Age of Tertiary formations on Spitsbergen

SVEIN B. MANUM AND TORBJØRN THRONDSEN

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Biostratigraphic evidence for the age of Tertiary formations on Spitsbergen is critically reviewed and new evidence from dinoflagellates is presented. The shift in basin geometry and sediment source area observed in the Gilsonryggen Formation is dated as latest Palaeocene, coinciding with the initial opening of the Norwegian Sea at anomaly 24–25 time. An Upper Eocene age is proposed for sediments from Forlandsundet (Sarsbukta), indicating that the Forlandsundet graben was created during the phase of shear movement between Greenland and Spitsbergen before anomaly 13 time.

Svein B. Manum, Department of Geology, University of Oslo, P.O. Box 1047, Blindern, N-0316 Oslo 3, Norway; Torbjørn Throndsen, Institute for Energy Technology, P.O. Box 40, N-2007 Kjeller, Norway;

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Tertiary sediments cover the greater part of Spitsbergen south of Isfjorden (Fig. 1). They are preserved in a north–south trending trough with an estimated maximum thickness exceeding 2300 metres (Harland et al. 1976). Lithostratigraphically they are divided into six formations (Major & Nagy 1972), starting with deltaic coal-bearing strata resting unconformably on late Lower Cretaceous sediments (Fig. 2). The succession continues through shallow marine deposits followed by deeper marine sediments and ends with massive deltaic sandstones including some coals (Steel et al. 1981). There is evidence from vitrinite reflectance studies that approximately 1500–2000 metres of sediments have overlain the presently preserved formations (Manum & Throndsen 1978).

Outside and to the west of the central basin of Mesozoic and Tertiary sediments, there are four small areas with Tertiary rocks preserved: Forlandsundet, Ny Ålesund, Renardodden, and Øyrlandet. Opinions vary considerably with regard to the correlation of these isolated outcrops with the formations of the central basin.

The age of the sediments has been recognized as Tertiary ever since the rich angiosperm floras of the basal and top formations of the central basin (and also of some of the isolated areas) were first discovered (Heer 1868, 1870, 1876; Nathorst 1910). However, more precise age determinations for these formations have remained controversial to the present day. The main reason for this is the poor yield of biostratigraphically diagnostic marine fossils in spite of impressive field and laboratory efforts by many scientists for more than a century.

There is now a greater need than ever before to solve the age problem of the Spitsbergen Tertiary. Recent attempts to correlate the observed changes in depositional environments with the established plate-tectonic events in the area suffer from lack of precise age determinations for the sediments (Steel et al. 1986). Moreover, the Tertiary events and the geology of Spitsbergen on the whole have recently attracted renewed interest because of Spitsbergen's key role as reference area for the off-shore geology of the Barents Sea.

In this paper we offer firstly a review of the status regarding the dating of the Tertiary formations, and secondly we present the results of our own efforts over more than a decade to establish a better biostratigraphy based on marine palynomorphs.

Material and Methods

Sample locations

Locality numbers used below refer to Fig. 1.

Gilsonryggen Formation. – Soft, yellow weathering clay, probably an ash-layer, collected by T. Throndsen 30 metres above the base of the formation at Nordenskiøldfjellet (loc. 1).

Similar lithology, collected in Grøndalen, 1 km

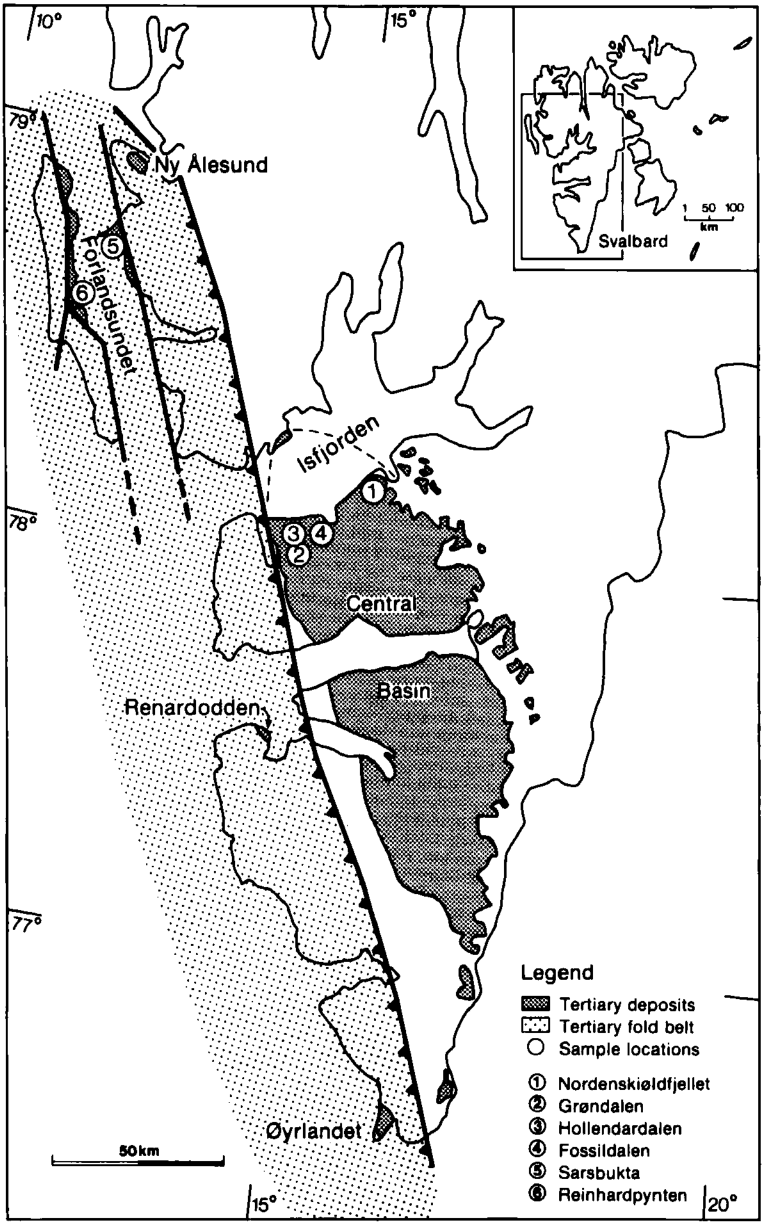

Fig. 1. Tertiary outcrops on Spitsbergen and position of sampling localities.

east of Bøhmdalen at 180 metres above sea level, by a field group from the University of Kiel in 1983 (Kiel sample No. SP83-V31/1; loc. 2).

Sarkofagen Formation. – Soft clay collected in Hollendardalen at 155 metres above sea level in the tributary from Häggbreen by a field group from the University of Kiel 1983 (Kiel sample No. SP83-V17/2; loc. 3).

Transition Sarkofagen–Gilsonryggen Formations. – Soft, yellow weathering clay collected in Grøndalen, at 140 metres above sea level in a northern tributary from Fossilfjellet, by a field group from the University of Kiel 1983 (Kiel sample Nos. SP83-106, 118, 120, 119; loc. 2).

Basilika Formation. – Calcareous nodules collected by Dr. D. E. Russel in Fossildalen (loc. 4).

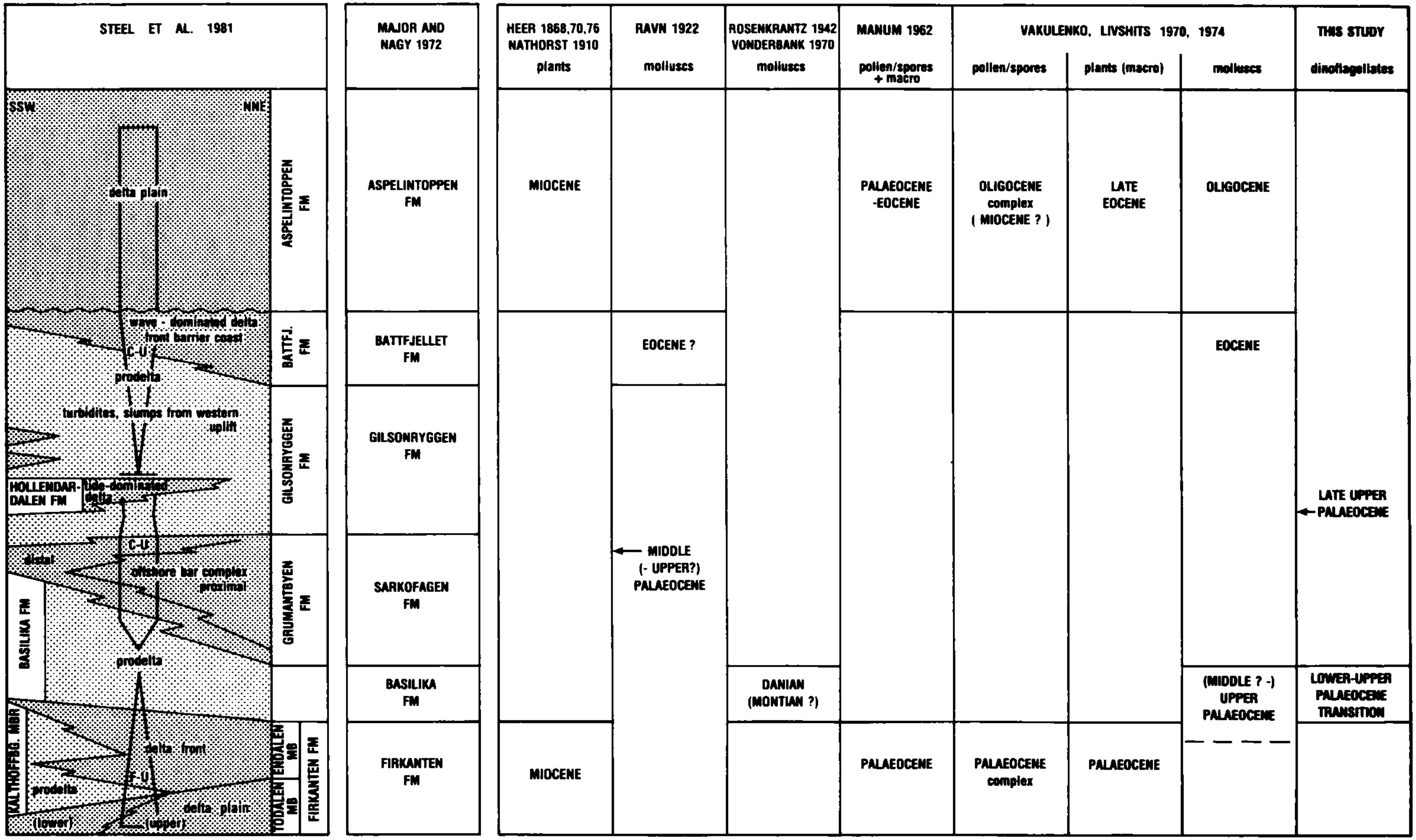

Fig. 2. Lithostratigraphy, depositional environments and biostratigraphic evidence for ages of the central basin Tertiary sequence on Spitsbergen.

