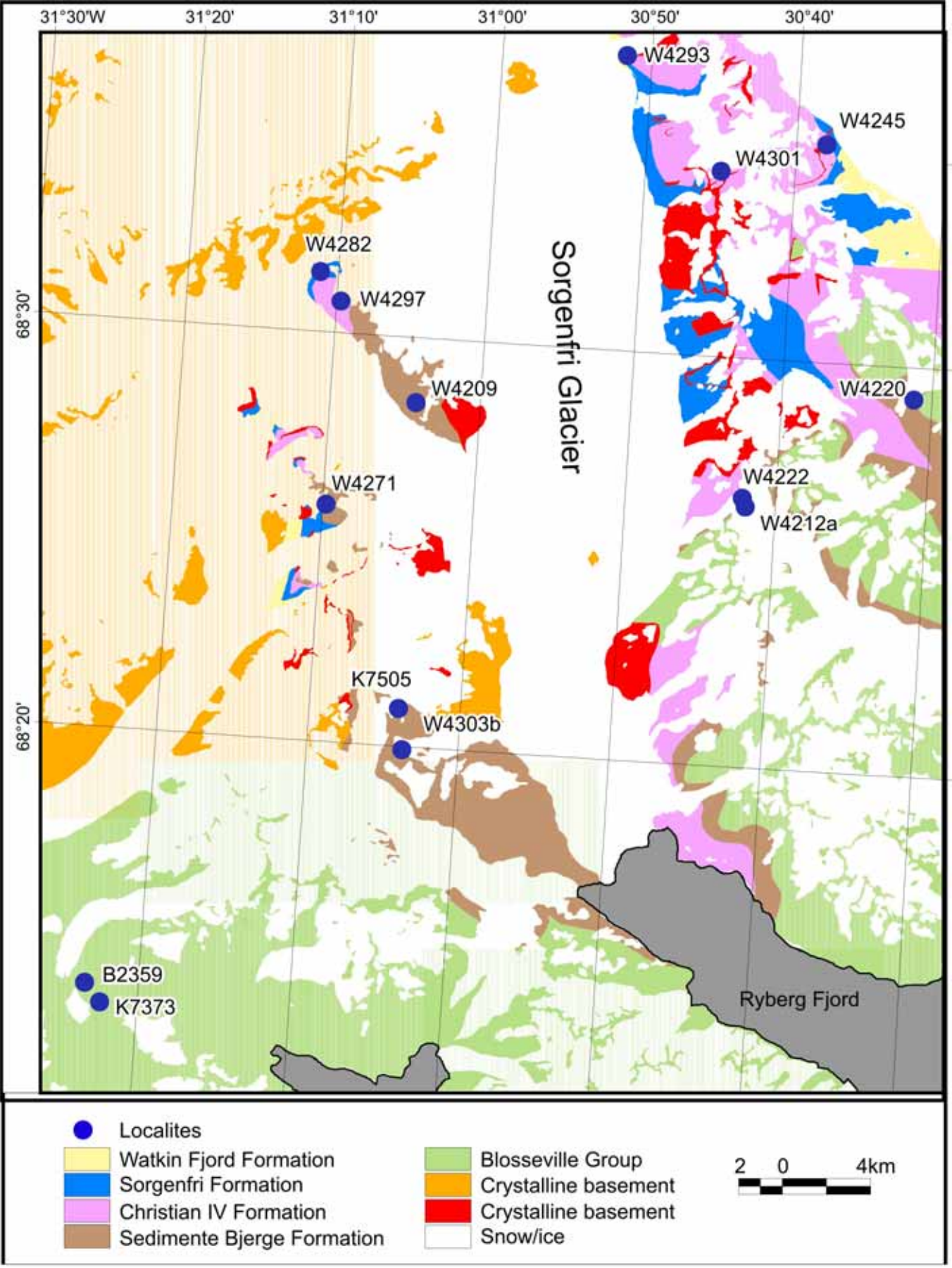


Figure 10. Location and geological map of Kangerlussaqsample locatlities

thick. Bedding is defined by variations in the sand:mud ratio and rare sand beds. Bioturbation is pervasive, and a large number of different types of trace fossil are recorded. The formation also contains a diverse assemblage of macrofaunas including ammonites, bivalves and echinoids. The succession is of the Late Campanian age at its base. The upper part of the succession is subject to some debate. On the basis of its macrofaunas a Late Maastrichtian age is indicated. Palynological studies indicate it may be as young as Danian in age (Larsen et al 2004).

Sediment Bjerge Formation: Interbedded sandstone and mudstone units form this unit, which is at least 174 m thick (Larsen et al., 1999). The sandstone units were largely deposited by sediment gravity flow processes in a deep marine setting and are up to 20 m thick. They form both lenticular and laterally continuous bodies. Sediment transport is towards the southeast (Larsen et al., 1999). Some conglomeratic beds are found which contain clasts of basement gneiss in excess of 8 m diameter. The top 15 m of the succession records a shallowing of depositional environment as indicated by the presence of hummocky cross-stratification in the section in Fairy Tale Valley. To the west at Gabbrofjeld a large-scale delta foreset is found at the top of the member. In contrast to the Christian IV Member this formation is less intensely bioturbated leading to the preservation of thin sandstone interbeds at many localities. The formation is also characterised by an almost complete absense of macrofaunas save for locally abundant oysters. Palynoforas are not common and poorly preserved. Kerogen is dominated by inertinite. The formation has a Selandian to Thanetian age (Larsen et al., 2004)

Vandfaldsdalen Formation: This fomation is a mixed unit of quartzose sandstones, volcanicalstic sandstones, pyroclastics and basalt lava flows up to 925 m thick (Soper et al., 1976; Larsen et al., 2004). Sandstones derived from the basement are restricted to the base of the member. The base of the Formation is marked by a sequence boundary. A 0-20 m thick unit of conglomerates and sandstones is found above this unit; the Schelderup Member. These sediments are fluvial in origin (Larsen et al., 1999: Larsen et al., 2004). Palaeocurrents indicate a sediment transport direction towards the SE. Above this basal unit the sediments become finer grained. In some places parallel bedded mudstones with thin graded sandstone beds and slumped redeposited units are

found. These sediments are of lacustrine origin and form the Kulhoje Member. In other areas mudstones are interbedded with sheet like sandstones and units of crossbedded sandstones sandstones. The depositional environment for this unit (Willow Pass Member) is thought to be a low lying flood plain dissected by small fluvial channels. The amount of deposits recording the interaction of basaltic lava flows and water decreases remainder of the formation is dominated by basalt. The basaltic lava flows record decreasing amounts of interaction with water as one passes upwards through the succession. Towards the present-day coastline, lavas record interaction with seawater and hyaloclastite, foreset breccias are formed. The Vandfaldsdalen Formation has a late T40 age (earliest Eocene, post Late Paleocene Thermal Maximum) as indicated by marine dinocysts and characteristic pollen floras (Jolley and Whitham, 2004).

For a more detailed description of all the above units readers are invited to read the latest SINDRI report by Larsen et al. (2004).

Greenland – evidence for the Paleocene flora

Sample material for palynology from southeast Greenland is derived from two sources. The larger proportion is derived from CASP sample sets, available as long successions of samples which are accurately positioned against lithological logs. A second smaller set of samples was made available for this study from GEUS collections by Michael Larsen. These are not associated with lithological logs, but are placed in the context of the lithological formations used in the section above.

At the commencement of this work, the age of the sediments now incorporated in the Sediment Bjerge Formation and uppermost Christian IV Formation was unclear. A number of sections were analysed and are discussed below according to their lithostratigraphical unit.

Christian IV Formation

1. Sequoia Nunatak

Pollen and spores (SA= highly abundant, A = abundant, C = common, F = frequent):

Pityosporites (SA)
Inaperturopollenties hiatus (A)

Deltoidospora addriennis (C)
Laevigatosporites haardtii (C)
Cupuliferoipollenites various sp. (F_C)
Stereisporites various sp. (F-C)
Trudopollis hammenii (F)
Fibulapollis mirificus
Cicatricosisporites rousei (F)

Algae:

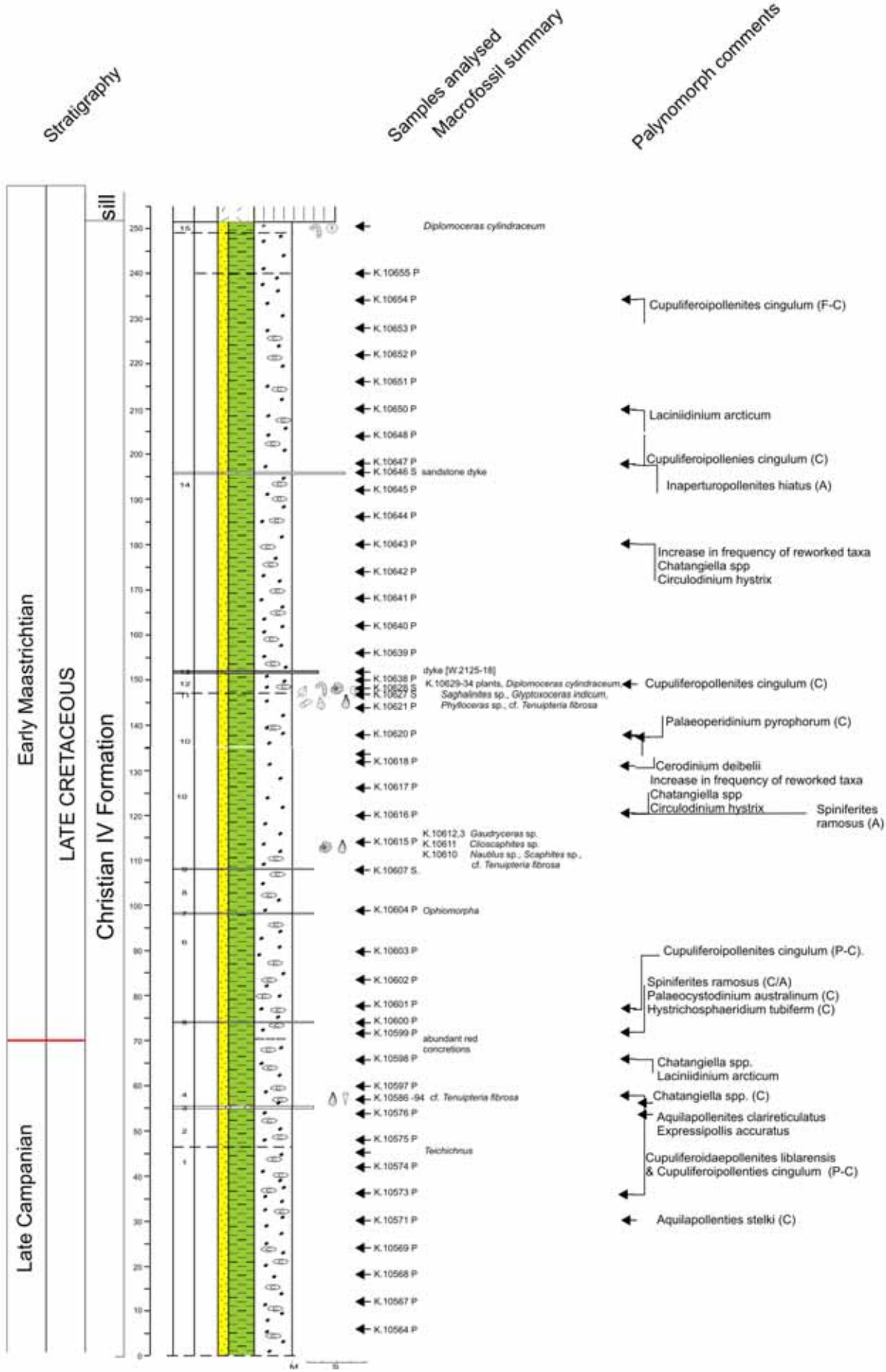
Cliestosphaeridium spp. (A)
Paralecaniella indentata (A)
Cerodinium diebelii
Hystrichosphaeridium propirium
Hystrichosphaeridium stellatum
Oligosphaeridium complex (C)
Laciniadinium arcticum (F)
Membranosphaera maastrichtia (F)
Tanyosphaeridium variecalamus (F)

This palynoflora confirms a Maastrichtian age for these sediments. The sediments are at the top of the Christian IV Formation, suggesting that it does not continue into the Maastrichtian in this area. The *Cicatricosisporites rousei* influx has been recorded by the authors in the mid part of the Maastrictian in offshore Norway.

2. Sedimentary mountains W4245:

This CASP section is amongst the best from this area. It yields a moderately diverse microplankton flora. Confusingly, a species similar to the unpublished *Spiniferites. 'magnificus'* used as a marker for Late Danian sediments within the hydrocarbon industry, occurs in this section. These specimens have a pentagonal (instead of rounded/oval) cyst, and belong to a currently unpublished species of the genus. Accordingly, the sequence here is determined as being Late Campanian at the base, with Early Maastrichtian resting disconformably above. The base Maastrichtian unconformity is marked by a concentration of red nodules (See Figure 11).The remainder of the Christian IV Formation in this section contains Maastrichtian palynofloras.
The upper part of the early Maastrichtian has an impoverished succession of floras, a feature which appears to be regionally continuous. This is an unusual feature for marine sediments. It may indicate shallowing and increased oxidation, but there seems to be a

Figure 11. Locality W.4245



lack of palynofloral coincidence with respect to the inception of poor floras. Instead, it could be suggested that these sediments were exposed to oxidative weathering during the period from the end of the Maastrichtian to the late Danaian or Selandian, a period of 5m.y. The effects of such oxidation would have been compounded by the thermal degredation associated with an increase in regional heat flow from sill intrusion.

3. Sedimentary Mountains W4293

In W4293, a small interval of the Turonian Sorgenfri Formation (Figure 12) is overlain by Christian IV Formation sediments. These have moderately diverse Maastrichtian palynofloras, which are similar to those of W4245. These floras are overlain by a highly impoverished section. This corresponds to the upper interval of poor floras in W4245, and provides further evidence for oxidative degradation of the insitu microplankton.

4. Sedimentary Mountains W4301

The Christian IV Formation sediments of W4301 are highly impoverished (Figure 13). In contrast to the other sections discussed above, the upper part of this section yields some poor dinoflagellate cyst floras. These are both degraded and thermally mature, but confirm a Maastrichtian age.

5. Sedimentary Mountains W4282

Overlying the Sorgenfri Formation in this section is a succession of Maastrichtian sediments of the Christian IV Formation. These have generally poor palynofloras, but do yield a probable early Maastrichtian assemblage (Figure 14).

