Palynology of the Lower Eocene deposits of northwest Jutland, Denmark

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Early Eocene spores and pollen assemblages from the uppermost part of the Stolle Klint Clay and the overlying Fur Formation are diverse and well preserved. The terrestrial microflora comprises 42 species of spores and 108 species of pollen and four spores and pollen zones are established i.e. Interpollis velum-Labrapollis globosus, Basopollis atumenscens, Basopollis orthobasalis and Thomsonipollis magnificus zones. The zones are directly correlated to the existing tephrachronology and stratigraphy. The dinoflagellate cysts assemblages are referred to Zones 6 and 7 of Heilmann-Clausen or the upper part of the Apectodinium hyperacanthum and Glaphyrocysta ordinate Interval Biozone of Powell. A marked shift in the terrestrial and marine palynomorph assemblages takes place at the transition between the two oldest spore and pollen zones at c. 1.2 m below ash layer –19b.

Keywords: Palynology, early Eocene, spores and pollen, Stolle Klint Clay, Fur Formation, tephrachronology, biostratigraphy, correlation.

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Palynological studies in Denmark of the Upper Paleocene and Lower Eocene strata have mainly focused on organic-walled marine microplankton or dinoflagellate cysts (Hansen 1979; Heilmann-Clausen 1982, 1985, 1988, 1994). Calcareous micro- and nanofossils in the sediments from the Paleocene–Eocene transition in Northwest Europe are sparse whereas palynomorphs are frequent and palynological zonations are the prime biostratigraphical tools for dating of the Paleocene–Eocene succession (Schröder 1992; Heilmann-Clausen 1994).

The excellent preserved palynomorph assemblages and relatively high sedimentation rate during the deposition of the Lower Eocene Fur Formation provide an excellent basis for a high-resolution palynological study of this interval (Willumsen 1997, 1998). In Denmark, Krutzsch (1966) examined early Eocene spores and pollen assemblages, but the Stolle Klint Clay and Fur Formation were not studied in detail nor correlated to the existing tephrachronology established by Bøggild (1918) and Gry (1960). Krutzsch (1966) found that the Stolle Klint Clay and Fur Formation contain a low diversity microflora. This study, however, shows that spores and pollen assemblages recorded from the Stolle Klint Clay and Fur Formation are well preserved and diverse. Hence, the purpose of this paper is to present the early Eocene terrestrial microflora and to establish a spores and pollen biozonation.

The spores and pollen assemblages are furthermore related to the established tephrachronology for Northwest Europe and to changes in the marine palynomorphs, mainly dinoflagellate cysts, with the aim to establish an integrated regional palynological zonation for the early Eocene in Denmark. Relation to early Eocene environmental changes is also discussed.

Lower Eocene sediments in Denmark

In Denmark, the Lower Eocene sediments are referred to the Ølst Formation, the Stolle Klint Clay and Fur Formation. The Lower Eocene sediments are exposed as coastal cliffs and in quarries in northern Jylland, Denmark (Fig. 1A, B). The sediments accumulated in a relatively offshore position within the North Sea Basin.

The Paleocene–Eocene Series boundary is placed
Fig. 1A. Location map showing the main localities mentioned in the text. Fig. 1B. Limfjorden area and the distribution of the Lower Eocene deposits. Stolle Klint, Firkanten Silstrup and Silstrup Sydklint locations are shown. The geological map is from Klint & Pedersen (1995).
**Fig. 2.** Lithostratigraphic relationships and correlation of the Lower Eocene Stolle Klint Clay and the Fur Formation with other lower Eocene formations from south-eastern Denmark, Central North Sea and south-eastern England. Nannofossils are not present in the Stolle Klint Clay and Fur Formation and correlations to the nannofossil Zones of Martini (1971) are based on indirect evidence.

at the base of the late Paleocene negative carbon excursion (CIE) or below the magnetic Chron 24r (ISPS Newsletter No. 9, November 2000). In Denmark, the Upper Paleocene Glaucoclitic Silt Unit was deposited during Chron 25n and the overlying Østerende Clay during Chron 25r. Accordingly, the Paleocene–Eocene boundary in Denmark is recorded at the top of the Glaucoclitic Silt Unit or at the base of the Stolle Klint Clay (Beyer et al. 2001) (Fig. 2).

**Stolle Klint Clay.** Stolle Klint Clay is dark-grey, fine-laminated clay with organic material; ash layers are present and the ash layers 34 to 39 occur in the Stolle Klint Clay (Bøggild 1918; Gry 1960). The Stolle Klint Clay is up to 15 m thick. It conformably overlies the Paleocene Østerende Clay or unconformable the Holmehus Formation and the boundary is usually marked by the Glaucoclitic Silt Unit; it is overlain by the Fur Formation. It constitutes the lower part of the Haslund Member of the Ølst Formation (Heilmann-Clausen 1995, fig. 12). The Stolle Klint Clay has also been referred to as Unfossiliferous Clay (Hansen 1979).