Forlandsundet. - Micaceous clay from Sarsbukta, collected by R. W. Feyling-Hanssen (F.-H-sample Nos. 248 and 260, locality description in Feyling-Hanssen & Ulleberg 1984); samples from same locality collected by T. Throndsen (loc. 5).

Reinhardpynten. – Black shale samples collected by T. Throndsen (loc. 6).

Laboratory treatment

Standard palynological processing, using hydrochloric and hydrofluoric acids to dissolve mineral components, was used. Oxidation was occasionally used to remove pyrite and to clear the residue of amorphous matter.

Sample productivity and palynomorph preservation

Our search for marine palynomorphs that could aid the dating of the Tertiary sequence has been going on since the first dinoflagellates were discovered in these sediments (Manum 1960, Sarsbukta loc. 5). Hundreds of samples have been processed, although mostly with disappointing results. If samples were at all productive, preservation was usually too poor to allow identifications of stratigraphic significance. Only a few samples have yielded diagnostic palynomorphs, and the present paper aims at documenting the most reliable records of dinoflagellates that we have been able to make so far.

The most useful palynological samples from the central basin have been collected from relatively thin and soft, usually yellowish weathering clay beds. They are apparently of volcanic ash origin (Dypvik & Nagy 1979). Ash deposition appears to have provided an environment that has been less destructive to palynomorphs. However, also in such samples preservation is highly variable. A typical degradation feature is a bubble-like structure which severely distorts the fossils' original morphology. Dinoflagellates have also been obtained from calcareous nodules of the Basilika Formation; these apparently have suffered little compression, indicating that the nodules were formed prior to compaction of the sediments. Specimens from this lithology, however, appear to have thinner walls than normal for the species present, and fragmentation is common.

In the samples from Sarsbukta – one of the localities outside the central basin – the preservation is considerably better and compression is negligible. The palynomorph productivity, however, is not particularly high and only a few specimens have been found of most of the species recorded. On the other hand, some of the samples from the central basin are quite productive, but even in the richer ones well preserved specimens are not very common. The fossils are often highly compressed and folded and otherwise degraded.

Previous age determinations

No radiometric age determinations for the Spitsbergen Tertiary exist so far. Biostratigraphic correlations can be made only with sequences that occur at considerably lower latitudes. While making such correlations one always assumes that the biostratigraphic criteria are valid over great palaeo-latitudinal spans. However, existing discrepancies between ages proposed by various authors for the Spitsbergen Tertiary indicate that the criteria are not always reliable. The inconsistencies are particularly noticeable for ages based on terrestrial floras. However, there are also problems with marine fossils; this is clearly demonstrated by our results from Forlandsundet which differ from previous conclusions based on foraminifera.

The lithostratigraphic terminology proposed by Major & Nagy (1972) for sediments of the central basin has been adopted in this paper. Correlation to other lithostratigraphic schemes for the same sediments poses no serious problem, and we refer the reader to the correlation table in Major & Nagy (1972, p. 22).

The central basin (Fig. 2)

Heer (1868, 1870, 1876) described rich floras from the basal and topmost formations (Firkanten and Aspelintoppen respectively) which he assigned to the Miocene because of their similarity to Swiss Miocene floras which he knew well. This age was also adopted by the Swedish explorer, geologist and palaeobotanist A. G. Nathorst in the first comprehensive monograph on the geology of the Svalbard archipelago to which Spitsbergen belongs (Nathorst 1910).

The concept of a Miocene age remained unchallenged until Ravn (1922) proposed a Palaeocene to Eocene age for the lower parts of the sequence based on marine and fresh-water molluscs, particularly from the Sarkofagen and Battfjellet Formations. In spite of the fact that Ravn expressed considerable reservation with regard to his age indications, mainly because of the poor quality of his specimens, his conclusion quickly replaced the palaeobotanically founded concept of a Miocene age for the sequence. Ravn's determination of 'a Middle Palaeocene or perhaps Upper Palaeocene age' for the Sarkofagen Formation was based on the identification of a single bivalve species, *Cyrena (Corbicula) angustidens*, which allowed him to make comparisons with identifications from the Palaeogene of France and Belgium. Other fossils from the Sarkofagen Formation could only be referred to the generic level or else to a new taxon. The fossils from the Battfjellet Formation were even more difficult to determine, and Ravn indicated an Eocene age with great reservations. It needs mentioning here that the stratigraphic significance of Ravn's identification of *Corbicula angustidens* has subsequently been played down considerably by Vonderbank (1970, p. 100). The study by Ravn (1922) offers a good example of the problems that palaeontologists and biostratigraphers have faced in the Spitsbergen Tertiary. Owing to poor preservation it becomes difficult to take identifications further than to the generic level, and when species can be distinguished, they are often described as new taxa. Obviously, this provides a poor basis for stratigraphic conclusions, and these therefore tend to lack precision.

Vonderbank (1970) studied extensive collections of foraminifera, molluscs, and crustaceans from several formations, but he was also severely limited in his taxonomic and stratigraphic conclusions by unsatisfactory preservation. Only 30 of the 72 taxa of foraminifera listed by Vonderbank were identified to known species, and these were of little stratigraphic significance. The crustacean remains were referred to a new species, as yet endemic. The biostratigraphically most significant among Vonderbank's identifications is one bivalve (*Modiolus hauniensis*) and two gastropod species (*Cylichna discifera* and *Chenopus gracilis*) from the Basilika Formation (based on fragmented or otherwise damaged specimens). These species occur in the Danian in Denmark ('Faxekalk'), and on this basis Vonderbank proposed a Danian age for the Basilika Formation. This age agrees with a suggestion made earlier by Rosenkrantz (1942) based on the find of the bivalve *Thyasira (Conchocele) conradii* in the Basilika Formation, a species which has been recorded in Greenland in strata referred to the Danian.

Palynological studies by Manum (1962), particularly of pollen and spores from coals in the basal and topmost units, offered no more precise age determinations than those of Ravn (1922). They appear, however, to support a Palaeocene to Eocene age for the entire sequence. The macro- as well as microfloras of the basal and the topmost units were not seen to be significantly different, suggesting that they are not of widely different ages.

In more recent years, Soviet scientists (Vakulenko & Livshits 1971; Livshits 1974) have contributed considerably to the palaeontology of the Spitsbergen Tertiary. Vakulenko & Livshits (1971) identified pollen and spores from all formations except the Basilika Formation, and a correlation to Soviet Arctic Tertiary was made on the basis of identifications of spore/pollen 'complexes'. A Palaeocene complex was identified in the Firkanten Formation, an Oligocene or possibly even Miocene complex was reported for the Aspelintoppen Formation, and Eocene was indicated for the intervening units. However, Vakulenko & Livshits (loc. cit.) were also constrained in their conclusions by poor preservation of the palynomorphs. This is reflected by the fact that out of more than 50 recorded pollen and spore taxa, only six were identified beyond the generic level. They also stated that the differences between the three identified complexes were not very pronounced. Their Oligocene or possibly Miocene age for the youngest formation was based on the somewhat impoverished palynoflora recovered from it. However, Manum (1962) concluded that there appeared to be no biostratigraphically significant differences between the macrofloras of the youngest and oldest units. The reduced palynoflora noticed in the youngest unit by Vakulenko & Livshits (loc. cit.) may well reflect different preservational and depositional conditions rather than real differences in the flora.

Livshits (1974) also reported the results of studies of plant macrofossils and of molluscs on the basis of which a Palaeocene age was indicated for the Firkanten Formation. For the Aspelintoppen Formation, the molluscs, identified only to generic level, were considered to indicate an Oligocene age; the plants, on the other hand, were

LOCALITY \ AUTHOR	MANUM 1960	FEYLING-HANSSEN & ULLEBERG 1984	LIVSHITS 1974	THIEDIG & al. 1980	HEAD 1984	THIS STUDY
FORLANDSUNDET (SARSBUKTA)	EOCENE/ OLIGOCENE dinoflagellates	MIDDLE/ UPPER OLIGOCENE foraminifera	UPPER EOCENE proposed correlation with Gilsonryggen Fm.			UPPER EOCENE dinoflagellates
RENARDODDEN			OLIGOCENE ? proposed correlation with Aspelintoppen Fm.	proposed correlation with Firkanten Fm. molluscs	UPPER EOCENE / LOWER OLIGOCENE dinoflagellates	
NY ÅLESUND						

Fig. 3. Stratigraphic assignments for Tertiary outcrops outside the central basin (only papers presenting new biostratigraphic evidence have been included).

considered to indicate an age no younger than late Eocene.