6. Sødalen, CASP sections B2359 and K7371

Palynofloras were examined from two Christian IV Formation sections (Figures 15, 16). They are mostly barren or extremely impoverished, with a few occurrences of Late Cretaceous microplankton.

7. Pyramiden, CASP section W4297

This extensive Pyramiden section adds little information to the dataset, most samples being highly impoverished. Some pollen and dinoflagellates are recovered (Figure 17).

Sediment Bjerge Formation

1. Sedimentary Mountains CASP sections W4212 and W4222.

This is very poor, but is different in having low salinity chlorophycean algae and acritarchs present (Figures 18, 19).

2. Sedimentary Mountains, CASP section P2373

This section is interpreted as being Vandfaldsdalen Formation resting on Christian IV Fm (Figure 20). From the lithogies it appears attributable to the Sediment Bjerge Formation. At the top of the section the microplankton are represented by chlorophyceae and acritarchs. At the upper limit of the section is a specimen of *Caryapollenites veripites*, indicating an age no older than TPaMFS130 (Sequence T40), and probably not younger than TPaMFS150 (Sequence T45). At the bottom of the section is a flora with the dinocyst *Oligosphaeridium complex* and pollen grains. This flora is not comparable with that at the top of the section. One explanation is that the top of the exposure is Sequence T40 Vandfalsdalen Fm, and the bottom, Sediment Bjerge Fm.

3. Sodalen, GEUS section

Sample numbers: 455576 & 455578

Lithological Unit: Fairy Tale Valley Mb

Algae:

Palaeoperidinium pyrophorum (A)

Areoligera medusettiformis (C)

Oligosphaeridium complex (F)

Spiniferites ramosus

Laciniadinium arcticum (Reworked)

Pollen and Spores:

Inpaerturopollenites hiatus (A)

Pityosporites (A)
Deltoidospora adriennis

Thermal Alteration Index (TAI) is 4+
Environment – mid/outer neritic. In good offshore transects *P pyrophorum* is replaced by *Membranosphaera* or *Microdinium* anywhere near the inner neritic zone. The common occurrence of *Areoligera medusettiformis* in this type of assemblage is most commonly seen in the Late Paleocene (Selandian) of offshore sections. More accurately, this can be attributed to the TPaMFS60 – TPaMFS75 interval (Sequence T22). Within the Faroe-Shetland and Corona basins, this sequence is represented as an onlapping marine shale between Danian and later Paleocene sandstones.

4. Watkins Fjord, GEUS section
Unknown sedimentary unit
Algae:-
Areoligera coronata,
Exochosphaeridium bifidum?
Oligosphaeridium complex
Palaeoperidinium pyrophurum (F)

Pollen and Spores:
Pityosporites spp.
Inaperturopollenites hiatus,
Nyssapollenites kruschii,
Stereisporites spp.
The evidence provided by this sample is here is not of good qualtiy. However, the combination of taxa suggests that a Paleocene age is possible, especially when compared to the flood of *P. pyrophorum* in Sodalen. This suggests that this unknown sedimentary unit is a TPaMFS60-TPaMFS75 deposit similar to that seen to the south.
TAI is high here 4+

Figure 12. Section W4268/W4293, Sedimentary Mountains

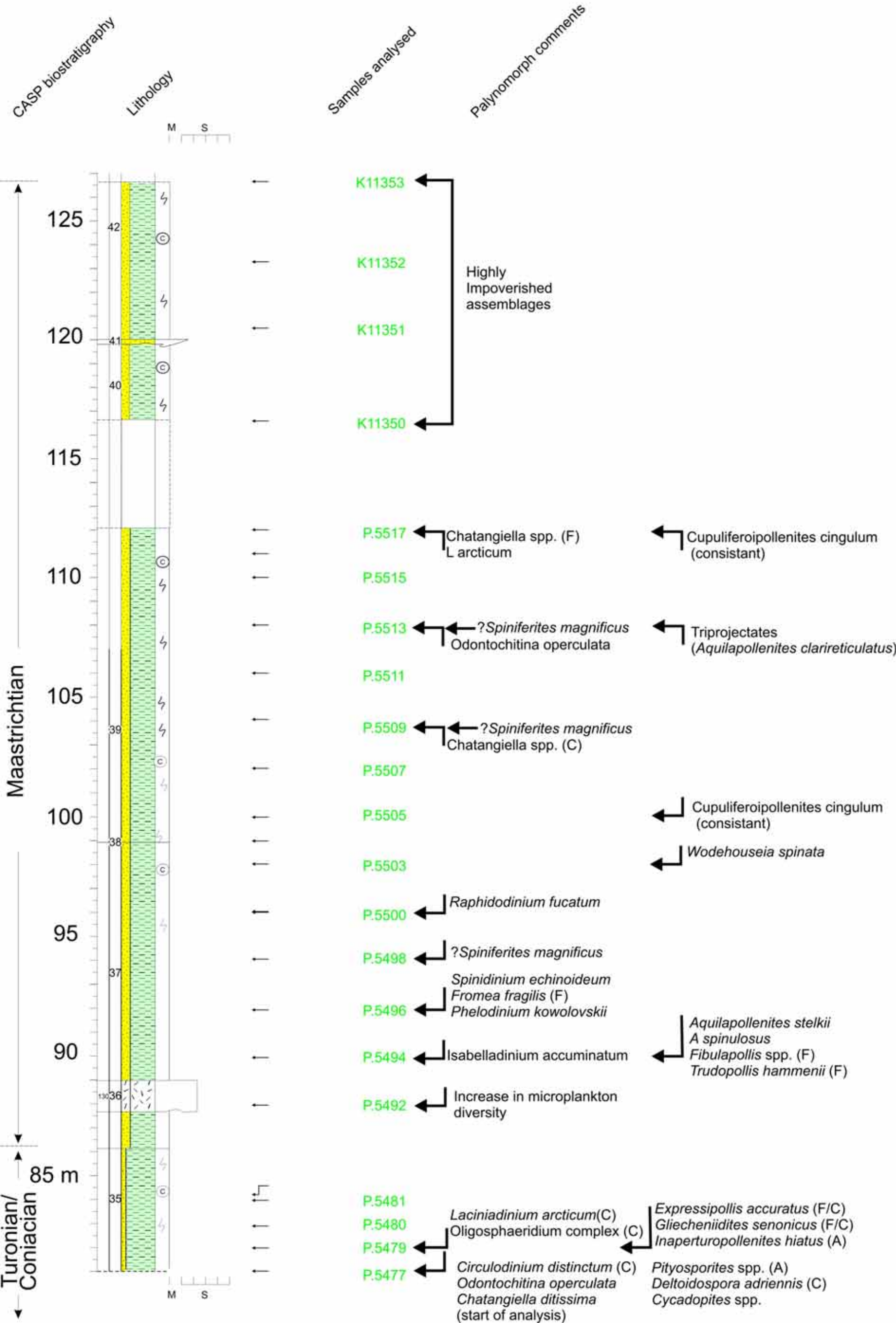


Figure 13. Locality W.4301, Sedimentary Mountains, N

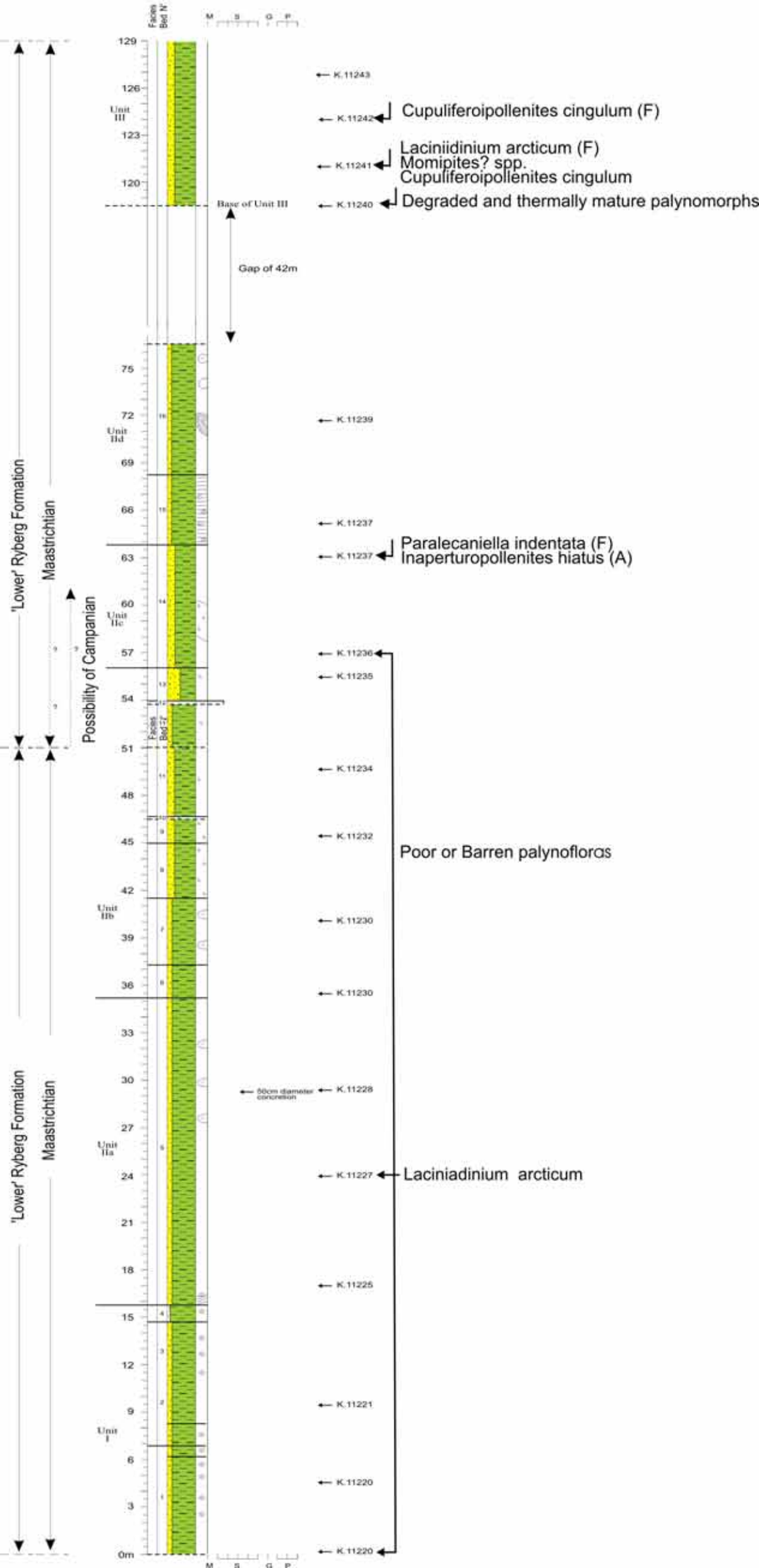


Figure 14. Locality W4282, Sedimentary Mountains

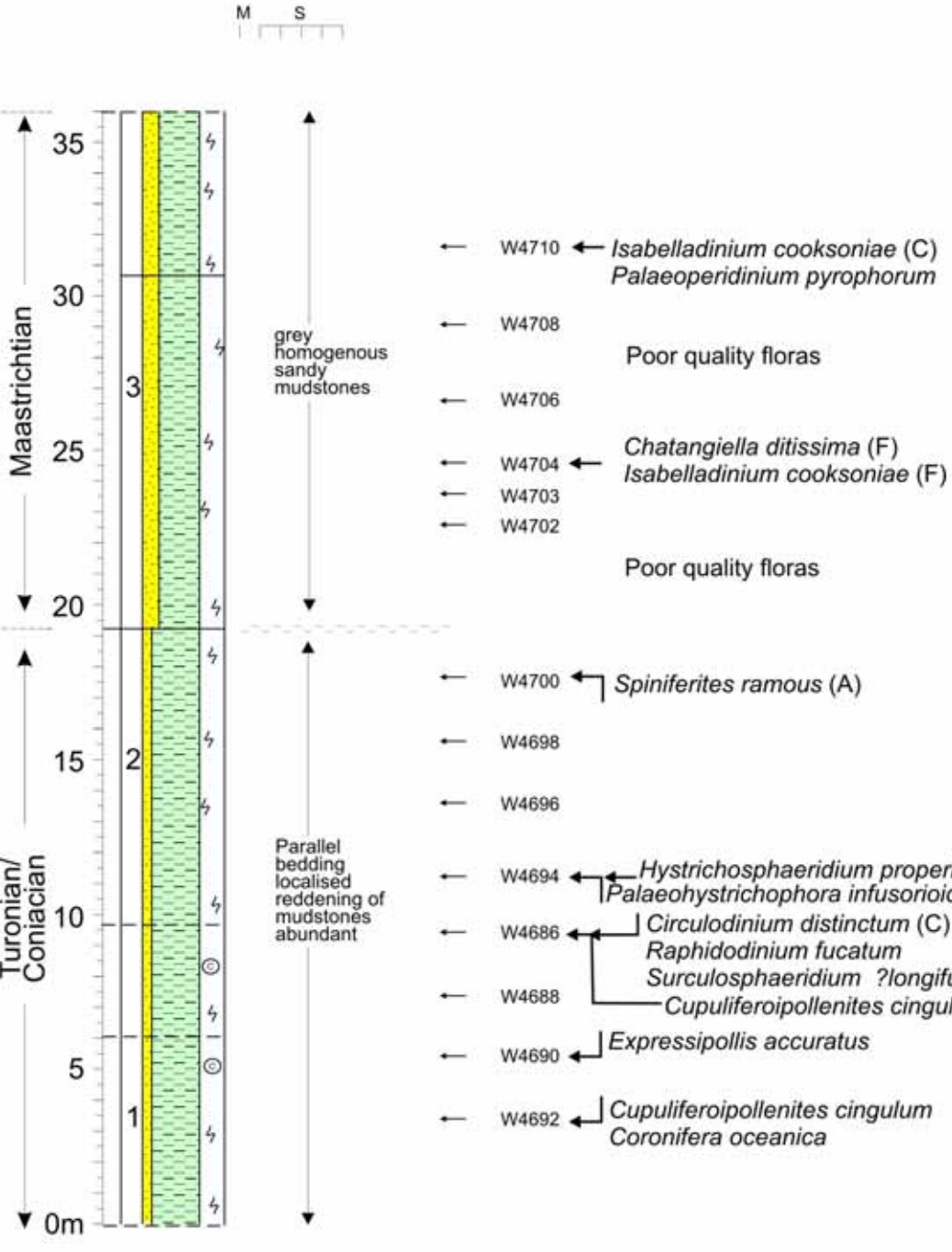
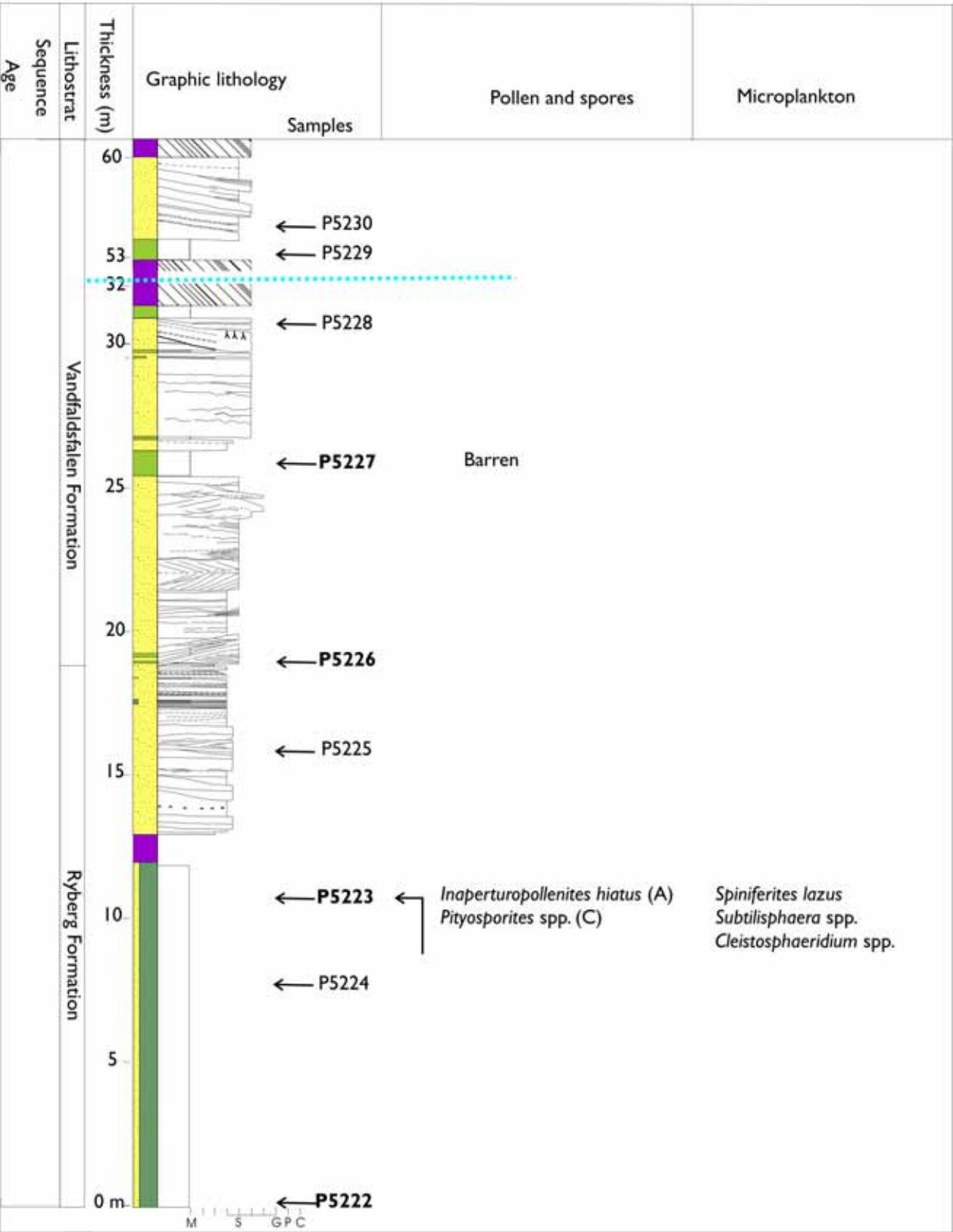