Pedersen & Suryk (1983) placed the sediments of the Stolle Klint Clay in the Fur Formation, but Heilmann-Clausen et al. (1985) found that the sediments containing the ash layers 34 to 39 should be considered as a separate lithological unit i.e. the Stolle Klint Clay (Fig. 2).

**Fur Formation.** The type locality for the Fur Formation is Knudeklint on the western side of the Fur (Pedersen & Suryk 1983) (Fig. 1A). The Fur Formation is c. 60 metre thick; it is a dark-grey to light-grey diatomite, which turns clayey white to light yellowish during weathering. Numerous alternating black to grey volcanic ash layers intersect the diatomite (Pedersen & Suryk 1983). The known occurrences of the diatomite are limited to the east, north and west by structural highs (Fig. 1B).

The Fur Formation is subdivided into the lower Knudeklint Member and upper Silstrup Member (Pedersen & Suryk 1983; Heilmann-Clausen et al. 1985).

The characteristic diatomite and interbedded dark ash layers are glacially folded and thrust faulted and brought into their present position during the Saalian to late Weichselian ice advances (Gry 1940, 1964, 1979; Pedersen & Suryk 1983; Klint & Pedersen 1995; Pedersen 1996). The detachment of the dislocation is situated below the base of the Fur Formation in the plastic clay at depth of 80-100 m (Pedersen 1996).

The two contemporaneous facies: the clayey diatomite (Stolle Klint Clay and Fur Formation) and mudstone (Ølst Formation) deposited in the Danish
part of the North Sea Basin (Heilmann-Clausen et al. 1985; Michelsen et al. 1998; Beyer et al. 2001) (Fig. 2). Beyer et al. (2001) showed that the Ólóst Formation is equivalent to the magnetic chron C24r. This indicates that the Ólóst Formation (and Stolle Klint Clay and Fur Formation) deposited in c. 1.1 Ma.

The Stolle Klint Clay, Fur and Ólóst formations are correlated to the upper Sele and the lower Balder formations in the Central North Sea and Upern Formation, Woolwich and Reading beds, Harwich Formation and the lower to middle part of the London Clay Formation in southeast England (Fig. 2; Knox & Harland 1979; Heilmann-Clausen et al. 1985; Knox & Holloway 1992; Beyer et al. 2001).

The study area

Stolle Klint Clay and Fur Formation are exposed in the coastal cliffs of the Limfjorden, northwest Jutland and three of these coastal cliffs were examined in this study (Fig. 1B).

The lower boundary of the Fur Formation is exposed at the Stolle Klint. Here, the clayey white to light yellow diatomite of the Fur Formation overlies dark-grey, slightly calcareous, silty clay with few, thin ash layers of the Stolle Klint Clay. The transition from the top of the Stolle Klint Clay and into the basal part of the Fur Formation was examined at Stolle Klint in this study (Fig. 3).

Tephchronology

Bøggild (1918) and Gry (1960) established the high-resolution tephchronology in the Stolle Klint Clay and Fur Formation. The ash layers are divided into a ‘negative ash series’ numbered -39 to -1 and a ‘positive ash series’ numbered +1 to +140.

The Knudeklint Member of Fur Formation includes the ‘negative ash series’ down to -33 and the ‘positive ash series’ from +1 to +140 belongs to the Silstrup Member of the Fur Formation (Pedersen & Surlýk 1983; Heilmann-Clausen et al. 1985). The uppermost part of the Fur Formation i.e. from the base of ash layer +1 to ash layer +140 is exposed at Silstrup Sydklint in the western part of the Limfjorden area (Fig. 1B).

Four volcanic phases within the nanoplankton interval NP9–NP10 of the North Sea Basin are recognized (Knox 1997). The phases are related to regional tectonic events including regional uplift of the NE Atlantic margin accompanied by uplift of the southern North Sea area and onset of pyroclastic activity in the Greenland-Faeroes Province (Fig. 2). The ash layers can be recognized over long distances (Knox 1989, 1992, 1996, 1997; Egger et al. 2000). The two distinct ash layers -17 and +19 are preserved in the borehole at the Wursterheide, North Germany. They have also been identified in the Hales and Harwich members in the lowest part of the London Clay Formation, onshore U.K., and in cores from the Deep Seas Drilling Project borehole 550 in the East Atlantic (Berggren et al. 1995) (Fig. 1A).

Tephchronology is important in the dating of the sediments at the Paleocene–Eocene transition in Northwest Europe. Ash layer -17 in the Fur Formation has been traced to various locations in Northwest Europe and the North Atlantic region (Berggren et al. 1995) and it has been dated radiometrically to 54.5–55.0 Ma (Swisher & Knox 1991; Wing et al. 1991).