Thus, to summarize the biostratigraphic status for the formations of the central basin, an early Tertiary age (Danian/Palaeocene) appears to be generally well agreed upon for the two oldest formations. For the youngest formations, however, the age indications range from Eocene to Oligocene, and possibly even Miocene; for the intervening formations evidence is indeed vague or lacking.

Areas outside the central basin (Fig. 3)

Plant macrofossils are common and coal seams occur at the Bellsund locality (Renardodden) and in the Ny Ålesund (Kings Bay) area. The floras do not seem to differ significantly from those found in the basal and topmost formations of the central basin. Unfortunately, they are of very little biostratigraphic value.

Renardodden. – Heer (1876) and subsequently Nathorst (1910) found the flora from Renardodden to be most similar to that of the Aspelintoppen Formation of the central basin. Livshits (1974) arrived at a similar conclusion based on the pollen and spores recovered from the sequence and proposed an Oligocene age. More recently, Head (1984) indicated a Late Eocene to Early Oligocene age based on dinoflagellates, which would also appear to support a correlation with the uppermost plant-bearing formation of the central basin (the Aspelintoppen Formation) rather than with the basal formation. (Head listed among others the following dinoflagellates: *Areosphaeridium arcuatum, A. diktyoplokus, Ceratiopsis depressa, Cordosphaeridium funiculatum, Corrudinium incompositum, Deflandrea spinulosa, Glaphyrocysta semitecta, 'Millioudodinium' giuseppei, Phthanoperidinium comatum, P. echinatum, P. geminatum, Wetzeliella articulata, W. ovalis,* and *W. symmetrica.*) Thiedig et al. (1980), on the other hand, considered a correlation with the lower parts of the central basin more likely, based on their finding of *Conchocele conradii*, a mollusc species first reported by Rosenkrantz (1942) in the Basilika Formation (cf. the discussion above of Vonderbank's study on this formation). In view of the available evidence, we would tend to favour Head's dinoflagellate-based correlation of the Renardodden sequence rather than rely on a single mollusc species whose range appears uncertain.

Ny Ålesund. – The Tertiary sequence of the Ny Ålesund area is generally considered to be a northerly extension of the central basin (Hjelle & Lauritzen 1982). However, there is no other biostratigraphic evidence available than the terrestrial flora, which is inconclusive. Vakulenko & Livshits (1971) correlated the sequence with the Aspelintoppen Formation without offering new biostratigraphic evidence.

Sarsbukta. – Manum (1960) reported the first find of dinoflagellates in the Spitsbergen Tertiary from the Sarsbukta locality at Forlandsundet; these were indicative of an Eocene to Oligocene age. The preservation of palynomorphs at this locality was found to be better than in the formations of the central basin, and a few plant taxa were recorded which were unknown from the central basin (e.g. *Tsuga*, Manum 1962). Recently, Feyling-Hanssen & Ulleberg (1984) reported foraminifera in Tertiary samples from Sarsbukta. They concluded that the sequence is 'most probably Middle to Upper Oligocene in age' (op. cit. p. 83). The same sequence was proposed by Livshits (1974) to be of Upper Eocene age and to correlate with the Gilsonryggen Formation, based on a combination of faunistic and floristic evidences, although not particularly decisive.

Øyrlandet. – No biostratigraphic evidence is available from this locality.

Dinoflagellates

Dinoflagellate taxa are listed below in alphabetical order. The nomenclature follows Lentin & Williams (1985) and we also refer to their list of references for author citations.

Division *Pyrrhophyta*
Class *Dinophyceae*
Order *Peridiniales*

Apectodinium Costa & Downie

Apectodinium augustum (Harland) L. & W.
Pl. 1, Figs. 1–6; Pl. 2, Fig. 1

This species forms a conspicuous component of samples from the Gilsonryggen Formation. Individuals present a range in variability much like that observed by Harland (1979). Some specimens show finer processes than the typical *A. augustum* (Pl. 1, Fig. 6 and Pl. 2, Fig. 1, the latter appears to approach *A. paniculatum*).

Spitsbergen record. – Gilsonryggen Fm., localities 1, 2.

Stratigraphic range. – Latest Palaeocene, NP9 equivalent (Harland 1979; Costa & Downie 1979b: Into NP10).

Apectodinium homomorphum (Deflandre & Cookson) L. & W.
Pl. 2, Fig. 2.

Specimens corresponding to the illustrations in Harland (1979, Pl. 1, Figs. 1–8) are recorded under this species. However, there appears to be a range of variability present (e.g. Pl. 2, Fig. 6), corresponding to the range in morphology exhibited by the *A. homomorphum–A. sumissum–A. quinquelatum* group of species (cf. Harland 1979).

Spitsbergen record. – Gilsonryggen Fm., locality 2.

Stratigraphic range. – Latest Palaeocene to Lower Oligocene (Harland 1979; Costa & Downie 1979b: To Middle Oligocene).

Apectodinium cf. *A. quinquelatum* (W. & D.) Costa & Downie
Pl. 2, Figs. 3–5

A distinctive group of specimens comes close to *A. quinquelatum* sensu Harland (1979, p. 67), except for their more prominent apical horn, which may place them somewhere between that species and *A. sumissum* (Harland) L. & W. Resemblance to cysts identified as *Wetzeliella (Apectodinium) hyperacantha* in Costa & Downie (1976, Pl. 92, Fig. 6), cf. that species by Harland (1979, Pl. 2, Fig. 19), is also exhibited in this group.

Spitsbergen record. – Sarkofagen and Gilsonryggen Fms., localities 2, 3.

Stratigraphic range. – *A. quinquelatum*: From latest Palaeocene to Lower Eocene, NP9–NP13 equivalent according to Harland (1979), extending into Upper Eocene according to Costa & Downie (1979b).

Cribroperidinium Neale & Sarjeant

Cribroperidinium giuseppei (Morgenroth) Helenes
Pl. 2, Figs. 7–8

Spitsbergen record. – Forlandsundet, locality 5.

Stratigraphic range – Eocene, top in NP19 equivalent strata (Williams & Bujak 1985); London

Clay through Barton Beds, southern England (Bujak et al. 1980).

Deflandrea Eisenack

Nomenclatural note. – Of the species recorded below, *D. dartmooria* and *D. striata* belong to a group which formerly has been separated from *Deflandrea* and placed under *Ceratiopsis* Vozzhennikova, likewise in Lentin & Williams (1985). However, Lindgren (1984, p. 154) pointed out that the latter name is a junior homonym of a genus of fungi, *Ceratiopsis* De Wilde. The reattribution here to *Deflandrea* therefore represents a deviation from Lentin & Williams (1985).

Deflandrea dartmooria Cookson & Eisenack
Pl. 3, Figs. 1–2

Spitsbergen record. – Basilika Fm., locality 4.

Stratigraphic range. – Upper Palaeocene to Lower Eocene, NP4–NP13 equivalent (Williams & Bujak 1985); North Sea: Upper Palaeocene–basal Lower Eocene (Ioakim 1979).

Deflandrea heterophlycta Deflandre & Cookson sensu Gocht
Pl. 4, Figs. 1, 3–4

☐1960 *Deflandrea phosphoritica* Eisenack: Manum, p. 18, Figs. 4–6, text-fig. 1. ☐1969 *Deflandrea* cf. *heterophlycta* Deflandre & Cookson: Gocht, p. 11, text-fig. 4. ☐1980 *Deflandrea* cf. *D. heterophlycta* Deflandre & Cookson sensu Gocht: Bujak, in Bujak et al., p. 50, Pl. 15, Fig. 4.

This form, which is characterized by a denticulate periphragm in a more or less clearly penitabular pattern and a warty endophragm, matches closely the Oligocene form referred to as *D.* cf. *heterophlycta* by Gocht (1969). Subsequently, Bujak (in Bujak et al. 1980, p. 50) recorded the same form in the Barton Beds of southern England. (Bujak listed the Spitsbergen form illustrated by Manum (1960) under *D. spinulosa* synonymy, but according to our present identification it should be assigned to *D. heterophlycta* sensu Gocht.)

Spitsbergen record. – Forlandsundet, locality 5.

Stratigraphic range. – Barton Beds, southern England (Bujak et al. 1980; Middle Eocene, NP16–17 equivalent acc. to Williams & Bujak 1985); Middle Oligocene, Germany (Gocht 1969). Williams & Bujak (1985) give the range of *D. heterophlycta* as Middle Palaeocene through Oligocene, NP16–NP25 equivalent.

Deflandrea oebisfeldensis Alberti
Pl. 3, Figs. 3–4

Spitsbergen record. – Gilsonryggen Fm., locality 2.

Stratigraphic range. – Upper Palaeocene to Lower Eocene, NP7–NP12 equivalent (Williams & Bujak 1985); North Sea and Labrador: Palaeocene to Lower Eocene (Ioakim 1979).

Deflandrea striata Drugg
Pl. 3, Figs. 5–7

Spitsbergen record. – Basilika Fm., locality 4.

Stratigraphic range. – Offshore eastern Canada: Maastrichtian – Lower Palaeocene (Williams & Bujak 1977); Denmark: Danian – Lower Selandian (Heilmann-Clausen 1985); Switzerland: Danian – Lowermost Thanetian (Jan du Chêne 1977); North Sea and Labrador: Lower Palaeocene (Danian) (Ioakim 1979).

Diphyes Cookson

Diphyes colligerum (Deflandre & Cookson) Cookson
Pl. 2, Fig. 9

Spitsbergen record. – Gilsonryggen Fm., locality 1.

Stratigraphic range. – Eocene (Williams & Bujak 1985); North Sea and Labrador: Lower Eocene (Ioakim 1979); southern England: London Clay through Barton Beds (Bujak et al. 1980); Denmark: Danian – Lower Ypresian (Heilmann-Clausen 1985).