Figure 15. Sødalen Gletscher, section B2359



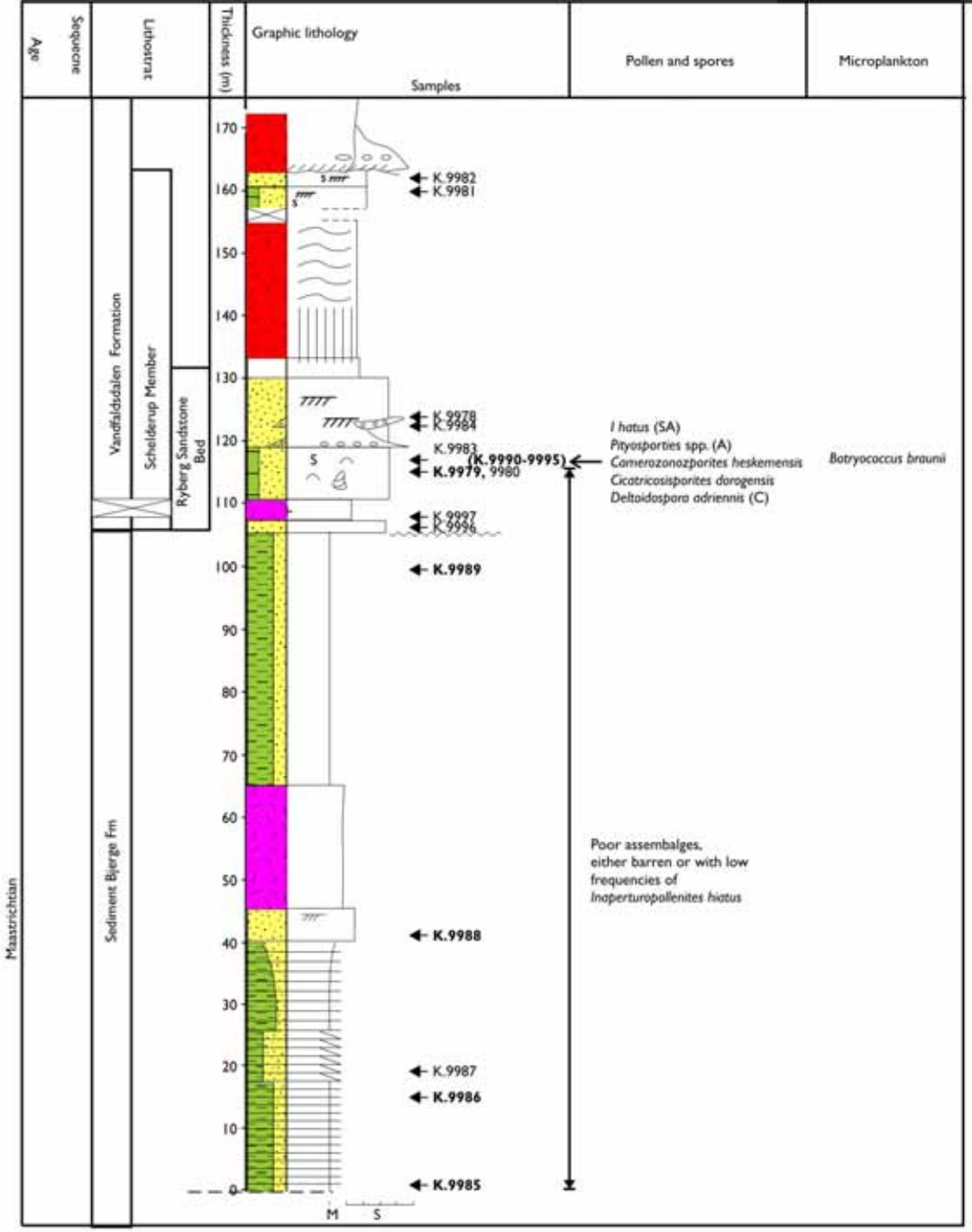


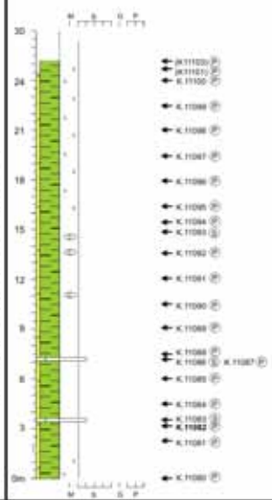
Figure 16. K.7371-3, Sødalen

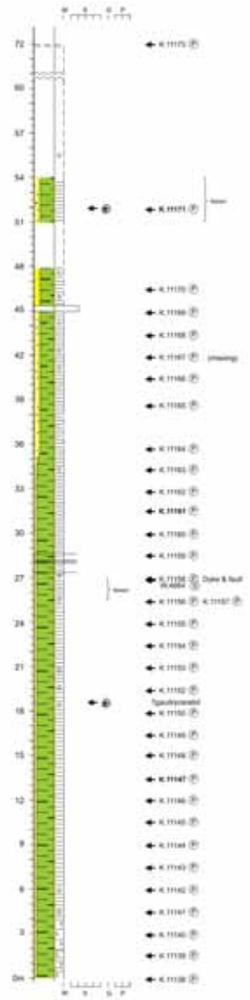
Figure 17. W.4297 I-V, Pyramiden

'Lower' Ryberg Formation

'Lower' Ryberg Formation

'Lower' Ryberg Formation





Pollen and Spores

Microplankton

← Inaperturopollenites hiatus (C)

← *Pityosporites* spp. (A)
I hiatus (A)

← *Inaperturopollenites hiatus* (SA)
Momipites spp.
Nyssapollenites kruschii subsp *analepticus*
Tricolpites cf *hians*

Spiniferites ramosus, *Chatangiella* spp.

← *Laevigatosporites haardtii*

← *Pityosporites* spp. (A)