Correlation of the ash layers in Denmark with the ash layers in the East Atlantic DSDP 550 borehole allows for correlation of the oceanic nanoplankton biozones and the magnetic chronostratigraphy to the North Sea area (Fig. 1A). The interval from ash layer -17 to ash layer +19 has been assigned to the lower third of NP10 Zone and to the lower half of the magnetic Chron C24r (Berggren et al. 1995; Knox 1997).

Palaeoenvironment

The clayey diatomite of the Stolle Klint Clay and Fur Formation accumulated below wave base and with several shifts between anaerobic and aerobic bottom conditions (Pedersen 1981; Pedersen & Surlýk 1983).

The dominance of neritic benthic diatoms indicates that water depth did not exceed 50 m (Fenner 1994; Mittehner 1996). A high number of land-derived fossils including insects, plants and birds, have been collected from the diatomite probably reflecting a relative nearshore depositional position (Larsson 1975; Pedersen & Surlýk 1983; Willmann 1990; Møller Andersen & Andersen 1996). Northerly winds probably caused upwelling in a nearly landlocked sea and the diatomite accumulated (Bonde 1974, 1979, 1987).

This sea was connected to the Atlantic Ocean through a narrow seaway between Norway and Scotland. Local structures probably put a limit the lateral distribution of diatomite in the north-western part of Jutland (Pedersen & Surlýk 1983). Danielsen & Thomsen (1997) fund that the regional depositional model proposed by Bonde (1974, 1979, 1987) could explain the occurrence of 1 to 15 m thick beds of diatomitic sediments in the Danish part of the North Sea Basin.
Material and methods

80 samples collected from the three coastal outcrops, Stolle Klint, Silstrup, Firkanten and Silstrup Sydklint were examined (Figs 1B, 3). The tephrachronology and geological profiles of Bøggild (1918) and Gry (1940, 1964, 1979) were used to correlate the sample series from the three localities (Fig. 3). Samples were collected from c. 2.5 m below ash layer -34 to c. 4.2 m above ash layer +118 (Willumsen 1997, 1998). Ash layer +138 was established in the Silstrup Sydklint.

The sample spacing is 1 m and Figure 3 shows the position of the collected samples in relation to the ash layers and lithostratigraphy.

All the samples were processed for palynology following the procedure presented by Willumsen (1997). 3–4 grams of sediment were treated with cold HCL (10%) in 1 hour followed by a treatment in cold HF with a concentration of 40% for a minimum of eight days. After removal of the HF 10% cold HCL was added and the sample was left for an hour before it was centrifuged and the HCL decanted. Treat-
ment with 10% KOH for 1–2 minutes was carried out on all samples after the HF and HCl had been removed. Heavy liquid separation and weak oxidation in 2 minutes in a 36% nitric acid were carried out on 10 samples. The organic debris was sieved through 6 mm filters and mounted in glycerine oil on microscope slides.

All occurrence data are based on examination of two to three palynological slides per sample. The spore and pollen content was counted in 23 samples. The counted 23 samples were selected based on their individual stratigraphical distance of maximal 3 to 4 metres. The samples from Silstrup and Firkanten were not counted due to the overall sparse terrestrial assemblages recovered in the palynological slides from this locality. The sparse spores and pollen assemblages prohibited correlation to intervals with overlapping sample series. These intervals are from the lower and upper part of the sample series from the Silstrup, Firkanten (samples Fir.01–08 and samples Fir.15–18) to the top of the Stolle Klint (samples Stk.47–52) and the lower part of the Silstrup Sydklint (samples Syd.01–04). Figure 5 shows the interval with sparse spores and pollen assemblages (marked by an asterisk).

A minimum of 250 spores and pollen were counted on species level in 23 samples. Spores and pollen that could not be referred to a distinct species are classified as trilete spores, undetermined disaccate pollen and other pollen.

Aleate azonala pollen such as Inaperturopollenites concedipites (Wodehouse, 1933; Krutzsch, 1971) and Inaperturopollenites hiatus (Potonië, 1931; Thomson & Pflug 1953) are collected into one morphological group: Inaperturopollenites spp. The morphological characteristics of these pollen species are few and therefore are considered as one major group.

The marine algae including the dinoflagellate cysts were counted along with the terrestrial palynomorphs. The dinoflagellate cysts are divided into the following five groups or species: Apectodinium group includes all the Apectodinium species observed except the species A. augustum. The species Apectodinium augustum and Deflandrea oebifeldensis were counted. The Cephalomycysta group includes all the observed Cephalomycysta and Areoligera species. The remaining dinoflagellate cysts are lumped into one group: other dinoflagellate cysts.

The brackish-water algae Pediasstrum is only observed in sample Stk.01, which is the stratigraphically oldest sample investigated in this study. All other observed algae are considered to be of marine origin. The relative frequency of the marine contra terrestrial palynomorphs is estimated by adding all the palynomorphs counted in each of the 23 samples counted. This number was then used to divide number of the spores and pollen counted in each of the 23 samples.