Fibrocysta Stover & Evitt

Fibrocysta axialis (Eisenack) Stover & Evitt
Pl. 2, Fig. 10

Spitsbergen record. – Gilsonryggen Fm., locality 1.

Stratigraphic range. – Lower Eocene to Lower Oligocene (Williams & Bujak 1985); North Sea: L. Eocene–L. Oligocene (Ioakim 1979); southern England: London Clay through Barton Beds (Bujak et al. 1980).

Glaphyrocysta Stover & Evitt

Glaphyrocysta exuberans (Defl. & Cooks.) Stover & Evitt
Pl. 6, Figs. 2–3

This species is a common and conspicuous element in the assemblage from the Gilsonryggen Formation.

Spitsbergen record. – Gilsonryggen Fm., locality 2.

Stratigraphic range. – From the Upper Palaeocene (Pyrenees, Caro 1973; offshore eastern Canada, Williams & Bujak 1977; Labrador, Ioakim 1979) to Upper Eocene (S. England, Eaton 1976; off-shore eastern Canada, Williams & Bujak 1977).

Kisselovia Vozzhennikova

Kisselovia crassoramosa (Williams & Downie) Damassa
Pl. 4, Fig. 8

The figured specimen does not exhibit the general shape well because of folding. However, the processes with trabeculae characteristic of this species are well shown.

Spitsbergen record. – Forlandsundet, locality 5.

Stratigraphic range. – Lower Eocene (London Clay, S. England, Williams & Downie 1966; N. Germany, *W. meckelfeldensis* zone, Costa & Downie 1976; Labrador, Ioakim 1979); Upper Eocene (offshore eastern Canada, Williams & Bujak 1977).

Lentinia Bujak

Lentinia serrata Bujak
Pl. 5, Figs. 1–3

Spitsbergen record. – Gilsonryggen Fm., locality 1; Forlandsundet, locality 5.

Stratigraphic range. – Late Middle Eocene to Lower Oligocene, NP16/17-NP23 equivalent (Williams & Bujak 1985); Barton Beds, S. England (Bujak et al. 1980).

Lentinia wetzelii (Morgenroth) Bujak
Pl. 5, Figs. 4–6

Spitsbergen record. – Gilsonryggen Fm., locality 1.

Stratigraphic range. – London Clay and Bracklesham Beds, S. England (Bujak et al. 1980; Lower Eocene–early Middle Eocene acc. to Williams & Bujak 1985).

Lentinia sp./*Spinidinium* sp.
Pl. 5, Figs. 7–9

Some specimens with wide archeopyles differ from *L. serrata* in their shape and development of horns (Figs. 7, 8); others appear to be more related to *Spinidinium* (Fig. 9).

Spitsbergen record. – Gilsonryggen Fm., locality 1.

Palaeoperidinium Deflandre

Palaeoperidinium pyrophorum (Ehrenberg) Sarjeant
Pl. 6, Figs. 5–6

The specimens appear to be smaller than usual for this species.

Spitsbergen record. – Basilika Fm., locality 4.

Stratigraphic range. – Campanian to Upper Palaeocene, top in NP8 equivalent strata (Williams & Bujak 1985).

? Palaeoperidinium sp.
Pl. 6, Figs. 7–9

Identification of this *Palaeoperidinium*-like form is uncertain because it lacks distinct ornamentation, and the archeopyle has not been observed.

Spitsbergen record. – Gilsonryggen Fm., locality 1.

Phthanoperidinium Drugg & Loeblich

Phthanoperidinium echinatum Eaton
Pl. 4, Figs. 5–7

Epicyst of illustrated specimen distorted. However, the characteristic parasutural double line of pin-like projections is shown.

Spitsbergen record. – Forlandsundet, locality 5.

Stratigraphic range. – Lower Eocene to Lower Oligocene (Williams & Bujak 1985); Bracklesham Beds to Barton Beds 3, S. England (Bujak et al. 1980; NP14–NP17 equivalent acc. to Williams & Bujak 1985); Norwegian Sea and North Sea: Middle and Upper Eocene (Manum 1976 and Ioakim 1979 respectively).

Selenopemphix Benedek

Selenopemphix nephroides Benedek
Pl. 5, Fig. 10

Spitsbergen record. – Forlandsundet, locality 5.

Stratigraphic range. – Late Middle Eocene to Upper Miocene, NP16–NN11 equivalent (Williams & Bujak 1985); Germany: Middle to Upper Oligocene (Benedek 1972); S. England: Barton Beds (Bujak et al. 1980, NP16/17 equivalent acc. to Williams & Bujak 1985).

Svalbardella Manum

Svalbardella cooksoniae Manum
Pl. 5, Figs. 11–15

The figured specimens show some of the variability exhibited by this species; they are all from the type material. For comparison one specimen from Upper Eocene sediments of the Norwegian Sea (DSDP Leg 38) is shown in Pl. 4, Fig. 1.

Spitsbergen record. – Forlandsundet, locality 5.

Stratigraphic range. – North Sea: Middle Eocene to Lower Oligocene (Ioakim 1979); Norwegian Sea: Upper Eocene (Johnsen 1981; Elde 1985).

Thalassiphora Eisenack & Gocht

Thalassiphora pelagica (Eisenack) Eisenack & Gocht
Pl. 6, Fig. 4

Spitsbergen record. – Forlandsundet, locality 5.

Stratigraphic range. – Maastrichtian to Lower Oligocene (Williams & Bujak 1985); Norwegian Sea and Rockall Plateau: Eocene (Manum 1976; Costa & Downie 1979a; North Sea: Lower Eocene to Lower Miocene (Ioakim 1979).

Turbiosphaera Archangelsky

Turbiosphaera cf. *T. filosa* Archangelsky
Pl. 6, Fig. 1

Preservation does not permit a definitive identification.

Spitsbergen record. – Gilsonryggen Fm., locality 2.

Stratigraphic range. – (For *T. filosa*) Maastrichtian to Middle Eocene (Williams & Bujak 1985).

Discussion

The recorded dinoflagellates are listed in Fig. 4, together with their stratigraphic ranges, forming a basis for discussion of the age of the individual formations.

Basilika Formation: Lower/Upper Palaeocene transition

Only *Deflandrea dartmooria, D. striata* and *Palaeoperidinium pyrophorum* have been identified from the Basilika Formation. Based on their known ranges we can only propose an age near the Lower to Upper Palaeocene transition. Thus, there is a fair amount of agreement with Rosenkrantz (1942) and Vonderbank (1970) who indicated a Danian age, and also with the (Middle?-) Upper Palaeocene age based on molluscs by Livshits (1974).

Sarkofagen Formation: Late Upper Palaeocene

In the upper part of this formation we have observed *Apectodinium*. For discussion of the age, see below under Gilsonryggen Formation.

Gilsonryggen Formation: Late Upper Palaeocene

A varied assemblage of *Apectodinium* species was recovered from apparent ash layers in this for-

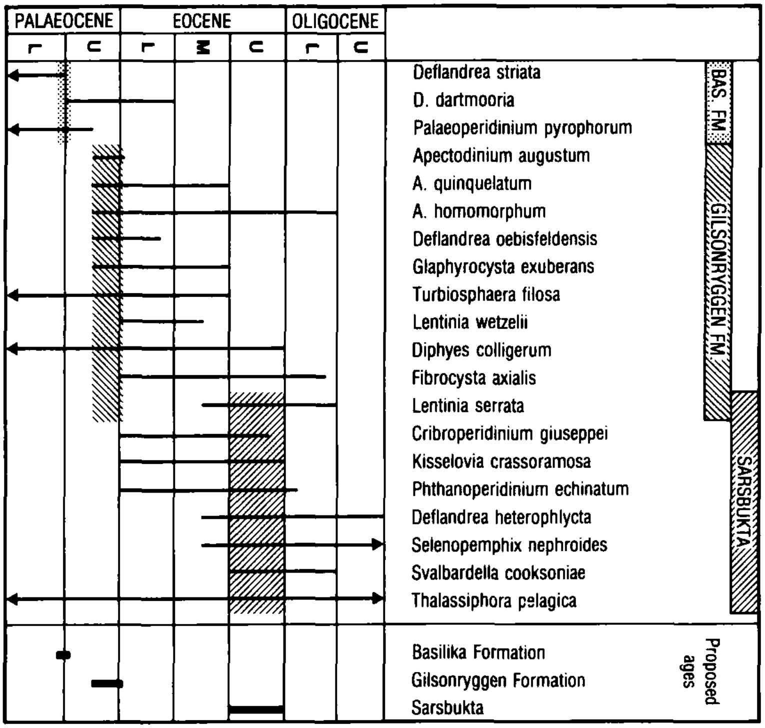

Fig. 4. Stratigraphic ranges for the recorded dinoflagellate species and proposed ages for the studied formations.