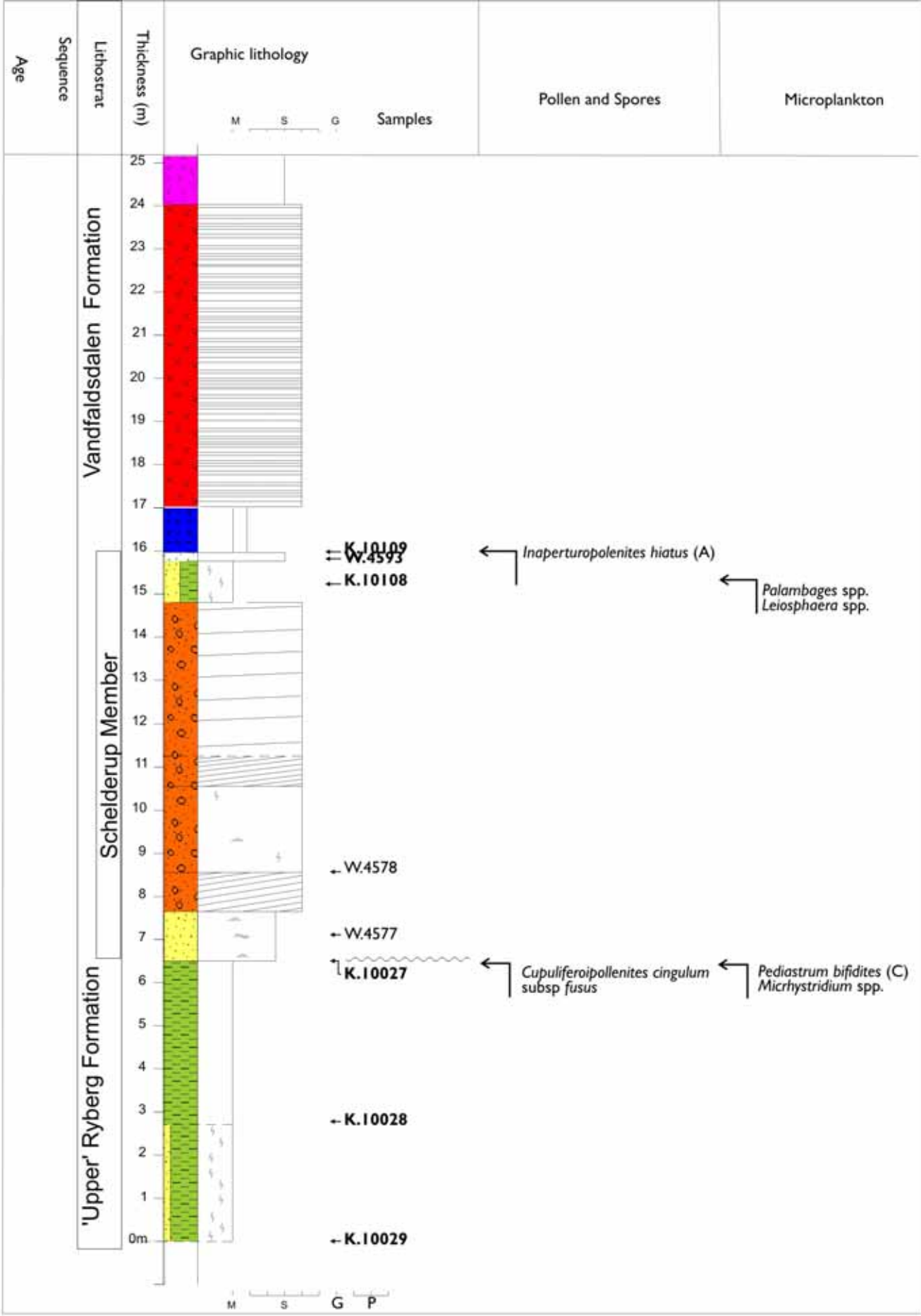


Figure 18.W. 4212, North Col

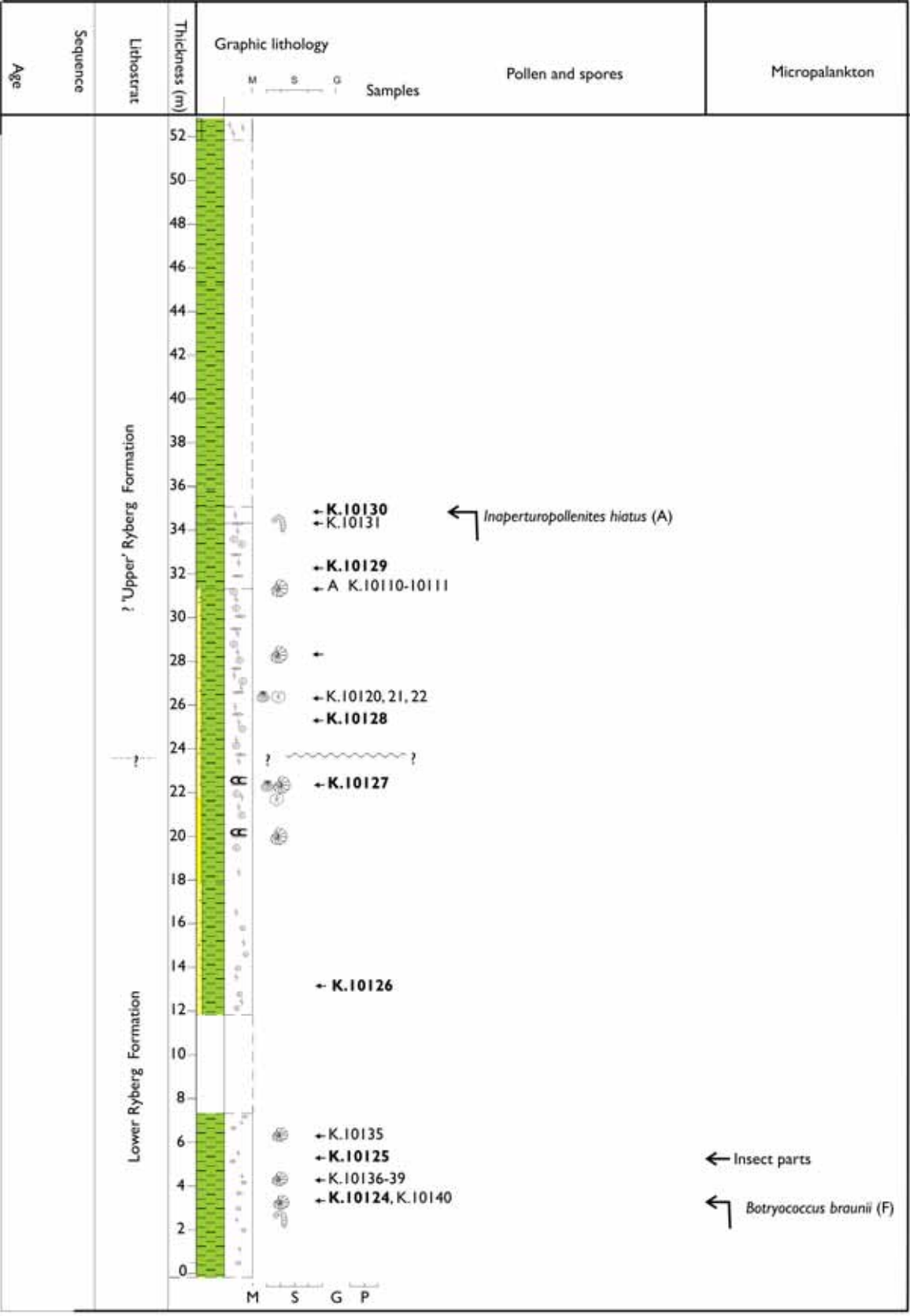


Figure 19. W.4222, North Col

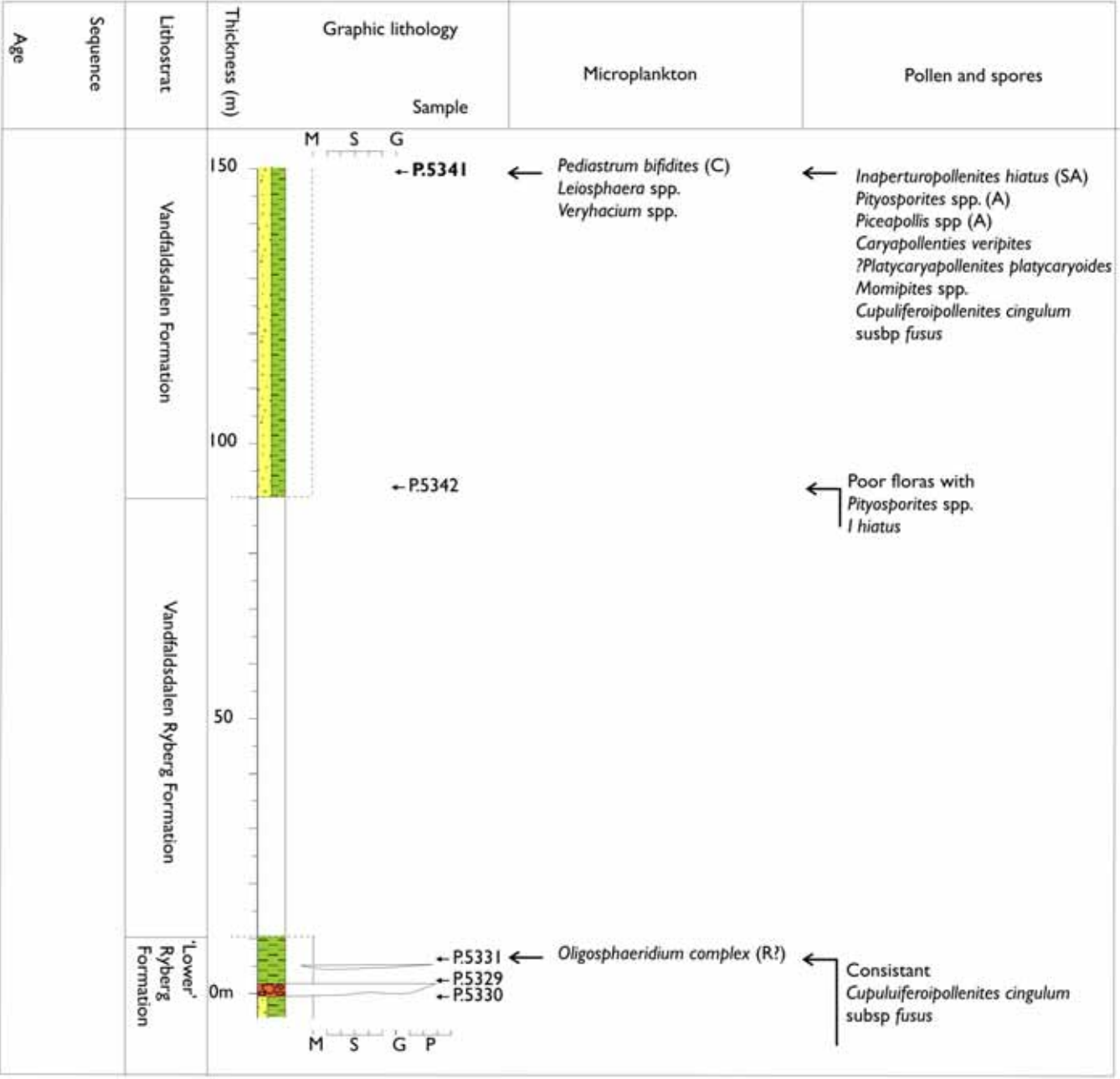


Figure 20, P2373, Veirgabet

5. Pyramiden, CASP sections W4209 and W4303

Palynofloras were examined from these Sediment Bjerge Formation, Klitterhorn Member sections (Figures 21,22). They are mostly barren or extremely impoverished and provide no useful stratigraphical information.

6. Pyramiden, CASP section W4271

This section has a thin representation of the Sorgenfri Formation at the base (Figure 23). This yields a marine dinoflagellate cyst flora which includes common to abundant *Cliestosphaeridium* spp. and *Spiniferite ramosus*. The presence of a Turonian belemnite species in the sediments above the location of this palynoflora supports a comparison with the palynofloras seen in the Sorgenfri Formation of W4282 in the Sedimentary Mountains (Figure 14).

Overlying these Turonian sediments are shales and sandstones which yielded poor assemblages. However, one sample (K10901), yielded the components of the Greenland Flora with an influx of *Paleoperidinium pyrophorum*. The influx of this dinocyst can be used to suggest a comparison with the TPaMFS60-TPaMFS75 age Sødalen samples provided by GEUS (see 4 above).

7. Sødalen, CASP section K7505

This is another section in which the palynofloras are impoverished. They do, however, yeild a number of pollen taxa which form a characteristic asssemblage of the Greenland Flora ((Figure 24).

Origin of the Greenland Flora

From the data gathered for this study, it is evident that the taxa comprising the Greenland Flora have formed a persistent part of the vegetation of the continent of Greenland since the Late Cretaceous. The evidence presented here does not provide detail of the origin of the Greenland Flora. However, it does demonstrate that the diagnostic Fagaceae elements of the flora have been an important part of the vegetation during the late Turonian, late Campanian and Maastrichtian. The presence of this flora