The palynological slides, remaining residues and samples are deposited at the Department of Geology, University of Aarhus, Denmark. The palynological slides with illustrated specimens (Plates 1 and 2) are stored at the Geological Museum, Copenhagen, Denmark (catalogue numbers MGUH 27024 to 27050).

Biostratigraphy

The samples yield a diverse and well-preserved terrestrial flora composed of 42 species of spores and 108 species of pollen (Appendix I). Characteristic species of spores, pollen and dinoflagellate cysts are shown on Plate 1 and Plate 2. The terrestrial microflora is divided into four spores and pollen zones, which are defined below.

Facing page:
Plate 1.
Fig. 1. Cicatricosiosporites dorogensis, Stk.10, slide 1-2 (H20, 2) MGUH 27024.
Fig. 2. Verrucatosporites favus Syd.02, slide 1-1 (I40, 4) MGUH 27034.
Fig. 3. Podocarpidites libellus Stk.20, slide 1-1 (E28, 1) MGUH 27047.
Fig. A. Zonalapollenites minimus Syd.10, slide 1-3 (K30, 1-3) MGUH 27033.
Fig. 5. Pitiosporites labdacus Stk.10, slide 1-2 (F33, 2; 4, E33) MGUH 27025.
Fig. 6. Pitiosporites alatus Stk.10, slide 1-2 (E24, 3; 1, F24) MGUH 27026.
Fig. 7. Zonalapollenites minimus Stk.36, slide 1-1 (E28, 2) MGUH 27037.
Fig. 8. Tricolporopollenites quercoides Stk.05, slide 1-1 (Q20, 3) MGUH 27046.
Fig. 9. Podocarpidites eocenicus Stk.39, slide 1-1 (S20, 4) MGUH 27049.
Fig. 10. Zonalapollenites maximus slide Stk.32, slide 1-1 (E20, 4; E21, 3) MGUH 27048.
Fig. 11. Basapolis atumescens Stk.16, slide 1-1 (G22, 1) MGUH 27041.
Fig. 12. Basapolis basalis Stk.36, slide 1-1 (N23, 2) MGUH 27038.
Fig. 13. Tricolporopollenites messeleensis Fir.02, slide 1-1 (L34, 1) MGUH 27050.
Fig. 14. Basapolis orthobasalis Stk.36, slide 1-1 (P20, 1) MGUH 27039.
Fig. 15. Carapollenites circulus Stk.10, slide 1-2 (I25, 4); 3, 126) MGUH 27027.
Fig. 16. Carapollenites triangulus Stk.10, slide 1-1 (G26, 3) MGUH 27030.
Interpollis velum - Labrapollis globosus Zone

Definition. The base of this spores and pollen zone is placed above the last occurrence of Tricolporopollenites quericioides at 0.4 m below ash layer −33 (sample Stk.05). The top of the zone is placed at the first occurrence of Basopollis atumenscens at 1.2 meters below ash layer −19b.

Characteristics. The Interpollis velum - Labrapollis globosus Zone ranges from above sample Stk.05 to Stk.15 (Figs 4–5). Interpollis velum has its last occurrence in the middle part of the zone (Stk.10) and Labrapollis globosus is relatively abundant in the lower part of the zone. Interpollis microsupplingensis and Platycaryapolletites platycaryoides are also relatively common within the zone. The relative frequency of trispores pollen is high in the lower to middle part of the interval due to an increase in relative abundance of Caryapolletites circulus and C. triangulus. The Inaperturapollenites spp. group is also common. Disaccate pollen are very rare (<2% of the relative amount of spores and pollen).

The last occurrence of the dinoflagellate cyst species Apectodinium augustum is at 2.2 m below ash layer −19b (sample Stk.14), but in the lower part of this interval this species comprises between 10–20% of the total dinoflagellate cysts counted. The genus Apectodinium is very abundant (>30% of total amount of dinoflagellate cyst assemblage) throughout the lower to middle part of the Interpollis velum - Labrapollis globosus Zone. The Apectodinium spp. group comprises >40% of the total dinoflagellate cyst encountered the interval below the Interpollis velum -

Labrapollis globosus Zone (from sample Stk.05 to Stk.01).

Reference section. Stolle Klint section, Fur, Denmark. Uppermost part of the Stolle Klint Clay and lower part of the Knudeklint Member of the Fur Formation.

Correlation and age. The spores and pollen assemblages (previously dated as late Paleocene) are earliest Eocene in age. The microflora assemblage correlates with 19.4 Subzone of Schröder (1992) and with Pg Zone 9 of Krutzsch (1966). Krutzsch’s (1966) spores and pollen Pg Zone 9 correlates to Meyers (1988, 1989) zones SP3/Wu2 (Figs 4, 5). The last occurrence of the dinoflagellate cyst index species A. augustum at the top of the I. velum - L. globosus Zone also suggests equivalence to the upper NP9 to lower NP10 zones (Powell 1992; Heilmann-Clausen 1994; Egger et al. 2000).