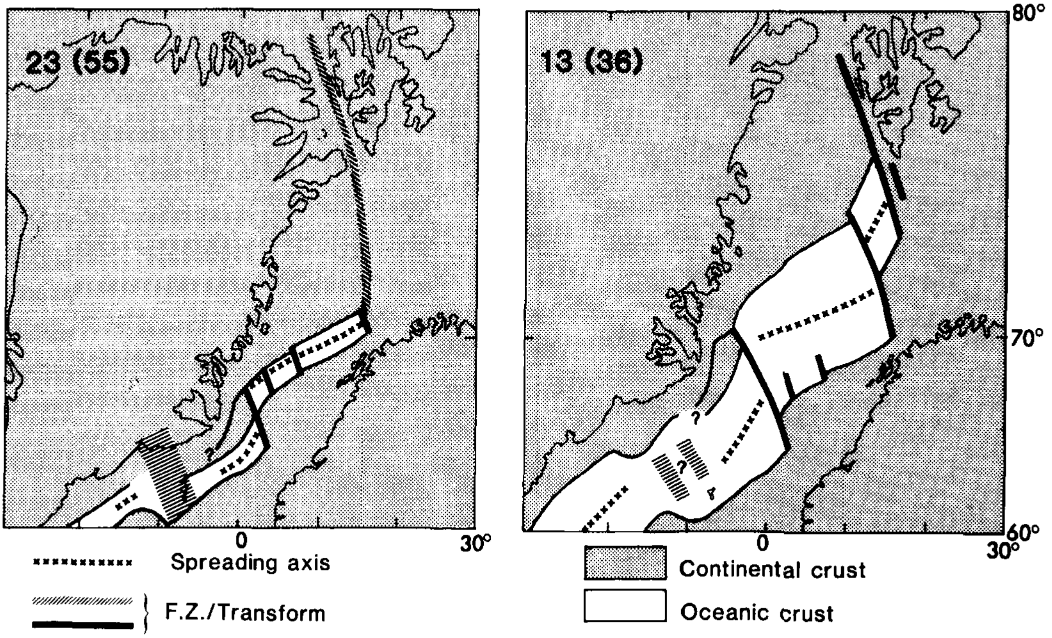

Fig. 5. Early stages in the plate tectonic evolution of the Norwegian Sea at anomaly 23 and 13 time (55 and 36 million years ago, respectively; from Eldholm et al. 1984).

mation. Particular attention is drawn to *Apectodinium augustum* which has a narrow stratigraphic range in Northwest Europe and the North Sea, restricted to the later part of the Upper Palaeocene (equivalent to NP9–10 strata). In addition, the assemblage presents a wide range of morphological variations corresponding to the '*Wetzeliella (Apectodinium) homomorphum* plexus' described by Harland (1979). This complex of morphotypes is characteristic of the *Apectodinium hyperacanthum* zone (= *W. hyperacantha* zone) of Costa & Downie (1976, text-fig. 5; 1979b). In NW Europe it is equivalent to NP9 and earliest NP10. The first appearance of *Apectodinium* in NW Europe is in strata equivalent to NP9 (Harland 1979). On the basis of this *Apectodinium* association we assign the Gilsonryggen Formation and also the upper part of the Sarkofagen Formation to late Upper Palaeocene.

Forlandsundet (Sarsbukta): Upper Eocene

The identifications of *Cribroperidinium giuseppei* and *Kisselovia crassoramosa* indicate that the Sarsbukta sediments are no younger than the Upper Eocene. The possibility of a somewhat greater age cannot be excluded, since most of the recorded species range down into Middle and Lower Eocene. However, we base the assignment to Upper Eocene on the presence of *Svalbardella cooksoniae*, which does not appear to range down into Middle Eocene. It is worth noting that all the recorded species occur in the Barton Beds (Upper Eocene) of southern England (Bujak et al. 1980). Our conclusion is at variance with that of Feyling-Hanssen & Ulleberg (1984: M.-U. Oligocene) but supports the more loosely founded Upper Eocene age proposed for the Sarsbukta sequence by Livshits (1974). Consequently, Livshits' proposed correlation with the Gilsonryggen Formation of the central basin cannot be supported.

Geological Synthesis

The Tertiary basin in Spitsbergen is situated close to the margin of the Barents Sea plate, and its development is clearly controlled by the plate tectonic events which led to the formation of the Norwegian–Greenland Sea and the connection between the North Atlantic and the Arctic Oceans (Fig. 5). The opening of the Norwegian Sea started at anomaly 24–25 time in the latest Palaeocene to earliest Eocene according to Palmer (1983). In Fig. 6 we have presented a time-stratigraphic correlation between the Tertiary deposits in the central basin, Forlandsundet (Sarsbukta), Renardodden, and plate tectonic events in the Norwegian–Greenland Sea.

The central basin

The sedimentological studies by Steel et al. (1981) have demonstrated three main stages of depositional development in the central basin which have been related to Palaeogene tectonic events in the Norwegian–Greenland Sea. The tectonic control of the depositional pattern was discussed in more detail by Steel et al. (1986).

The first stage, according to Steel et al. (1981), is represented by the Firkanten and Basilika Formations and presents a period of transgression with sediment supply from the east and northeast. This development took place in the Palaeocene. The subsidence probably resulted from an early transtensional regime between the Greenland and the Barents Sea blocks.

The second stage, represented by the Sarkofagen and the lower part of the Gilsonryggen Formations, shows a period of regression. During the ultimate phase of this development (represented by the Hollendardalen Formation), sediment influx was from the west. This incipient sediment supply from the west is taken by Steel et al. (op. cit.) as evidence of initiation of western uplift and onset of a transpressional regime along the sheared margin. This shift in basin geometry is dated by our dinoflagellates from the Gilsonryggen Formation to late Upper Palaeocene, thus associating it in time with starting of sea floor spreading in the Norwegian Sea at anomaly 24–25 time.

The third stage of sedimentary development according to Steel et al. (1981) is represented by the upper part of the Gilsonryggen Formation and the Battfjellet and Aspelintoppen Formations, and this presents a second period of regression with sediment supply from the west and north. According to our age assignment for the Gilsonryggen Formation, this development took place from the earliest Eocene onwards, when a sheared margin and a transpressional regime still existed between the Greenland and the Barents Sea blocks. During the latest part of

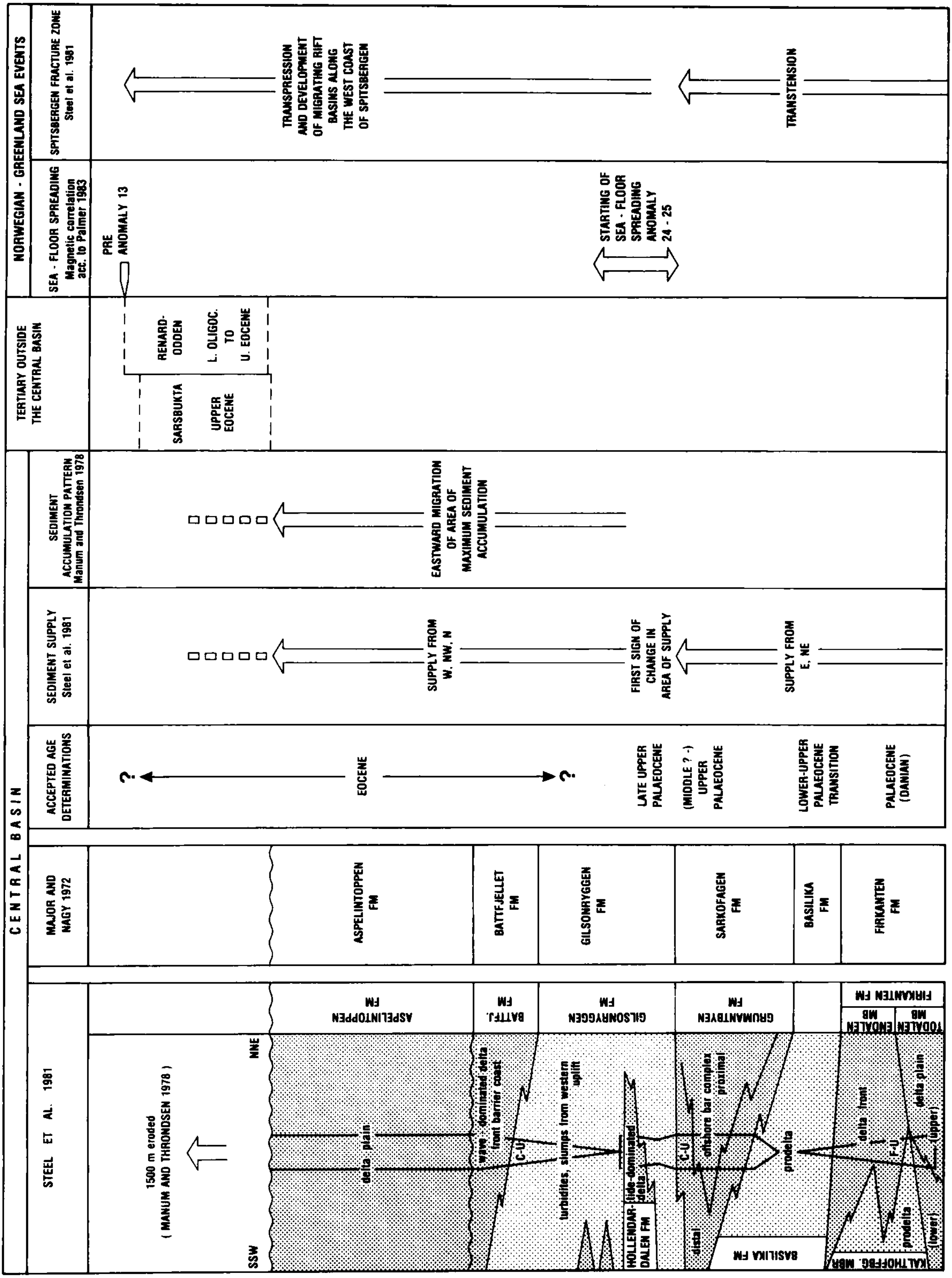

Fig. 6. Proposed synthesis of Spitsbergen Tertiary biostratigraphy, basinal evolution, and major plate tectonic events in the Norwegian–Greenland Sea.

this stage there was an increasingly rapid uplift and high sediment influx as evidenced by the great thickness of sandstones of the Aspelintoppen Formation. Vitrinite reflectance studies (Manum & Throndsen 1978; Throndsen 1982) indicate that another 1500 metres of sediments were deposited on top of the existing formations. These missing sediments were conceivably also deposited during this stage of high accretion. There is no reliable indication so far that they extended into the Oligocene.