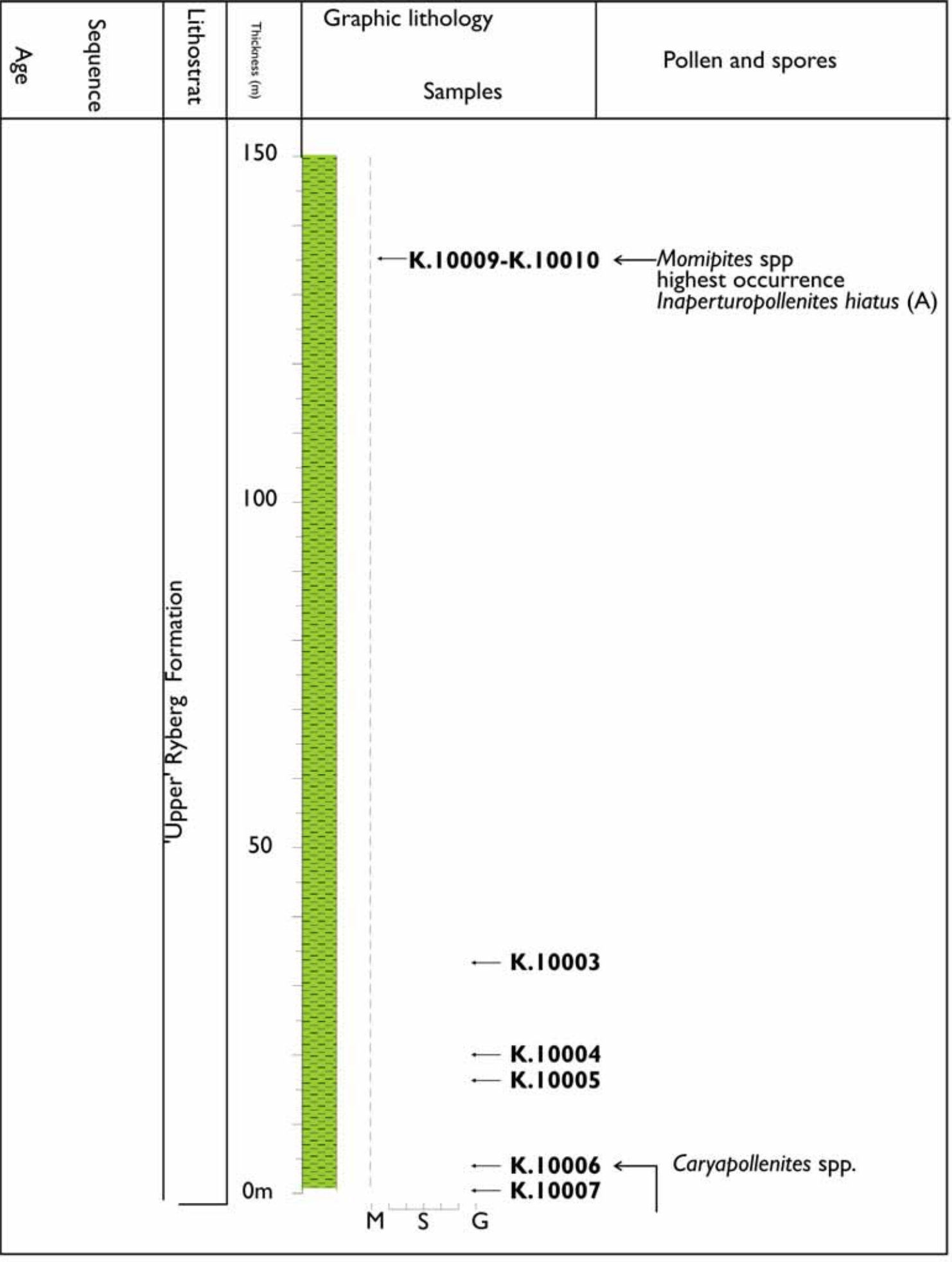


Figure 21. W.4209, Pyramiden

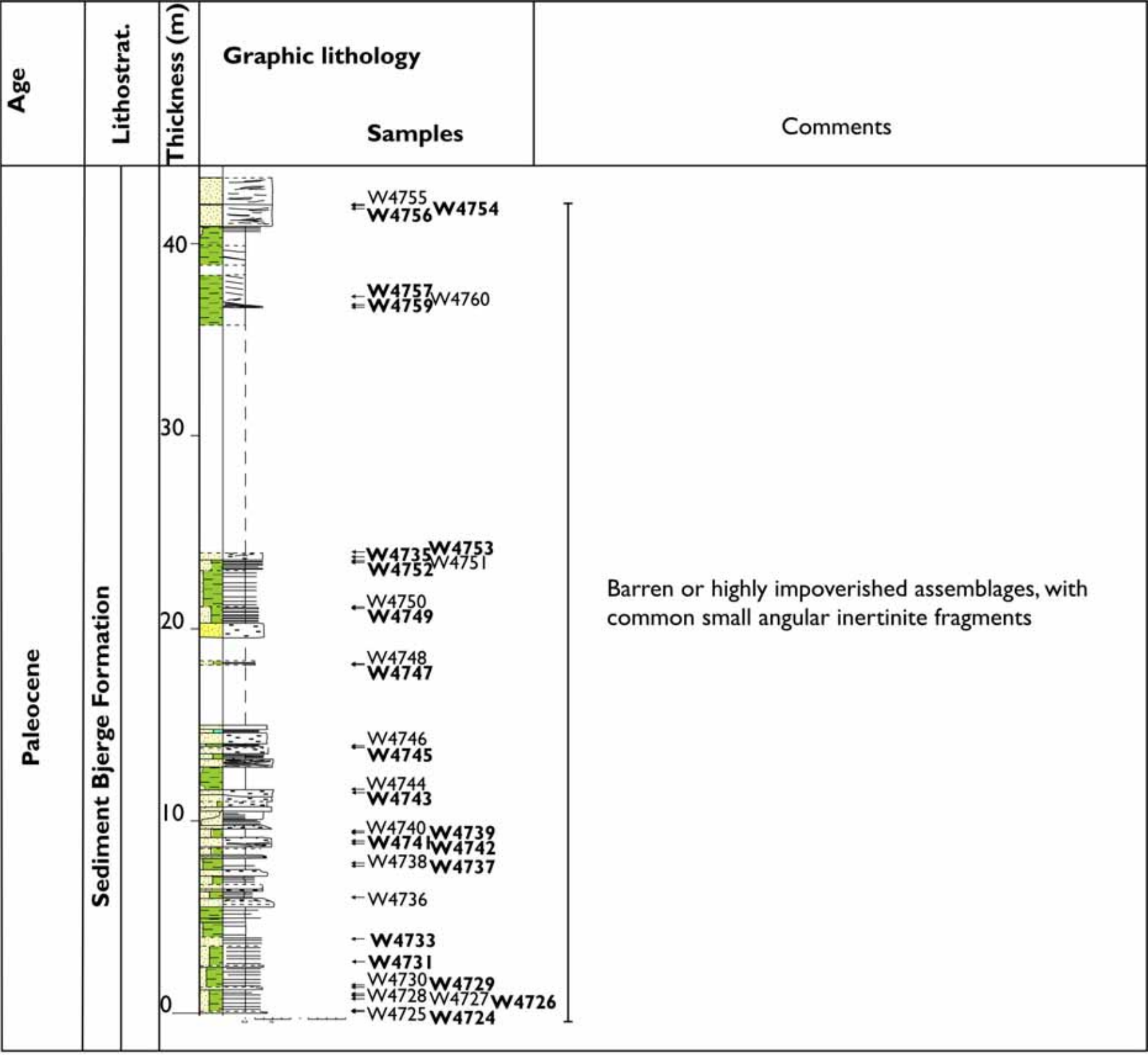


Figure 22. W4303

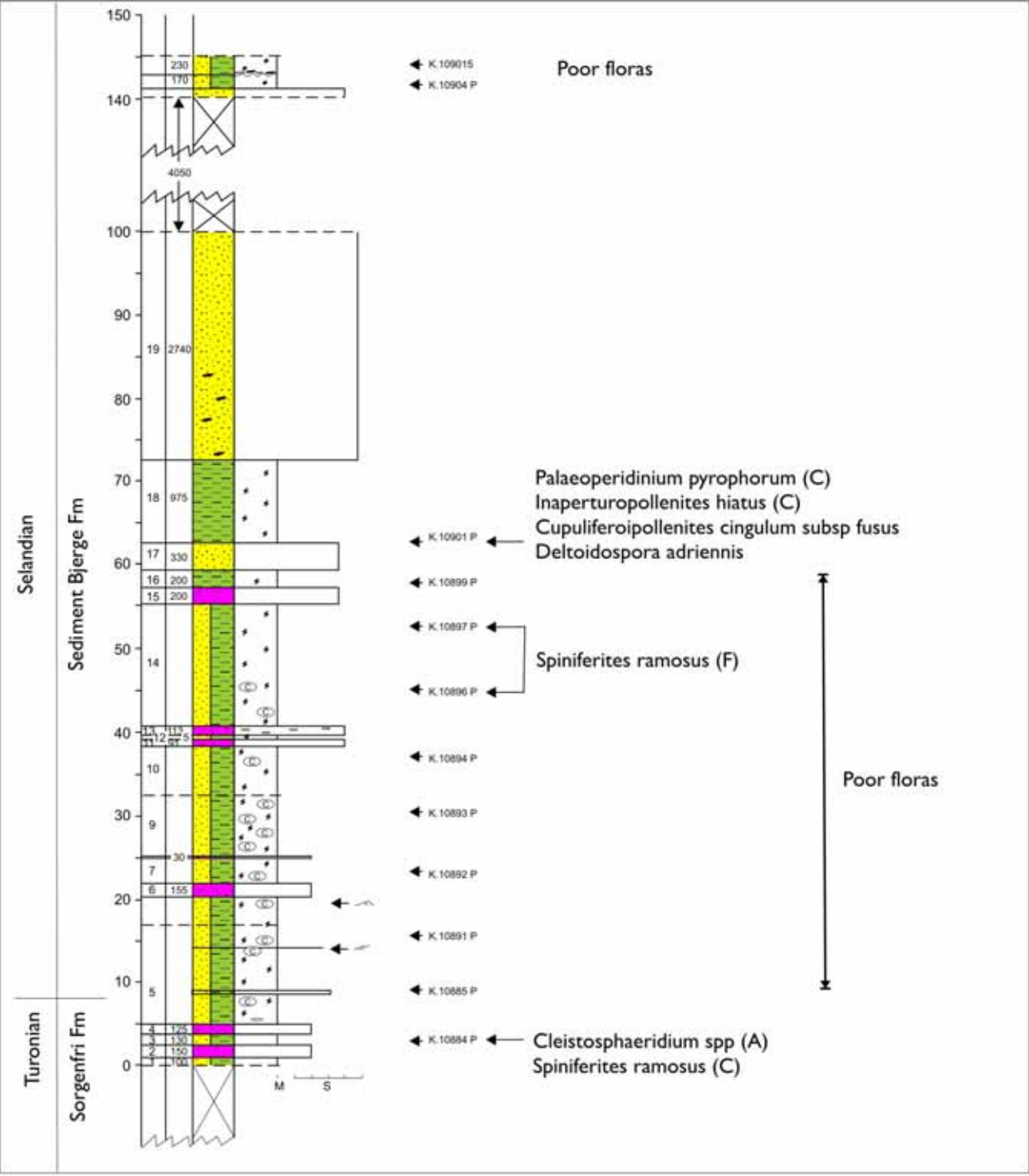


Figure 23.W4271

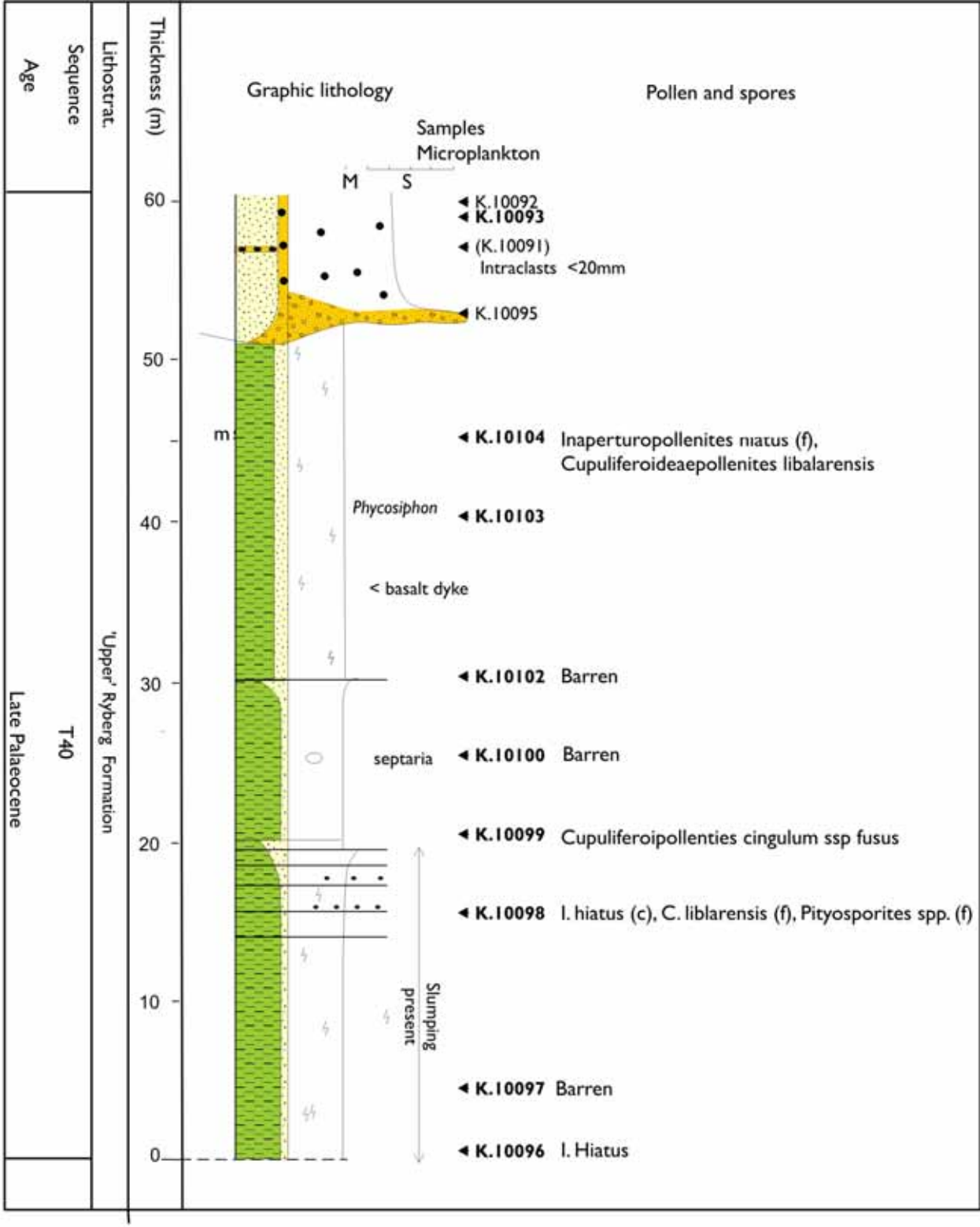


Figure 24. K.7505, Schelderup Glacier Region

onshore in southeast Greenland during the Paleocene is confirmed by the occurrence of the diagnostic assemblages in strata from the Sediment Bjerge Formation in Sødalen and the Sedimentary Mountains. These sediments are dated as being at least in part attributable to the TPaMFS60 to TPaMFS75 interval (T22 of Ebdon et al., 1995). The implications of the age determination of these shelf sediments and the extent of the bounding unconformities are discussed below.

8. PHYTOGEOGRAPHIC EVIDENCE FOR SEDIMENT TRANSFER PATHWAYS

Geographical distribution of the Greenland Flora – the westerly source

The intervals which yield palynofloras with a component derived from the west of the basin have been summarised (Figure 4) into TPaMFSS60 (T10), TPaMFS80 (T26), TPaMFS90-95 (T32-35) and TPaMFS100, (T36). Although the data set is of variable quality in the older interval, it is possible to map out the potential sources of the four Hebrides – Shetland floras and the Greenland Flora.

In all three primary intervals in which the Greenland Flora is recovered, the location of wells with respect to transfer zones is of primary importance. These NW-SE trending structural lineations were identified as being of importance in the structural and sedimentological development (Naylor et al., 1999) of the Paleocene Faroe-Shetland Basin. More recently, Johnson et al. (2004), determined Palaeogene sinistral strike-slip movement on these major structures, evidenced by the shift of the trend of anticlines from NE to NNE in the Erlend and Magnus transfer zone areas.

During deposition of the upper Sullom Formation, data from wells in the southern part of Quadrant 214 confirm that transportation of fine-grained sediment occurred from the northwest along the Victory Transfer Zone. Wells situated adjacent to the Clair and Westray transfer zones do not yield the Greenland Flora in this interval (Figure 25). A lack of available data to the northwest of the Corona Ridge may mask transportation into the Corona Basin. However, the available data demonstrate that argillaceous sediment transportation from this source did not extend over the Corona Ridge into the Foinaven – Schiehallion area of Quadrant 204.

Evidence for the transfer of sediment from the Greenland area in the TPaMFS80 interval is strong (Figure 26). However, the current data set is not sufficient to determine if this pulse is separate from the younger TPaMFS90-95 interval within the Corona Basin. Into the Faroe-Shetland Basin, the peak of transfer appears to come around TPaMFS90, with breakthrough of argillaceous sediment from the south Corona Basin at this time.

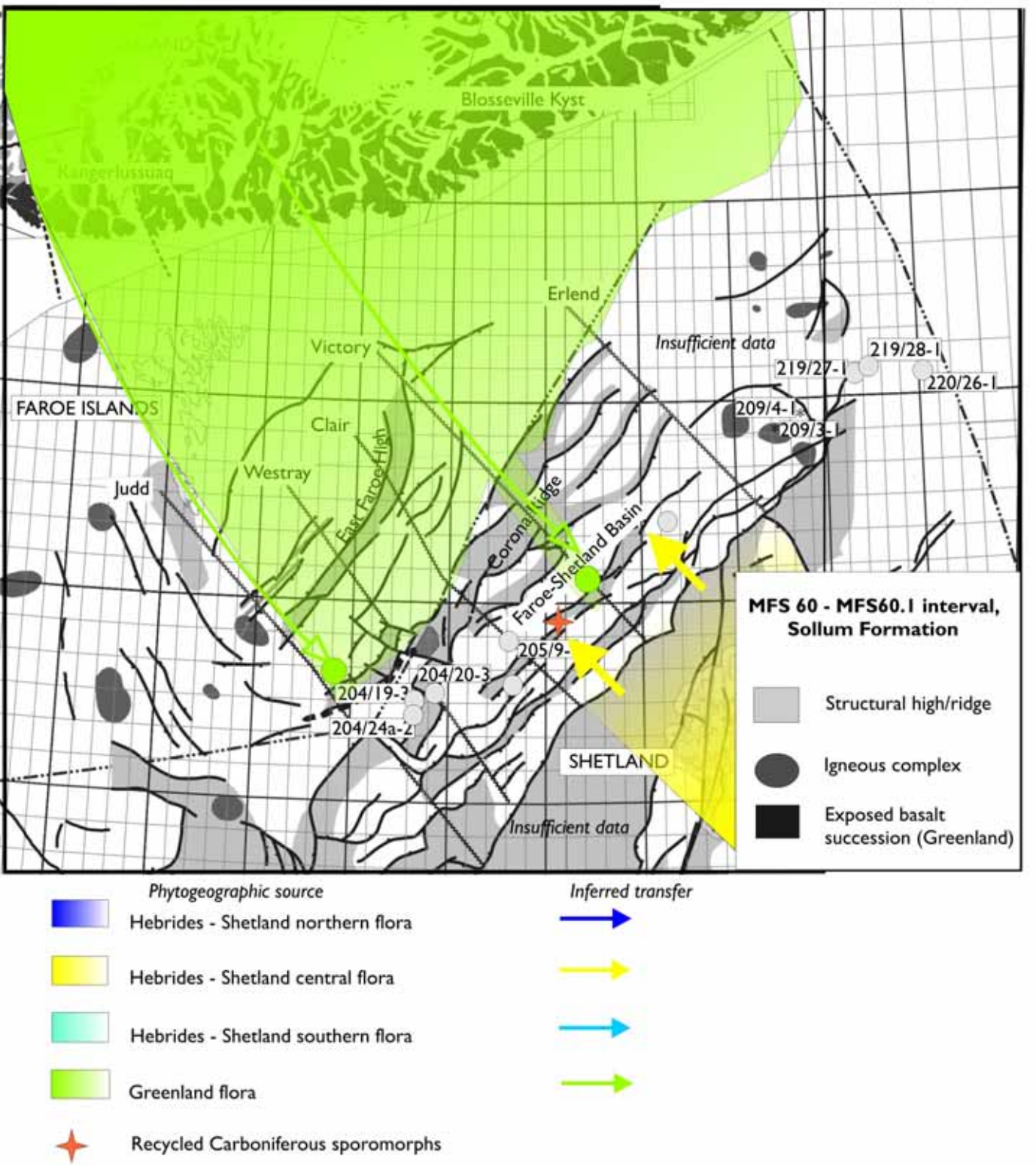

Blosseville Kyst
Kangerlussuaq
Erlend
Victory
Clair
Westray
Judd
East Faroe High
Coronal Ridge
Faroe-Shetland Basin
FAROE ISLANDS
SHETLAND
Insufficient data
Insufficient data
219/28-1
219/27-1
220/26-1
209/4-1
209/3-1
205/9-
204/20-3
204/19-3
204/24a-2
MFS 60 - MFS60.1 interval, Sollum Formation
Structural high/ridge
Igneous complex
Exposed basalt succession (Greenland)
Phytogeographic source
Inferred transfer
Hebrides - Shetland northern flora
Hebrides - Shetland central flora
Hebrides - Shetland southern flora
Greenland flora
Recycled Carboniferous sporomorphs

Figure 25

In the TPaMFS95 – subTPaMFS90 (T31-T34) interval of the Vaila Formation, records of the Greenland Flora are seen in wells adjacent to the Clair (e.g. 205/9-1), Westray (e.g. 204/20-3) and Judd transfer zones. Frequencies of the Greenland Flora increase from >5% in the most easterly examples to <20% in the most westerly examples studied (Figure 27). Diminution of the frequency of the Greenland Flora to the east is reconcilable with a westerly source. However, the role of the transfer zones in breaching the NE-SW trending barrier of the Corona Ridge is highlighted by the absence of the Greenland Flora in wells from the Cuillin and Foinaven fields distal to the Westray Transfer Zone.