Basopollis atumenscens Zone

Definition. The base of this zone is placed at the first occurrence of Basopollis atumenscens. The top of the zone is defined by the first occurrence of Basopollis orthobasalis.

Characteristics. Pollen belonging to the morphological pollen group disaccates and the genus Inaperturapollenites are relative abundant in the lower part of this zone (Fig. 5). Labrapollis globosus has its last occurrence in the lower part of the zone. Tripolarpollenites robustus has its first constant occurrence in the lowermost part of the zone. Podocarpidites libellus, Podocarpidites ecaenicus, Pityosporites alatus, and Pityosporites labdacus have their first occurrences directly below the base of the zone within the topmost samples in the underlying Interpollis velum-Labrapollis globosus Zone (Sample Stk.12–14). Disaccate pollen is common to abundant part of the assemblages from the Basopollis atumenscens Zone and this is in contrast to the underlying L. velum-L. globosus Zone. Zonalpollenites maximus occurs sporadically in the upper part of the Basopollis atumenscens Zone.

Deflandrea oceanfeldensis is increasingly abundant in the lower part of this zone. This acme interval of D. oceanfeldensis (>25% of total marine palynomorphs) is succeeded by a high relative abundance of Glaiphyrocysta spp. (Fig. 5).

Reference section. The Stolle Klint section, Fur, Denmark; the lower part of the Knudeklint Member in the Fur Formation.
Correlation and age. The spores and pollen zone is correlated to Schröders (1992) Zone 20 and Meyers (1988, 1989) zones SP4A/Wu3a (Figs 4–5). The first occurrence of Basopollis atumenscens is according to Krutzsch (1966) in the Eocene Pg. 10–11 Zone and this corresponds well with observations made in this study. The last occurrence of A. augustum directly below the base of the Basopollis atumenscens Zone indicates that this zone correlates to the lower part of the calcareous nannoplankton NP10 Zone (Fowell 1992). High abundances of Deflandrea oebisfeldensis have been recorded elsewhere from lower Eocene sediments in the North Sea area, but it is not a regional stratigraphic event (De Coninck 1993).

### Basopollis orthobasalis Zone

**Definition.** The base of this zone is defined as the first occurrence of Basopollis orthobasalis (Fig. 5). The top of the zone placed at the first occurrence of the index fossil Thomsonipollis magnificus.

**Characteristics.** Zonalapollenites maximus and Z. minimus have their first consistent occurrence in the lower part of this zone. The relative abundance of Inapertu pollenites spp. and Caryapollenites spp. increases in the middle to upper part of the zone (Fig. 5). Tricolpapollenites messeleensis has only been observed in the middle to lower part of the zone. The abundance of terrestrial palynomorphs decreases up through the interval from ca. 60% to <3% of the total amount of palynomorphs (Fig. 5). The uppermost part of the interval from samples S5k.50 to Syd.01 can not be characterised on the basis of spores and pollen, because dinoflagellate cysts dominate the palynological assemblages. Especially, Clamydocysta spp. dominate in the lower part of the interval, where this group comprises 25–70% of the palynomorphs. The relative abundance of D. oebisfeldensis is below 20% throughout this interval (Fig. 5).

**Reference section.** The Stolle Klint section, Fur, Denmark; the upper part of the Knudeklint Member and lower to middle part of the Siltrup Member.

Correlation and age. The first occurrence of the Basopollis orthobasalis is correlated to the Eocene Pg, zones 11–13a/b of Krutzsch (1966) or upper part of SP4a or SP4b lower/Wu3a-b zones of Meyer (1988, 1989). The terrestrial microflora from ash layer +62 to +118 is very sparse and shows little resemblance with the

**Remarks.** Roche (1983) used the last occurrence of *B. autumescens*, *B. basalis* and *B. orthobasalis* to define subzones within the Paleocene–Eocene transition in Belgium. *Basopollis autumescens* and *B. basalis* have their last occurrence at the top of lower Landénian (NP9) and *B. orthobasalis* has last occurrence at the top of upper Landénian (NP10) (Roche 1983).

**Thomsonipollis magnificus** Zone

**Definition.** The base of this zone is defined by the first occurrence of *Thomsonipollis magnificus*. The top of this zone was not observed in this study, but is tentatively placed at the last occurrences of *Thomsonipollis magnificus*.

**Characteristics.** Spores are relatively abundant, especially *Cicatricosisporites dorogensis*. *Inaperturopollenites* spp. is also abundant in this interval. *Deflandrea oebisfeldensis* is very abundant (>20% of the total marine flora) (Fig. 5). *Apectodinium parvum* and *A. quinquelatum* reappear in the *T. magnificus* Zone, but are a relatively rare part of the total marine microflora (0.5–1.5%) compared with the underlying *Apectodinium* acme interval within the *Interpollis velum* - *Labrapollis globosus* spores and pollen Zone. The marine microflora from the Silstrup Member has been correlated to the dinoflagellate cyst Zone 7 of Heilmann-Clausen (1985, 1994) and the *G. ordinata* Interval Biozone of Powell (1992).