Nøttvedt (1985, p. 44) and Steel et al. (1986, p. 342) proposed a correlation between the initiation of the regressive cycle observed at the base of the Sarkofagen Formation and the global eustatic drop in sea level at the Early–Late Palaeocene transition proposed by Vail et al. (1977). This would seem to agree well with the dinoflagellate based age proposed here for the Basilika Formation (Lower–Upper Palaeocene transition). However, in our opinion this regressive event may equally well be controlled by the local tectonic setting.

The numerous yellowish weathering clays in the Gilsonryggen Formation, some of which have yielded useful dinoflagellate assemblages, appear to be ash layers. Apparently there was considerable volcanic activity in or near the Spitsbergen area at the time of the Palaeocene–Eocene transition, at about the same time as the 'ash-markers' occur in the North Sea.

Forlandsundet

The Tertiary sequence of Forlandsundet is preserved in a narrow, elongated graben structure within the West Spitsbergen fold belt (Fig. 1) which is isolated from the central Tertiary basin. The graben cuts into pre-Devonian strata along steeply dipping faults on either side of Forlandsundet (Atkinson 1962; Livshits 1974). It displays a sequence of alluvial fan, fan delta, nearshore marine, and submarine fan deposits with an estimated stratigraphic thickness of more than 5 kilometres (Rye-Larsen 1982).

Vitrinite reflectance measurements on Tertiary samples from either side of Forlandsundet, from Sarsbukta and Reinhardpynten respectively, show highly contrasting values. The measurements from Sarsbukta give values of around Rm = 0.3, suggesting a modest overburden in the order of maximum 2 kilometres (depending on the geothermal regime in the area). The measurements from Reinhardpynten, on the other hand, give very much higher values, Rm = 4.0, indicating the anthracite stage of organic maturation. This is an abnormally high maturation level for the Spitsbergen Tertiary and indicates either a very thick overburden (6–8 km), or a lesser overburden in combination with a higher than normal heat flow (possibly from igneous activity). The latter explanation appears more likely in view of the modest maturation level recorded at Sarsbukta only a few kilometres away.

Steel & Worsley (1984) and subsequently Steel et al. (1985) proposed that the Forlandsundet graben originated in the Late Palaeocene–Eocene and developed as a southerly migrating trough within the mobile belt under a transpressional strike-slip regime. Our identification of an Upper Eocene dinoflagellate assemblage in sediments from Sarsbukta supports this timing of the event.

The Middle to Upper Oligocene age indicated by Feyling-Hanssen & Ulleberg (1984), which is not supported by our study, would imply that the Forlandsundet graben and its sediments were formed under quite a different tectonic regime, namely when rifting had already started between the Greenland and the Barents Sea blocks (post anomaly 13 time).

Renardodden

The Tertiary deposits at Renardodden consist of conglomerates (at base), coal-bearing shales and sandstones resting unconformably on rocks of the Hecla Hoek basement complex (Precambrian). Total thickness of the sequence is estimated at around 300 metres by Atkinson (1963) and Thiedig et al. (1980), whereas Vonderbank (1970) estimated 130 metres.

As discussed earlier, age assignment and correlation with formations of the central basin are equivocal. We favour Head's (1984) indication of an Upper Eocene to Lower Oligocene age. It would follow from this that this sub-basin developed during the tectonic stage of shear movement and transpressional regime between the Greenland and the Barents Sea blocks (Fig. 5). This is in agreement with the interpretation offered by Kellogg (1975) and Harland et al. (1976) that the sequence was deposited in a local basin faulted into the structures of the West Spitsbergen orogenic belt at about the same time as the formation of the Forlandsundet basin.

Conclusion

A review of biostratigraphic evidence for the age of the Tertiary formations on Spitsbergen reveals that remarkably few useful fossil assemblages have been found. Proposed ages are generally vague and often equivocal.

An early Palaeocene age (Danian) for the Firkanten Formation and part of the Basilika Formation appears to be well established and is supported by the present study. However, a more precise age for the initiation of deposition of the Firkanten Formation following the Upper Cretaceous hiatus is still lacking.

The lower part of the Gilsonryggen Formation is dated herein to late Upper Palaeocene; consequently, this also becomes the age of the change in basin geometry and sediment source area observed in the formation. The timing of this event is thus associated with initiation of sea floor spreading in the Norwegian Sea at anomaly 24–25 time.

The younger formations of the central basin (Battfjellet and Aspelintoppen Formations) have so far yielded very little of biostratigraphic value. An Eocene age appears most acceptable from available evidence from palaeontology as well as general basinal considerations; no clear evidence exists for an Oligocene or younger age.

The ages of the Tertiary sub-basins outside the central basin and their correlation with formations of the central basin as proposed by various authors are equivocal. An Upper Eocene age is proposed herein for the sequence at Sarsbukta, whereas no new evidence is available for Prins Karls Forland itself. Head (1984) indicated an Upper Eocene to Lower Oligocene age for the Renardodden sub-basin based on dinoflagellates. These ages fit a model which places the formation of these sub-basins before anomaly 13 time, that is, under a transpressional regime along the shear-zone before the two plates started to separate.

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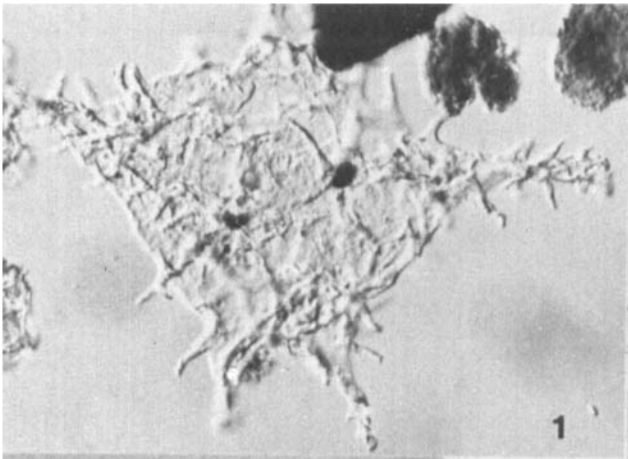
Plates 1–6

All magnifications are 550× unless otherwise stated. Slides are kept in the Palaeontological Museum of the University of Oslo; the indicated prep. numbers refer to the Museum's PA series of types. Specimen locations in the slides have been indicated by means of 'England Finder' coordinates.

Plate 1

Figs. 1–6. Apectodinium augustum (Harl.) L. & W., specimens in Figs. 1–5 are from the Gilsonryggen Fm., specimen in Fig. 6 is from the Sarkofagen Fm. Fig. 1: Prep. 4383: T38/1, loc. 1. Fig. 2: Showing state of preservation with partly distorted and partly broken horns; prep. 4385: R34/4, loc. 1. Fig. 3: Prep. 4384: P53, loc. 1. Fig. 4: Prep. 4383: L30/1, loc. 1 (500×). Fig. 5: Prep. 3890: R49, loc. 2. Fig. 6: Showing variety with finer and more closely spaced ornamentation; prep. 3889: J43–44/1–2, loc. 2.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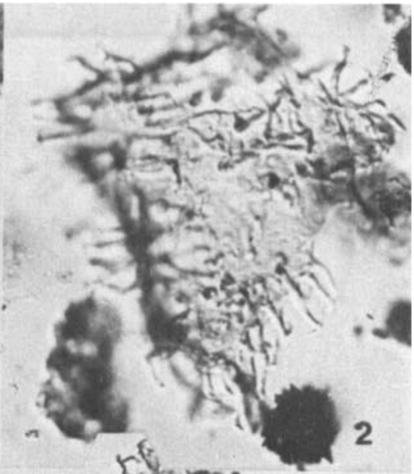
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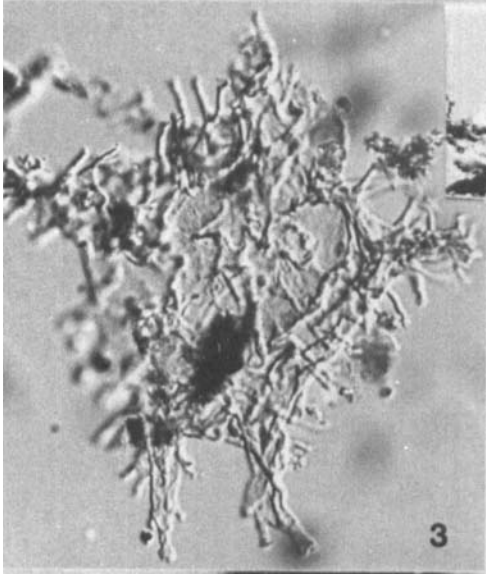
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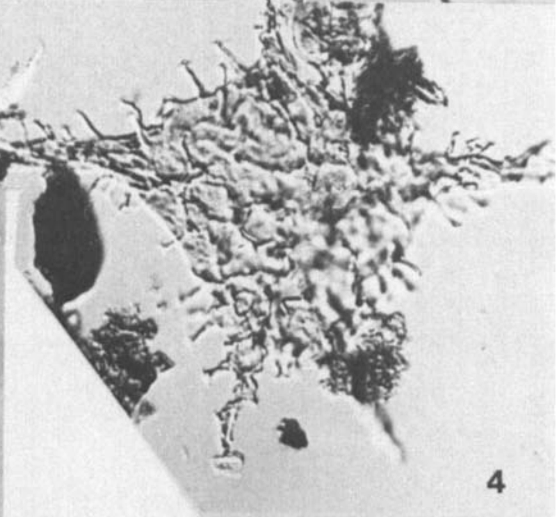
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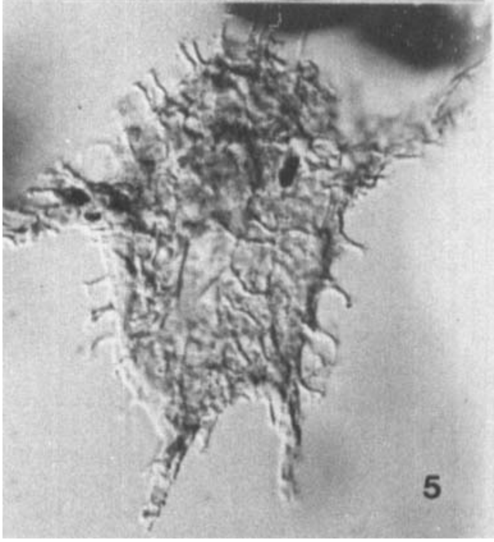
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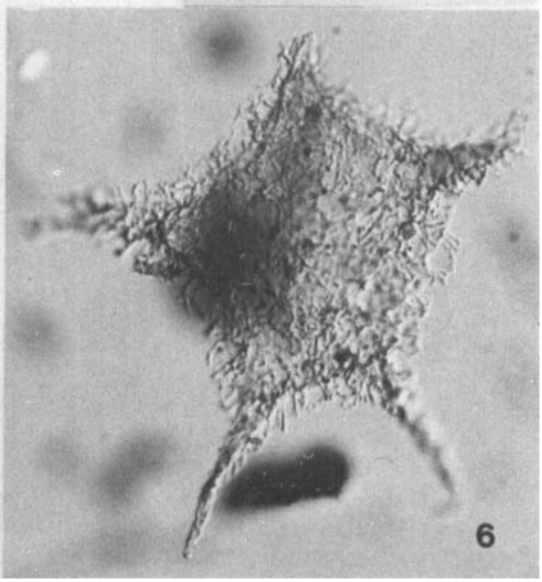
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Plate 2