While the volcaniclastic sandstones of the Kettla Member are widespread across the Faroe Shetland Basin, occurrences of the Greenland Flora in these sediments are more restricted. Current records suggest the transportation of westerly - derived argillaceous sediment into the Faroe-Shetland Basin was restricted to the area between the Clair and Westray transfer zones (Figure 28). Within this area, frequencies of the Greenland Flora decline from >5% adjacent to the transfer zones to <5% in the separating distal region.

Because of the limitations of the data set, it is not possible to determine if sediment conduits from the northwest were dependent on the northwestern extension of the transfer zones. It is possible to trace the north westerly extension of the Westray Transfer Zone through Kalsoyarfjørður in the Faroe Islands and onwards to Christian IV Glacier in Kangerlussuaq. This structure could have sourced the bulk of the sediment into the Corona Basin, with the Corona Ridge acting as a further barrier to southeasterly transportation. This would involve sedimentary transfer across the area of the future rift and the Faroe Platform. Transfer from this platform through the East Faroe High and into the Corona Basin could again have been via the Judd, Westray and Clair transfer zones.

It is equally possible that concentration of clastic material and funnelling southwest down the Corona Basin could have achieved an apparent eastwards transfer of argillaceous sediment. There is currently insufficient evidence to favour either model. However, because the current data set indicates that not all transfer zones were

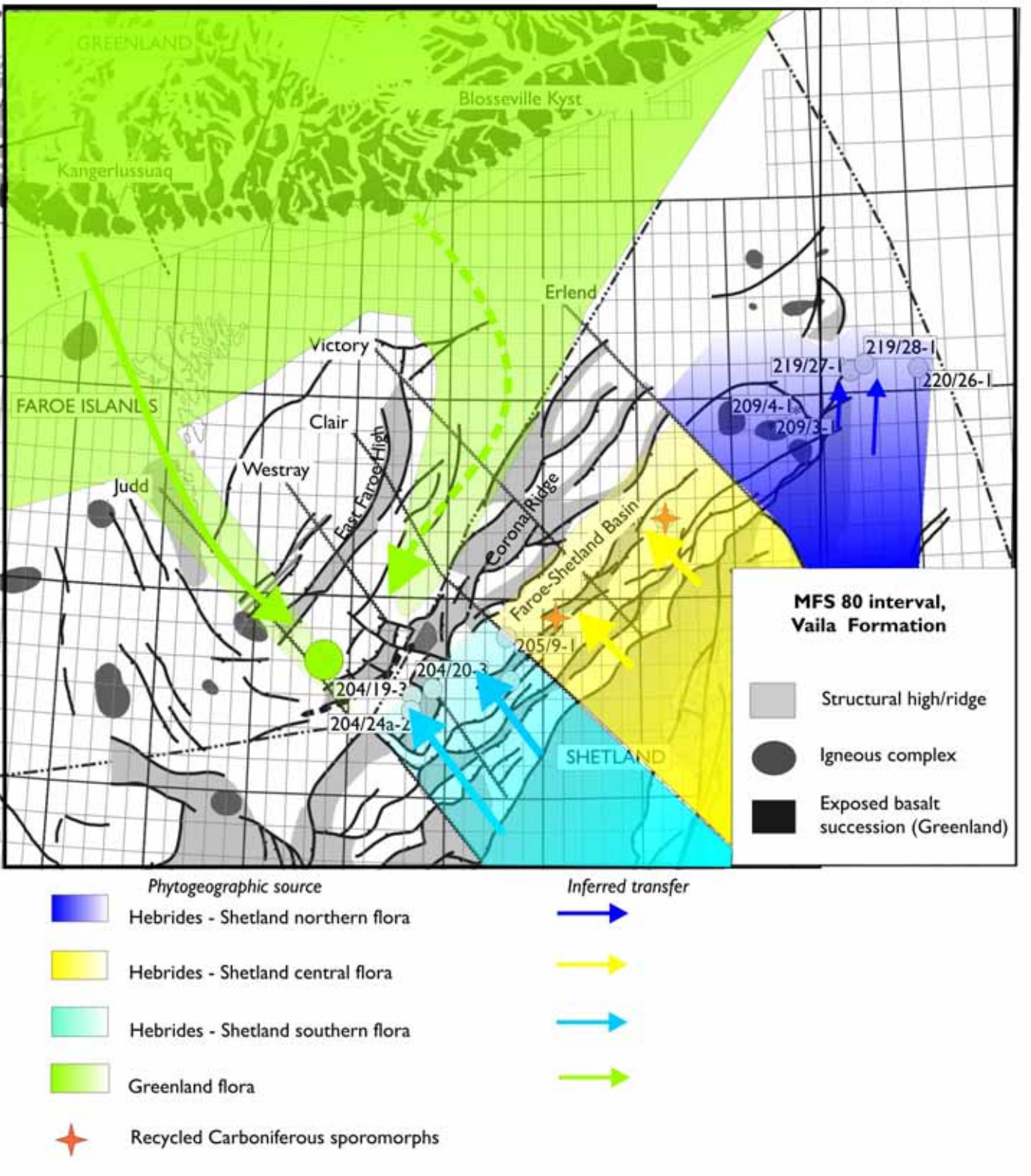

GREENLAND
Blosseville Kyst
Kangerlussuaq
Erlend
Victory
Clair
Westray
Judd
East Faroe High
Corona Ridge
Faroe-Shetland Basin
FAROE ISLANDS
219/28-1
219/27-1
220/26-1
209/4-1
209/3-1
205/9-1
204/20-3
204/19-3
204/24a-2
SHETLAND
MFS 80 interval,
Vaila Formation
Structural high/ridge
Igneous complex
Exposed basalt succession (Greenland)
Phytogeographic source
Inferred transfer
Hebrides - Shetland northern flora
Hebrides - Shetland central flora
Hebrides - Shetland southern flora
Greenland flora
Recycled Carboniferous sporomorphs

Figure 26.

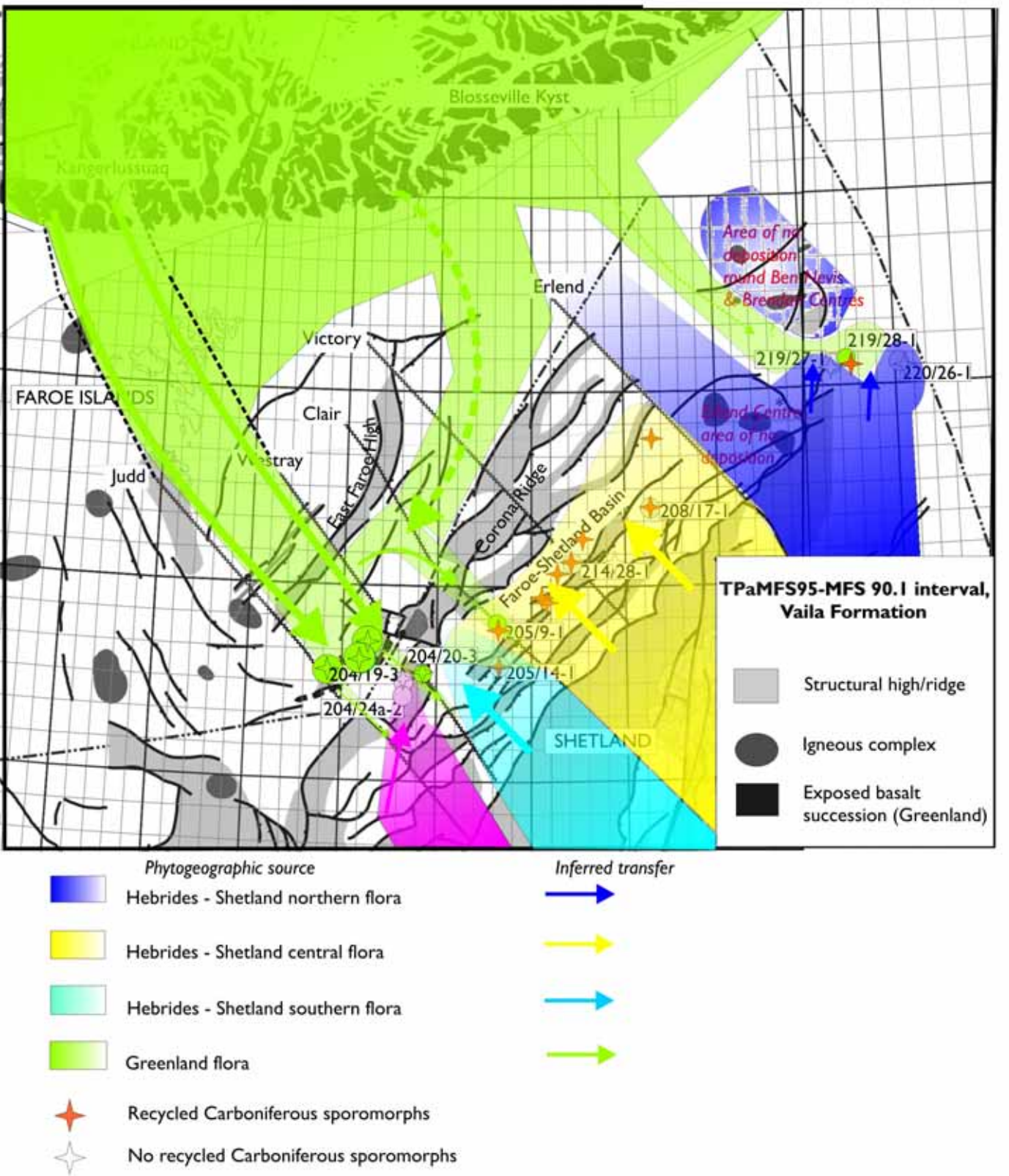

Blosseville Kyst
Kangerlussuaq
Erlend
Victory
Clair
FAROE ISLANDS
Judd
Westray
East Faroe High
Corona Ridge
Faroe-Shetland Basin
Area of no deposition round Ben Nevis & Breadalbane Centres
219/28-1
219/27-1
220/26-1
208/17-1
214/28-1
205/9-1
204/20-3
205/14-1
204/19-3
204/24a-2
SHETLAND
TPaMFS95-MFS 90.1 interval, Vaila Formation
Structural high/ridge
Igneous complex
Exposed basalt succession (Greenland)
Phytogeographic source
Inferred transfer
Hebrides - Shetland northern flora
Hebrides - Shetland central flora
Hebrides - Shetland southern flora
Greenland flora
Recycled Carboniferous sporomorphs
No recycled Carboniferous sporomorphs

Figure 27

instrumental in transporting sediment to the southeast during any one period, a model in which each transfer zone acts as an independent conduit appears more likely.

Geographical distribution of the Hebrides – Shetland floras – the easterly source

As discussed above, the Hebrides – Shetland flora is divisible into different floras

- A 'northern flora' seen in well between the Erlend Volcanic Complex and Brendan's Dome Volcanic complex
- A 'central flora' seen in the area south of the Erlend Volcanic Complex as far as the Clair Transfer Zone.
- A 'southern flora' seen from the Clair Transfer Zone area as far south as the Schiehallion field.
- A Foinaven flora, seen in a Foinaven field well.

These four floras reflect different source areas supporting communities of plants with different ecologies.

Brendan's Dome - Erlend source area

The area south of Brendan's Dome accrued sediment from the north of the Shetland Platform. This region was isolated from the areas south of the Erlend Platform throughout the Paleocene (Figures 26-28).