**Reference section.** Silstrup Sydklint locality, Fur, Denmark; the uppermost part of the Silstrup Member. This spores and pollen zone may reach into overlying stratigraphically younger deposits and the top of the zone is only tentatively defined.

**Correlation and age.** The first occurrence of *T. magnificus* is used to define the base of Subzone Wu3b.

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**Fig. 5.** Stratigraphic range of selected spores and pollen species from the three Danish localities. The relative frequency of selected dinoflagellate cyst is shown as the relative abundance of the total number of marine algae counted. The position of the most distinct ash layers are indicated and the absolute thickness of the individual ash layer are schematic.
Changes in the marine palynomorphs assemblages

The dinoflagellate genus *Apectodinium* is very abundant from the top of the Stolle Klint Clay to the lowermost part of the Fur Formation i.e. the Knudekliint Member (samples Stk.01 to Stk.14) (Fig. 5). The last occurrence of the index fossil *Apectodinium augustum* is c. 0.5 m below ash layer –19b in the Fur Formation. This stratigraphic event coincides with a prominent drop in the abundance of *Apectodinium* spp.

The abundances of *Apectodinium quinquelatum* and *A. pavum* are relatively low in the Silstrup Member i.e. upper part of the Fur Formation (from above ash layer +114; sample Fir.15 to Fir.18 and sample Syd. 01 to Syd.10). Heilmann-Clausen (1982) did the same observation. Collinson et al. (2003) recorded abundance intervals of the genus *Apectodinium* in lower Eocene strata from the southern England. Crouch et al. (2001) also reported two intervals with relative high abundance *Apectodinium* spp. and concurrent increase in *Glaphyrocysta* spp. in the interval around ash layer –19b is succeeded relatively abruptly by *D. oebisfeldensis*. This change in the marine palynomorph assemblage takes place within a succession of 6 m in the Stolle Klint section (samples Stk.15 to Stk.24; Figs 3, 5). The relative abundance of *D. oebisfeldensis* varies and two intervals with dominance of *D. oebisfeldensis* are separated by an acme interval of *Glaphyrocysta* spp. (Fig. 5).

The most pronounced change in the marine microflora occurs around ash layer –19b, where the observed decrease in *Apectodinium* spp. and the concurrent increase in *D. oebisfeldensis* are distinct. Egger et al. (2000) recorded a similar Eocene acme interval of *Apectodinium* spp. from the Rhenodanubian Flysch at Anthering, near Salzburg, Austria. In the Rhenodanubian Flysch, as well as in the present study, the relative abundance of *Apectodinium* exceeds 60% of the total amount of dinoflagellate cysts. Regular occurrence of the species *Apectodinium augustum* is also restricted to the same interval as the acme of the genus *Apectodinium*. In the Fur Formation, the interval with abundant *Apectodinium* spp. is located below ash layer –19b, which is within the Knudekliint Member. The interval corresponds to the onset of the global dinoflagellate cyst event that has been observed at the Paleocene–Eocene thermal maximum (PETM) (Bujak & Brinkhuis 1998; Crouch et al. 2001, 2003).

In lower Eocene sediments from Denmark the bloom of *Apectodinium* spp. is succeed by an interval with abundant *Glaphyrocysta* spp., which is in contrast to the observations of Tawanui, New Zealand.
where a peak of *Glyphyrocysta* spp. precedes the first bloom of *Apectodinium* spp. at the Paleocene–Eocene thermal maximum (Crouch et al. 2001, 2003). Intervals with high relative abundance of *Apectodinium* spp. have been related to periods of lowered sea level by Thomas (1996), but Crouch et al. (2001, 2003) interpreted the bloom of dinoflagellate cyst assemblage in New Zealand as indication for a sea-level rise occurring at the Paleocene–Eocene thermal maximum (PETM). In the Fur Formation intervals of high relative abundance of the genus *Apectodinium* is not related to periods with relative higher abundance of terrestrial *versus* marine palynomorphs or changes in lithology.

Changes in the relative abundance of the species *Deflandrea oebisfeldensis* are related to local changes in the palaeogeography and palaeohydrography of the North Sea (de Coninck 1993). Furthermore, Buja & Brinkhuis (1998) interpreted the shift in the North Sea from the dominating *Apectodinium* spp. assemblage to the assemblage dominated by *D. oebisfeldensis* as a change from warmer to cooler surface water. Data from the diatoms assemblages in the Fur Formation suggest that an environmental shift takes place at ash layer ~20 and that the diatoms flora indicate relatively more shallow water conditions followed by a transgression in the upper part of the negative ash series (Mitlehner 1996).