Fig. 1: Apectodinium augustum (Harl.) L. & W. Specimen with less developed horns, somewhat approaching *A. paniculatum* (Costa & Downie) L. & W. Prep. 3889: L32/2–4, Gilsonryggen Fm. loc. 2.

Fig. 2: Apectodinium homomorphum (Defl. & Cooks.) L. & W. Prep. 3890: W44/1, Gilsonryggen Fm. loc. 2.

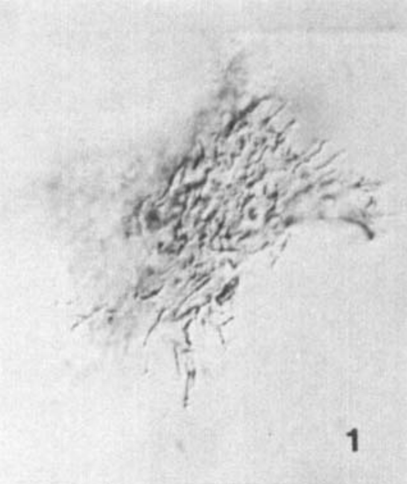
Figs. 3–5: Apectodinium cf. *A. quinquelatum* (W. & D.) Costa & Downie. Fig. 3: Prep. 3888: M38–39, Sarkofagen Fm. loc. 3. Figs 4–5: Prep. 3890: VW40/3–1, Gilsonryggen Fm. loc. 2.

Fig. 6: Apectodinium aff. *A. homomorphum/sumissum/quinquelatum*-complex. Prep. 3890: QR48–49, Gilsonryggen Fm. loc. 2.

Figs. 7–8: Cribroperidinium giuseppei (Morg.) Helenes. Prep. 3882: J38–39/1–2, Sarsbukta loc. 5.

Fig. 9: Diphyes colligerum (Defl. & Cooks.) Cooks. Prep. 4383: T40, Gilsonryggen Fm. loc. 1.

Fig. 10: Fibrocysta axialis (Eis.) Stover & Evitt. Prep. 4383: D38/4, Gilsonryggen Fm. loc. 1.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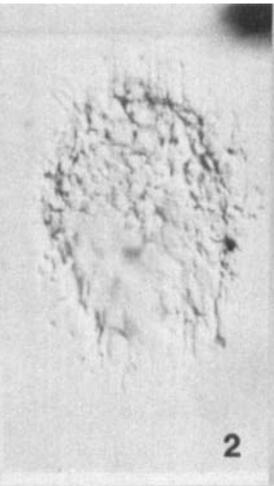
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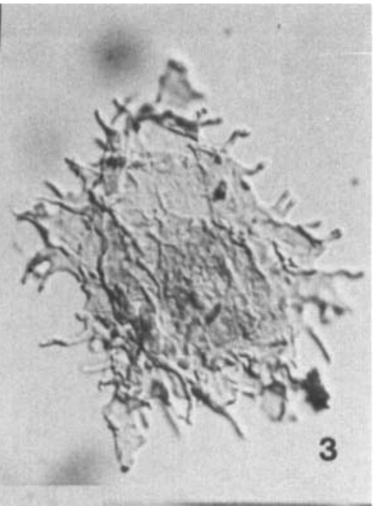
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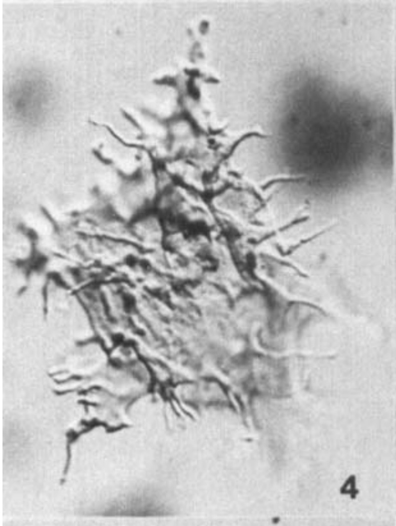
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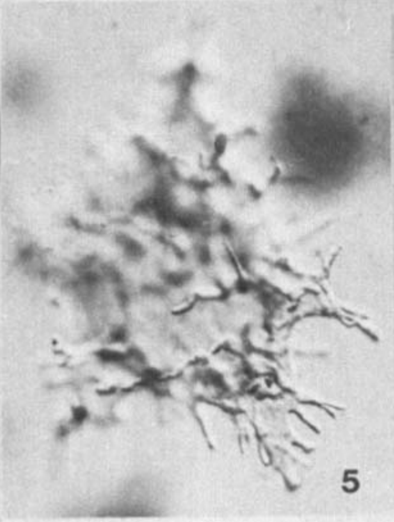
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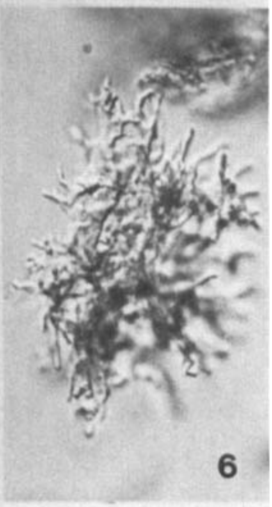
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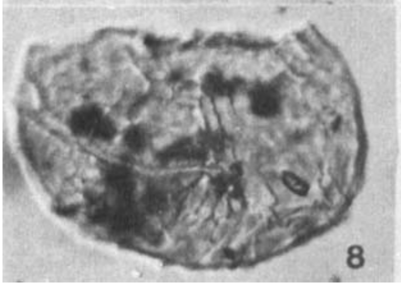
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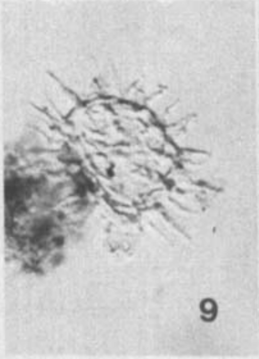
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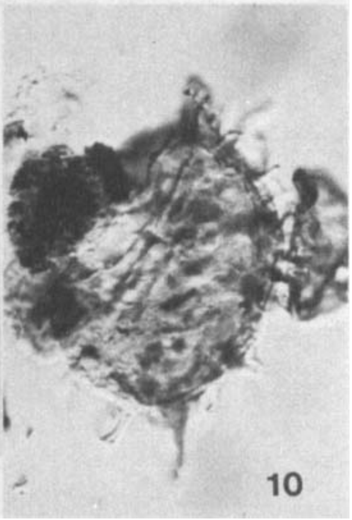
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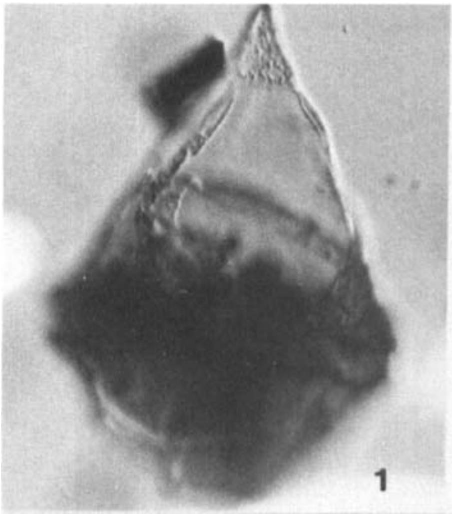
Plate 3