Clair Transfer Zone – Erlend Platform source area

This area is separated from the northern, enclosed, end of the Faroe-Shetland Basin by the Erlend Platform. The northern end of the Faroe-Shetland Basin lies to the south of this platform, with the west Shetland Platform to the east and the northern complex of the Corona Ridge on the west. Although some minor input from the west penetrates through the area of the Victory Transfer Zone during TPaMFS60, it is not seen in the Late Paleocene (Figures 26-28). Paleocene argillaceous sediment in the north of the Faroe-Shetland Basin is mostly derived from the west Shetland Platform. Palynofloral evidence suggests that the coastal belt was dominated by floodplains with some mires

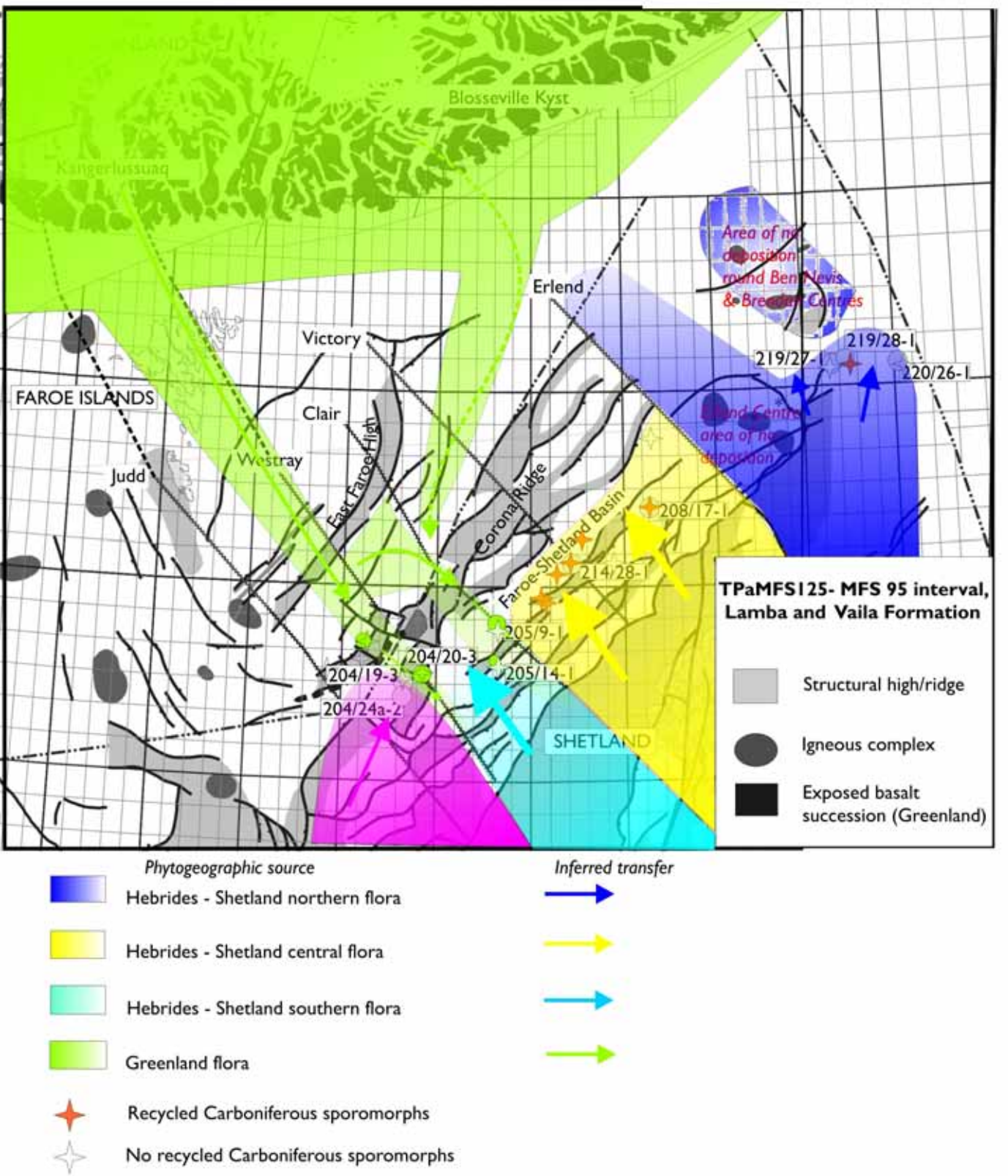

Blosseville Kyst
Kangerlussuaq
Erlend
Victory
Clair
FAROE ISLANDS
Westray
Judd
East Faroe High
Corona Ridge
Faroe-Shetland Basin
Area of no deposition round Ben Nevis & Breadalbane Centres
219/28-1
219/27-1
220/26-1
208/17-1
214/28-1
205/9-1
204/20-3
204/19-3
205/14-1
204/24a-2
SHETLAND
TPaMFS125- MFS 95 interval, Lamba and Vaila Formation
Structural high/ridge
Igneous complex
Exposed basalt succession (Greenland)
Phytogeographic source
Inferred transfer
Hebrides - Shetland northern flora
Hebrides - Shetland central flora
Hebrides - Shetland southern flora
Greenland flora
Recycled Carboniferous sporomorphs
No recycled Carboniferous sporomorphs

Figure 28

developed. These data suggest that the coastal belt was restricted in extent, and experienced disturbance.

Carboniferous sporomorphs reworked into the Paleocene occur throughout the TPaMFS80 – 100 interval north of the Clair Transfer Zone. Throughout the interval characterised by this recycling, it remains restricted to the Clair – Erlend transfer zone region. Their occurrence south of the Clair Transfer Zone only in the TPaMFS90-95 interval suggests sediment mixing along the boundary of the southern and northern Hebrides – Shetland flora sediment transfer paths. These data suggest that the source of this clastic material was restricted to fault scarp reworking on the Corona ridge or West Shetland Platform.

Judd Transfer Zone – Clair Transfer Zone source area

In the southern part of the Faroe-Shetland Basin, sedimentation was more rapid, with thicker sections developed. These were derived from both the westerly source, and from the west Shetland Platform. The west Shetland Platform argillaceous sediment was mostly derived from an area between the Clair and Judd Transfer Zones (Figures 26-28). The palynofloras indicate that this was dominated by a complex of mire and floodplain plant communities.

Within the top of the Vaila Formation and into the base of the Lamba Formation, the quantity of argillaceous sediment transported from the west undergoes a minor resurgence. However, this influx is limited to the south of the Faroe-Shetland Basin with the Clair and Westray transfer zones acting as conduits. A clear division remains between southern and central Hebrides – Shetland floras. Input from the Foinaven flora continued in the south, but data from recycled Carboniferous sporomorphs indicates a lack of mixing between southern and central Hebrides-Shetland floras.

Foinaven source area

A southerly source, the Foinaven flora, is recorded from south of the Judd Transfer Zone. It corresponds with the southerly arenaceous source for Foinaven Field wells

recorded by Morton et al. (2002). These authors recorded this southerly source as being restricted to late T36. Within the palynofloral data, this influence can be seen extending throughout the TPaMFS90 – TPaMFS100 interval (Figures 26, 27). Again, this emphasises the differences in arenaceous and argillaceous sediment distribution patterns. This is directly comparable to the differences in heavy mineral and Greenland Flora distribution seen in the south of the Corona Basin.

9. CONTROLS ON SEDIMENT TRANSFER

Importance of the Greenland Stratigraphic Record

The determination of the ages of the lithological units in the Kangerlussuaq region has important consequences for to our understanding of offshore sequence development and sediment transfer. The Paleocene sediments of Kangerlussuaq demonstrate a close similarity with those penetrated by wells on the Rona Ridge (Quadrants 202 and 203). Here terriginous TPaMFS135-TPaMFS140 age sediments rest unconformably on marine shales of TPaMFS60-TPaMFS75 age. Comparison with wells drilled in the south of the Corona Basin provides further information. Wells like the example in Figure 29 show late Danian arenaceous deposits and extensive arenaceous strata above TPaMFS75. Between TPaMFS60 and TPaMFS75 is a dominantly argillaceous unit. This corresponds to the onlap onto the Kangerlussaq coast represented by the Sediment Bjerge Formaton. Before and after this event, sediment supply bypassed the Kangerlussuaq shelf and was transported into the deeper basins to the east. Given the dominantly argillaceous nature of the Sediment Bjerge Formation, it is unlikely that sediment supply from Greenland was mud prone. The consequence of this is likely to be the abundant occurrence of arenaceous units in the Danian, and in the late Paleocene from TPaMFS75 to TPaMFS140. This abundance of sand may prove to be a continuing hazard in petroleum exploration in the Corona Basin where the westerly source plays an important role in sediment input. In particular, the absence of any shale units above TPaMFS75 may negate hydrocarbon prospectivity in younger strata on the grounds of insufficient seal.

Pulsing of westerly sediment source

Immediately recognisable from the pollen frequency data is the relationship between westerly sourced Greenland Flora abundance and relative sea level. This shows a clear correspondence between maximum flooding surfaces, subsequent highstand sedimentation and low frequencies of the Greenland Flora. The maximum abundance of the Greenland Flora record is reached during lowstand intervals, declining with rising relative sea level. This relationship to sea level fluctuation is highlighted by the inception

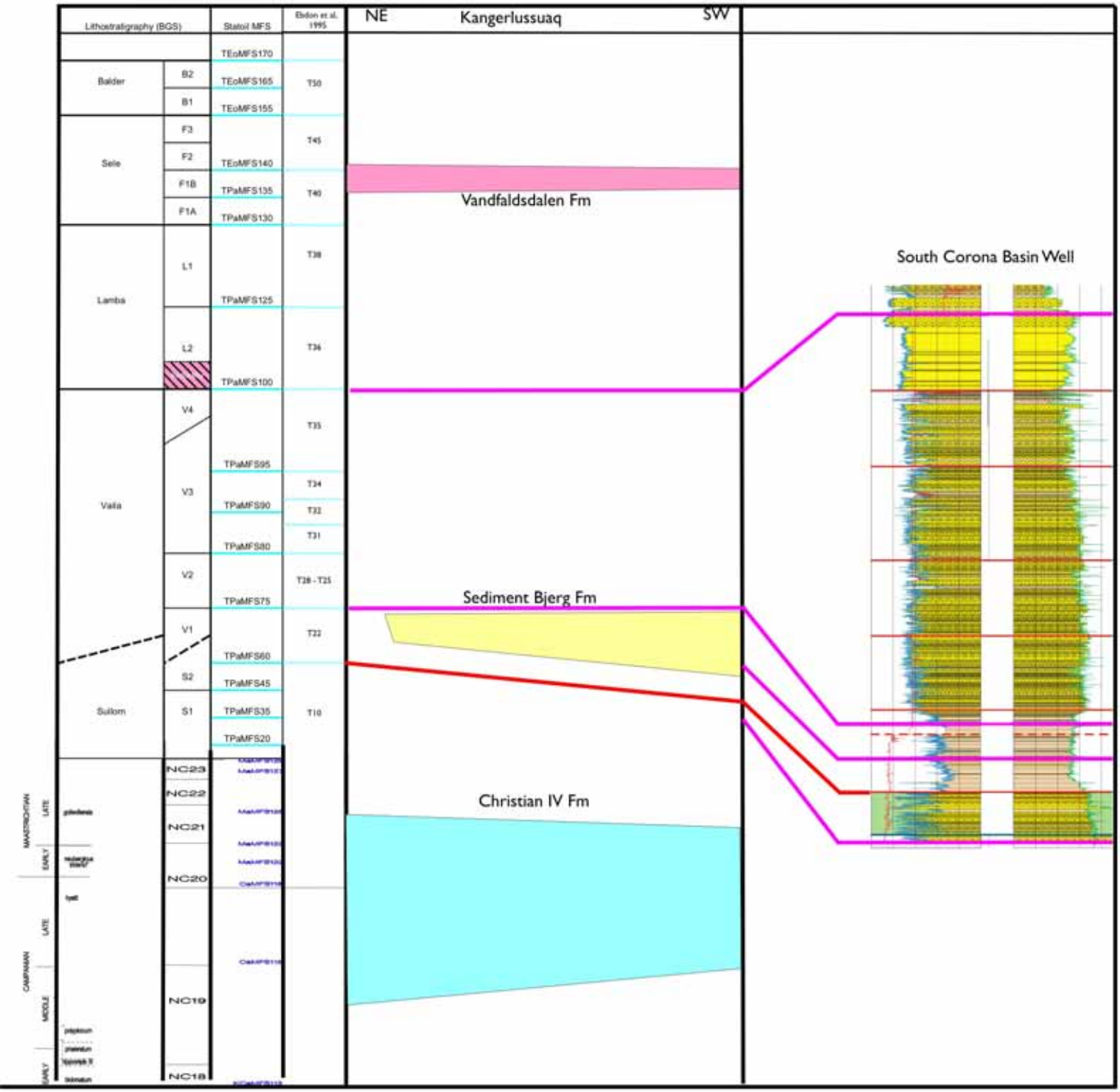

Lithostratigraphy (BGS)
Statoil MFS
Ebdon et al. 1995
NE
Kangerlussuaq
SW
Balder
B2
B1
Sele
F3
F2
F1B
F1A
Lamba
L1
L2
Vaila
V4
V3
V2
V1
Sullom
S2
S1
TEoMFS170
TEoMFS165
TEoMFS155
TEoMFS140
TPaMFS135
TPaMFS130
TPaMFS125
TPaMFS100
TPaMFS95
TPaMFS90
TPaMFS80
TPaMFS75
TPaMFS60
TPaMFS45
TPaMFS35
TPaMFS20
T50
T45
T40
T38
T36
T35
T34
T32
T31
T28 - T25
T22
T10
Vandfaldsdalen Fm
Sediment Bjerg Fm
Christian IV Fm
South Corona Basin Well
NC23
NC22
NC21
NC20
NC19
NC18
MAASTRICHTIAN
CAMPANIAN
LATE
EARLY
MIDDLE

Figure 29

of the TPaMFS95 – sub TPaMFS90 Greenland flora immediately following a sequence boundary (Figure 30). It can therefore be surmised that low relative sea levels resulted in the mobilisation of clastic material on the shelf to the northwest and its transference into the Faroe-Shetland Basin.

While the relationship between sediment transfer and relative sea level is demonstrated clearly, the pulsed nature of the Greenland Flora record cannot satisfactorily be explained by long-term sea level trends (Ebdon et al., 1995), or climatic variation (Jolley et al., in press). The coincidence of the three main incursions of the Greenland Flora with volcanogenic sediments or tephras is thought to be significant. Both the Kettla Member and older Vaila Formation tephras and volcaniclastics (see Naylor et al., 1999, and Ellis et al., 2004) occur in sediments that demonstrate a westerly source from their pollen and heavy mineral contents.

Comparison with the stratigraphical age of volcanic units across the NAIP shows that there are local sources for the TPaMFS80 – TPaMFS95 pulse of the Greenland Flora (Poulsen et al., 2004). However, other igneous events of possible consequence are further removed from the sedimentary depocentres. Contemporary igneous activity is recorded in the Hebrides and in West Greenland. It is the Hebrides activity that is of most interest, there being a close coincidence between intrusion of the Rum Centre, extrusion of the Skye Main Lava Series (based on its biostratigraphical age, Jolley, 1997), and the Cuillins Centre (Figure 31).

In conclusion, it is possible to suggest that the pulsed nature of the Greenland Flora record is attributable to variations in thermal support of the source areas. During periods of relative uplift, increased weathering and clastic transportation into the basins to the east would have been enhanced. Thermal collapse between these episodes would have resulted in more sluggish drainage regimes and a cut off of sediment transfer to the east. During these periods, sediments derived from the Hebrides-Shetland region would have dominated deposition in the Faroe-Shetland Basin.