**Summary**

The study of terrestrial microflora from the lower Eocene sediments in Denmark is based on 80 samples collected from the uppermost part of the Stolle Klint Clay and the Fur Formation. The examined samples come from three different coastal outcrops in the Limfjorden area i.e. Stolle Klint, Silstrup Firkanten and Silstrup Sydklint. The samples yield a record of excellent preserved early Eocene palynological assemblages. Several changes in both the terrestrial and marine microflora are used to subdivide the lower Eocene sediments into four spores and pollen zones: *Interpollis velum* - Labrapollis globosus, Basapolis atumenscens, Basapolis orthobasalis and Thomonapolis magnificus zones. The zones are correlated directly with the established tephrochronology and lithostratigraphy (Bøggild 1918; Gry 1940, 1965, 1979; Pedersen & Surlisky 1983; Heilmann-Clausen 1985, 1995; Nielsen & Heilmann-Clausen 1986; Beyer et al. 2001).

Figure 4 shows correlation of the four spores and pollen zones to the Palaeogene spores and pollen zonations in Europe. The range and relative abundance of key species of spores, pollen and dinoflagellate cysts are related to the tephrochronology, lithostratigraphy and other palynological zonations (Fig. 5). The two stratigraphically oldest spores and pollen zones, *Interpollis velum*-Labrapollis globosus and Basapolis atumenscens Zones, comprise the top of the Stolle Klint clay and the lower part of the Knudeklint Member in the Fur Formation. The overlying Basapolis orthobasalis Zone spans the upper part of the Knudeklint Member and the lower part of the Silstrup Member in the Fur Formation. The base of the youngest Thomonapolis magnificus Zone comprises the upper part of the Silstrup Member of the Fur Formation.

The most pronounced changes in both the terrestrial and marine microflora occurs in the interval around ~19b or at the top of the *Interpollis velum*-Labrapollis globosus Zone. This spores and pollen zone corresponds to the upper part of the dinoflagellate Zone 6 of Heilmann-Clausen (1985, 1994) or the *A. augustum* Interval Biozone of Powell (1992).

The terrestrial microflora from the *Interpollis velum*-Labrapollis globosus Zone is correlated to Zone 19.4 of Schröder (1992), Pg. Zone 9 of Krutzsch (1966) and the uppermost part of Meyers (1988, 1989) SP3/Wu2 zones (Figs. 4, 5). The stratigraphically youngest spores and pollen zones, Basapolis atumenscens, Basapolis orthobasalis and Thomonapolis magnificus zones corresponds to the dinoflagellate cyst zone *G. ordinata* Zone of Powell (1992) or Zone 7 of Heilmann-Clausen (1985, 1994). The microflora assemblages from the top of the *B. orthobasalis* Zone contain very few spores and pollen in relation to marine palynomorphs and this interval could therefore not be correlated to any of the established spores and pollen zonations shown in Figure 4. The top of the *B. orthobasalis* Zone is placed at the first occurrence of the index fossil *T. magnificus*. The Basapolis atumenscens and Basapolis orthobasalis zones are correlated to the following spores and pollen zones Pg. 10-12 of Krutzsch’s (1966) and SP4a/Wu3a zones of Meyers (1988, 1989) (Fig. 4). The youngest spores and pollen zone the Thomonapolis magnificus Zone, is correlated to Zone Pg. 13a of Krutzsch (1966) and SP4b/Wu36b/SP4b zones of Meyers (1989). The pollen Thomonapolis magnificus is recorded within the upper part of the dinoflagellate cyst Zone 7 of Heilmann-Clausen (1985, 1994) or *G. ordinata* Interval Biozone of Powell (1992).

The first occurrence of the pollen species *Zonalapollenites minimus* and *Z. maximus* is in the early Eocene. In North Europe the first occurrence of *Zonalapollenites minimus* and *Z. maximus* has previously been considered to be from the upper Eocene to Oligocene (Krutzsch 1966; Hochuli 1984).
The last occurrence of *Apectodinium augustum* has in the past been used to define the Paleocene–Eocene boundary in the North Sea Basin (Schröder 1992; Heilmann-Clausen 1994; Mudge & Bujak 1996). In the present study the last occurrence of *A. augustum* is ca. 5.2 meters above ash layer –33 (sample Stk.14) and according to the new definition of the Paleocene–Eocene boundary the last occurrence of *A. augustum* is now in the earliest Eocene (Beyer *et al.* 2001).

This study shows that species belonging to the pollen genus *Basapolis* are stratigraphically useful in the Danish lower Eocene sediments. This observation corresponds well with the Paleocene and Eocene strata from Belgium (Roche’s 1983), where the Normapolles group such as *Basapolis basalis*, *B. atumescens*, *B. orthobasalis*, *Interpolis supplingensis*, *Nudapolis endanguelatus*, *Plicapolis pseudoexselsis* contribute to determine the precise position of the Paleocene–Eocene boundary.

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Appendix I

(Species are listed alphabetically)

- Abiespollenites latissacatus (Trevisan 1967) Krutzsch 1971
- Anacolosites efflatus (Potonié 1934) Cookson & Pike 1954
- Arecipites eapapillosus Krutzsch 1977
- Bucalatisporites nanus subsp. robustus Krutzsch 1967
- Bucalatisporites primarius (Wolf 1934) Thomson & Pflug 1953
- Bucalatisporites quintites (Thomson & Pflug 1953) Krutzsch 1967
- Basapolis atumescens (Pflug 1953)
- Basapolis basalis Pflug 1953
- Basapolis orthobasalis (Pflug 1953) Pflug 1953
- Bombacacidites reticulatus Krutzsch 1961
- Brosipollis striatoborus (Krutzsch 1961) Krutzsch 1968
- Camarozonosporites camarozonosporites subsp. decorus (Wolf 1934) Krutzsch 1959
- Caryapollenites circulus (Pflug 1953) Krutzsch 1961
- Caryapollenites simplex (Potonié 1931) Potonié 1960
- Caryapollenites triangularis (Pflug 1953) Krutzsch 1961
- Cedripites lusaticus Krutzsch 1971
- Celtipollenites infrastructurus (Krutzsch & Vanhoorne 1977)
- Compositoapollenites medius Krutzsch & Vanhoorne 1977
- Compositoapollenites rhizophorus (Potonié 1934) Potonié 1960
- Conbaculatisporites trichopunctatus (Thiergart 1949) Klaus 1960
- Cricotricosporites doroagensis Potonié & Gellertich 1933
- Cricotricosporites sp. 1
- Cricotricosporites sp. 2
- Cyadipites microbucculatus Krutzsch 1970
- Emapollice pseudodmaenensis Krutzsch 1970
- Ephedripites spp.
- Ericipites callidus (Potonié 1931) Krutzsch 1970
- Extraphucipinotomites microtenuatus Krutzsch 1967
- Foveotriletes triangularis Krutzsch 1962
- Hydrosorpus levis Krutzsch 1962
- Ilexpollenites iliacus (Thiergart 1937) Potonié 1960
- Ilexpollenites marginatus (Potonié 1931) Thiergart 1937 ex. Inaperturopollenites concipitata (Wodehouse 1933) Krutzsch 1971
- Inaperturopollenites hiatus (Potonié 1931) Thomson & Pflug 1953
- Interpolis microsupplingensis (Pflug 1953) Krutzsch 1961
- Interpolis velum Krutzsch 1960
- Intrapitporpollenites microrectatus Mai 1961
- Intrapitporpollenites minimus Mai 1961
- Intrapitporpollenites pseudostructurus Mai 1961
- Ischyosporites foevaris Krutzsch 1967
- Ischyosporites microfoearis Krutzsch & Vanhoorne 1977
- Labaripollis globosus (Pflug 1953) Krutzsch 1968
- Larvigatosporites discordatus Pflug 1953
- Larvigatosporites gracilis Wilson & Webster 1946
- Larvigatosporites haardti subsp. haardti Krutzsch 1967
- Larvigatosporites haardti subsp. haardtiodes Krutzsch 1967
- Larvigatosporites nutidus subsp. nutidus (Mameza 1969) Krutzsch 1967
- Leiostrillices maxoides subsp. maxoides Krutzsch 1962
- Leiostrillices maxoides subsp. minoris Krutzsch 1962
- Leiostrillices sinuosoides Krutzsch 1959
- Leiostrillices trianguloides Krutzsch 1962
- Leiostrillices triangulos Krutzsch 1962
- Leiostrillices woffi subsp. woffi Krutzsch 1962
- Liriodendropollis semiverrucatus subsp. minor Krutzsch 1970
- Magnolipollis neogenicus subsp. minor Krutzsch 1970
- Magnolipollis neogenicus subsp. neogenicus Krutzsch 1970
- Mikrofossilostorites neogranuloides Krutzsch 1967
- Milfordia hungarica (Kedwa 1965) Krutzsch & Vanhoorne 1977
- Monocolpapollenites tranquillus (Potonié) Thomson & Pflug 1953
- Neogenipollis neogenicus Krutzsch 1962
- Neogenipollis plicatoides Krutzsch 1962
- Neogenipollis pseudonoddeni Krutzsch 1962
- Nudapolis endanguelatus Pflug 1953
- Nudapolis terminalis subsp. hastatiforimens Pflug 1953
- Nupharipollenes sp. 1 Mohr 1984
- Nupharipollenes sp. 2 Potonié 1934
- Nyssapollenites kruschi subsp. analepticus (Potonié 1934) Nagy 1969
- Pentapollenes pentagulas (Pflug 1953) Krutzsch 1958
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