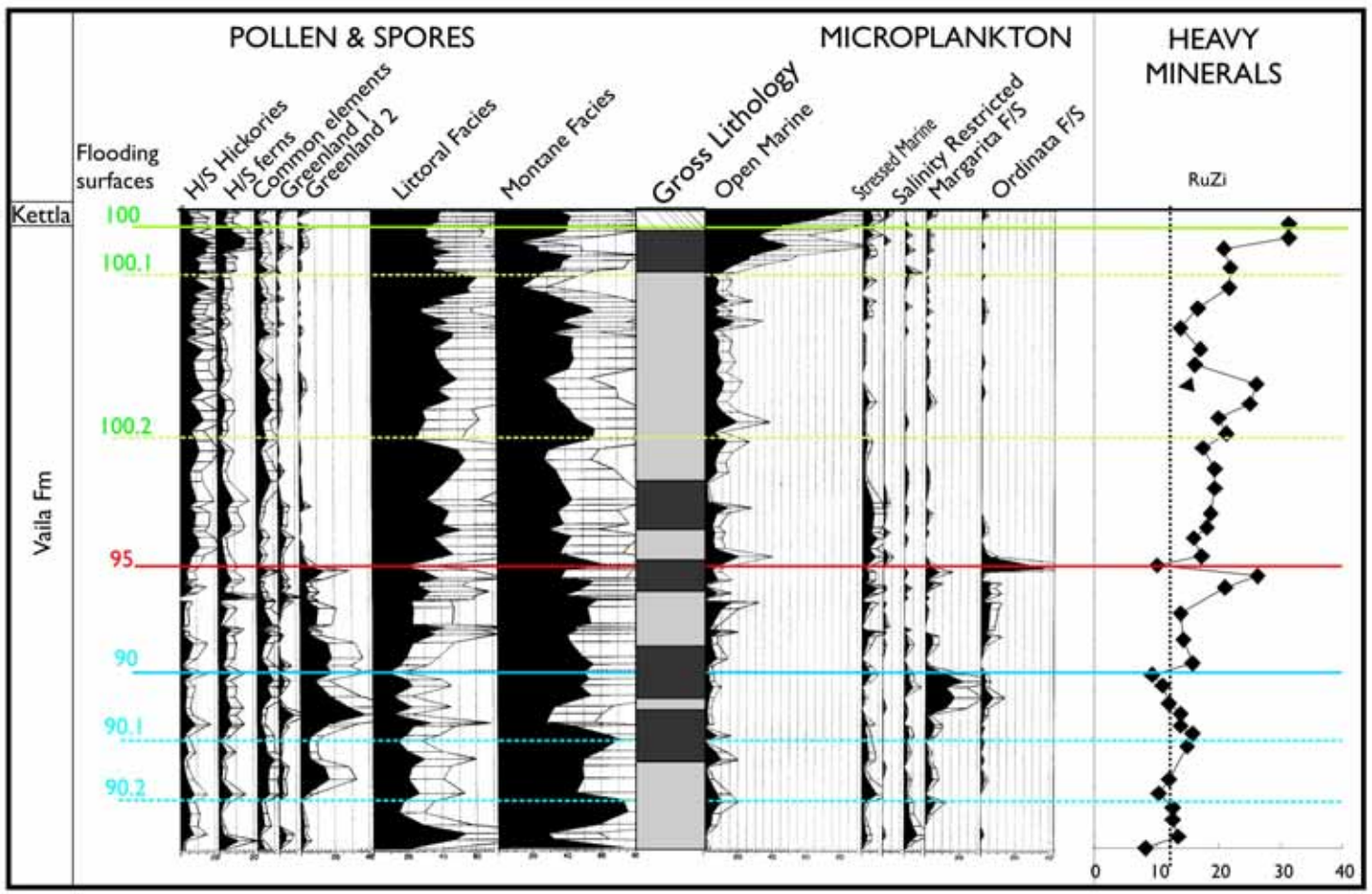


Figure 30. Greenland Flora and heavy mineral record from a Corona Basin well after Jolley et al., In press.
Note the lower frequencies of the Greenland Flora at flooding surfaces, increasing during the subsequent lowstands

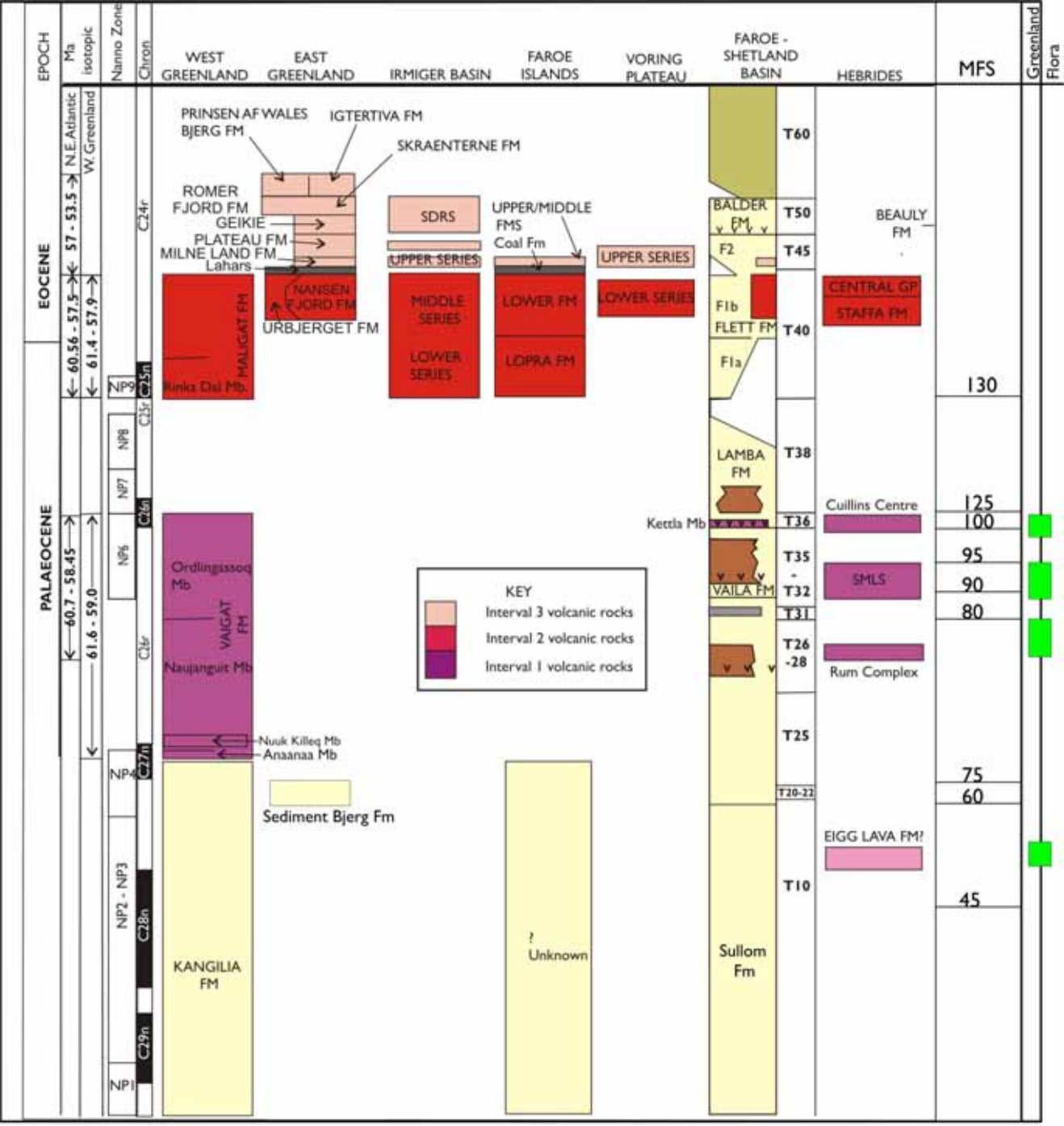


Figure 31. Stratigraphical comparison of pulses of the Greenland Flora in the Corona and Faroe-Shetland basins with the occurrence of igneous rocks in the region

10. REFERENCES

Collinson, M.E., 2002. Cainozoic ferns and their distribution. Brittonia 53, 173-235.

Crouch, E.M., Heilmann-Clausen, C., Brinkhuis, H, Morgans, H.E.G, Rogers, K.M., Egger, H. and Schmitz, B., 2001. Global dinoflagellate event associated with the late Paleocene thermal maximum, Geology 29, 315-318.

Ebdon, C.C., Granger, P.J., Johnson, H.D., and Evans A.M., 1995. Early Tertiary evolution and stratigraphy of the Faeroe-Shetland Basin: Implications for hydrocarbon prospectivity. In: Scrutton R.A., et al. (eds), Sedimentation and palaeoceanography of the North Atlantic region. Geological Society of London, Special Publication, 90, 51-69.

Ellis, D., Poulsen, R., Dromgoole, P and Gallagher J.W. 2004. Transfer Zones:Their influence on the onshore and offshore geological development of the Faroes underground. Faroe Islands Exploration Conference Abstracts.

Ellis, D., Bell, B.R., Jolley, D.W. and 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 of London Special Publication, 197, 253-270.

Evans, D., Morton, A.C., Wilson, S.J., Jolley, D.W. and Barreiro, B. 1997. Marine and terrestrial Tertiary sediments in BGS borehole 77/7, north of Scotland. Scottish Journal of Geology 33; 31-42.

Hitchen, K., Jolley, D.W., Harland R. and Jones J.M. 1995. Regional implications of micropalaeontological and palaeo-environmental investigations of the early Eocene interval in BGS borehole 90/3, offshore N.W. Scotland. Scottish Journal of Geology 31; 117-24.

Johnson, H., Ritchie, J.D., Hitchen, K., McInroy, D.M. and Kimball G.S. in press. The Cenozoic deformational history of the UK Atlantic Margin.

Jolley, D.W., Morton, A.C. and Prince, I.P. in press. Volcanogenic impact on phytogeography and sediment dispersal patterns in the NE Atlantic. Petroleum Geology of NW Europe, proceedings of the 6th Conference 2003.

Jolley , D.W. & Whitham A.G., 2004. A stratigraphical and palaeoenvironmental analysis of the sub-basaltic Palaeogene sediments of East Greenland. Petroleum Geology10, 53-60.

Jolley, D.W., Clarke, B. & Kelley, S.R.A, 2002, Paleogene time scale miscalibration: evidence from the dating of the North Atlantic Igneous Province. Geology 30, 7-10.

Jolley D.W. & Bell., B.R., 2002. The evolution of the Tertiary North Atlantic Igneous Province, and the opening of the northeast Atlantic rift. In: Jolley, D.W. & Bell, B.R. (eds). The North Atlantic Igneous Province; stratigraphy, tectonic, volcanic and magmatic processes. Geological Society of London Special Publication 197,1-14.

Jolley, D.W. & Morton, A.C., 1992. Palynological and petrological characterization of a North Sea Palaeocene volcaniclastic sequence. Proceedings of the Geologists Association 103, 119-127.

Jolley, D.W., 1998. Palynostratigraphy and depositional history of the Palaeocene Ormesby/Thanet depositional sequence set in southeastern England and its correlation with continental West Europe and the Lista Formation, North Sea. Review of Palaeobotany and Palynology 99, 265-315.

Jolley, D. W., 1997. Palaeosurface palynofloras of the Skye lava field and the age of the British Tertiary volcanic province. In : Widdowson, M. (ed). Palaeosurfaces: Recognition, Reconstruction and Palaeoenvironmental Interpretation. Geological Society, London, Special Publication 120, 67-94.

Jolley, D.W., 1996. The earliest Eocene sediments of eastern England; an ultra high resolution palynological correlation. In: Knox, R.W.O'B. Corfield, R. & Dunay, R.E. (eds.). Correlation of the Early Paleogene in Northwest Europe: Geological Society of London, Special Publication 101, 219 -254.

Jolley, D.W. 1992. Palynofloral association sequence stratigraphy of the Palaeocene Thanet Beds and equivalent sediment in eastern England. Review of Palaeobotany & Palynology 74, 207-237.

Knox, R.W.O & Holloway, S., 1992, Palaeogene of the central and northern North Sea, in Knox R.W.O., et al., (eds), Lithostratigraphic nomenclature of the UK North Sea: Nottingham, British Geological Survey 1, 133 p.

Larsen, M. and Whitham, A.G. In press. Evidence for a major sediment input point into the Faroe-Shetland Basin from the Kangerlussuaq region of southern East Greenland. In. 2003 NW European Margin Conference: conference volume

Larsen, M., Hamberg, L., Olaussen, S. and Stemmerik, L. 1996. Cretaceous-Tertiary pre-drift sediments of the Kangerlussuaq area, southern East Greenland. In. Bulletin Grønlands Geologiske Undersøgelse 172, 37-41

Larsen, M., Nøhr-Hansen, H., Whitham, A.G. and Kelley, S.R.A. 2004. Stratigraphy of the pre-basaltic sedimentary succession of the Kangerlussuaq Basin. Volcanic basin of the North Atlantic. Report 2, June 2004, SINDRI Group, 67.

Lamers, E. & Carmichael, S.M.M. 1999. The Paleocene deepwater sandstone play west of Shetland. In: Flett, A.J. & Boldy, S.A.R. (eds). Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference. Geological Society, London 645-659.

Lund, J., 1989. A late Paleocene non-marine microflora from interbasaltic coals of the Faeroe Islands, North Atlantic. Bulletin of the Geological Society of Denmark 37, 181-203.

Morton, A.C., Boyd, J.D. & Ewen, D.F., 2002. Evolution of Paleocene sediment dispersal systems in the Foinaven sub-basin, west of Shetland. In: Jolley, D.W. & Bell, B.R. (eds). The North Atlantic Igneous Province; stratigraphy, tectonic, volcanic and magmatic processes. Geological Society of London, Special Publication 197, 69-94.

Morton, A.C. & Hallsworth, C.R., 1994. Identifying provenance-specific features of detrital heavy mineral assemblages in sandstones. Sedimentary Geology 90, 241-256.

Naylor, P.H., Bell. B.R., Jolley, D.W., Durnall, P. & Fredstead, R., 1999. Palaeogene magmatism in the Faeroe-Shetland Basin: influences on uplift history and sedimentation. In: Fleet & Boldy, Petroleum Geology of Northwest Europe, Proceedings of the 5th Conference, Geological Society of London, 545-558.

Schroder, T., 1992, A palynological zonation for the Paleocene of the North Sea Basin. Journal of Micropalaeontology 11, 113-126

Stoker, M., Hitchen, K & Graham C.C. 1993. The geology of the Hebrides and West Shetland shelves, and adjacent deep-water areas. British Geological Survey, United Kingdom Offshore Regional Report, p39-53.

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.

Winkler, W. & Gawenda, P., 1999. Distinguishing climate and tectonic forcing of turbidite sedimentation and the bearing on turbidite bed scaling: Palaeocene – Eocene of northern Spain. Journal of the Geological Society of London 156, 791- 800