Figs. 1–2: Deflandrea dartmooria Cooks. & Eis. Prep. 3884: Q34–35, Basilika Fm. loc. 4.
Figs. 3–4: Deflandrea oebisfeldensis Alb. Prep. 3889: MN40/1–3, Gilsonryggen Fm. loc. 2.
Figs. 5–7: Deflandrea striata Drugg. Prep. 3885. Basilika Fm. loc. 4. Figs. 5–6: T45. Fig. 7: S41.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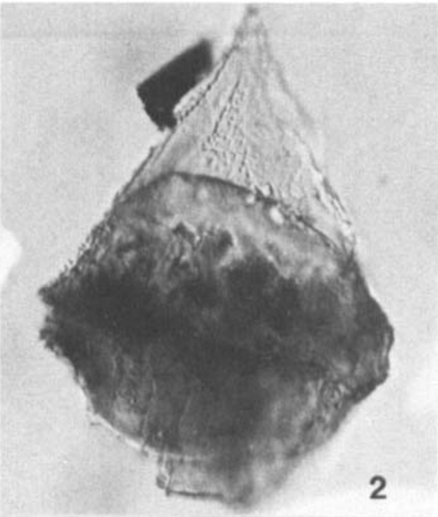
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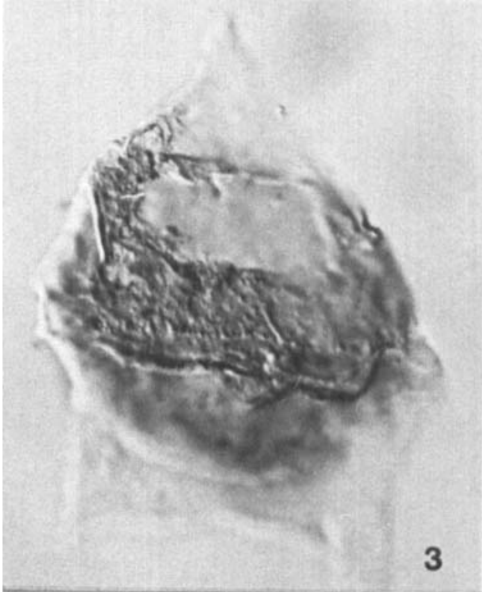
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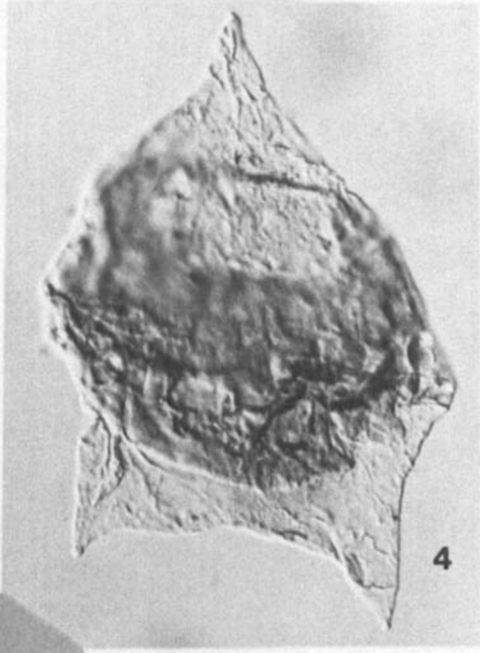
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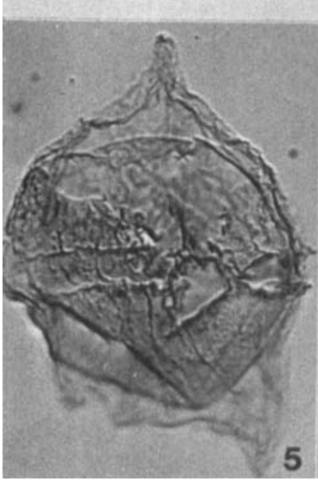
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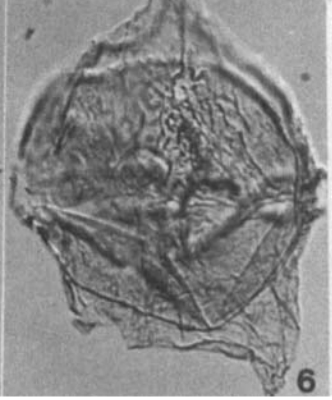
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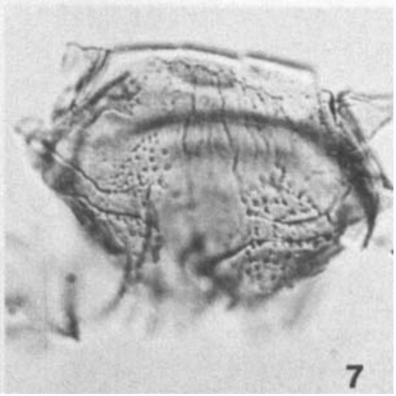
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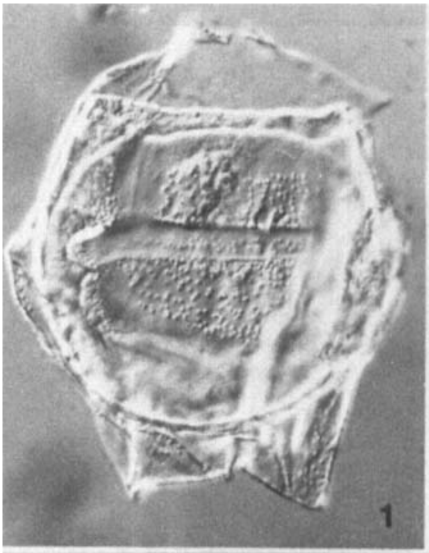
Plate 4

Figs. 1, 3–4: Deflandrea heterophlycta Defl. & Cooks. sensu Gocht. Sarsbukta loc. 5. Fig. 1: Prep. 3883: P42/1. Fig. 3: Prep. 3881: K42/2. Fig. 4: Prep. 3880: R42/1.
Fig. 2: Svalbardella cooksoniae Man. Showing specimen from Upper Eocene Norwegian Sea sediments, DSDP 336-23-4.
Figs. 5–7: Phthanoperidinium echinatum Eaton. Prep. 3880: T47/3, Sarsbukta loc. 5 (850×).
Fig. 8: Kisselovia crassoramosa (Will. & Downie) Dam. Prep. 3879: W32/2–4, Sarsbukta loc. 5.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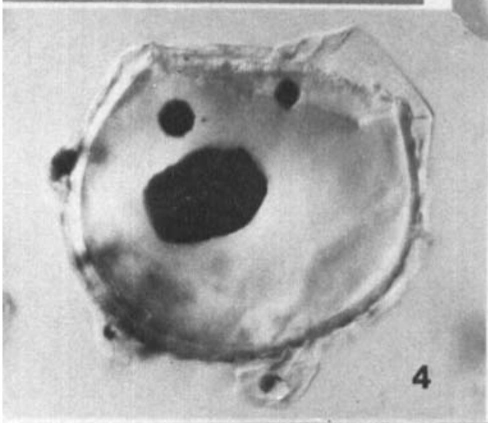
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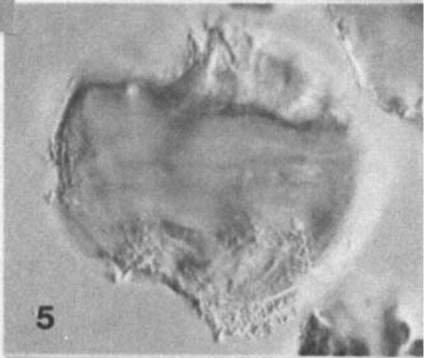
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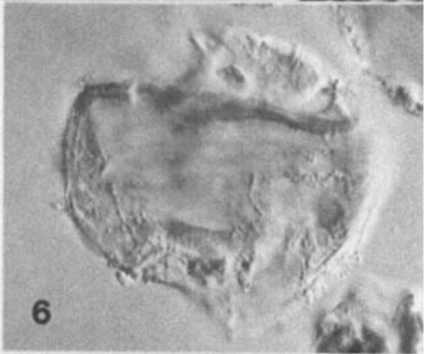
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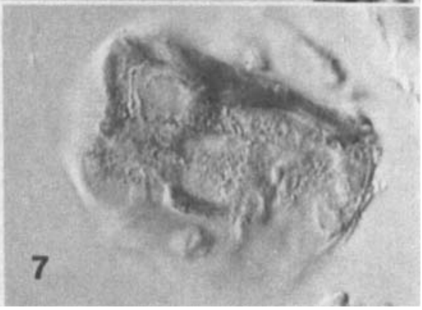
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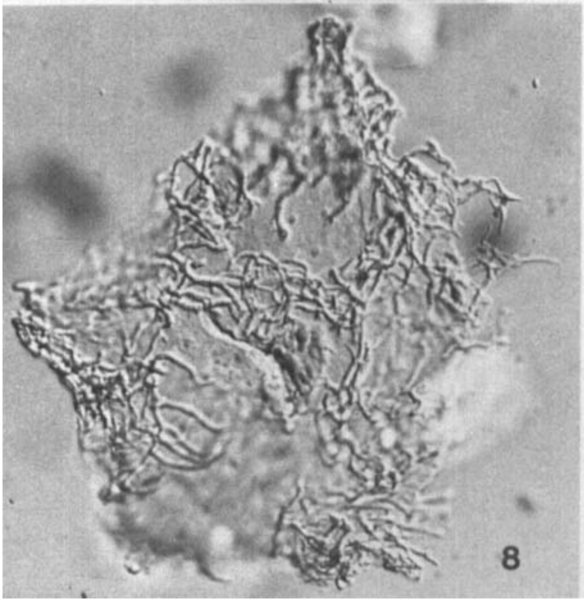
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Plate 5

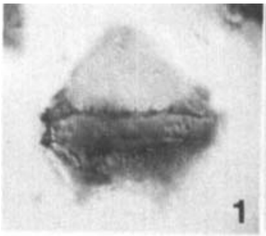
Figs. 1–3: Lentinia serrata Bujak. Figs. 1–2: Prep. 4385: O36/4, Gilsonryggen Fm. loc. 1. Fig. 3: Prep. 3878: EF/29, Sarsbukta loc. 5.

Figs. 4–6: Lentinia wetzelii (Morg.) Bujak. Prep. 4383: Gilsonryggen Fm. loc. 1; Fig. 4: P37/3. Figs. 5–6: M44.

Figs. 7–9: Lentinia sp./*Spinidinium* sp. Prep. 4383: Gilsonryggen Fm. loc. 1. Fig. 7: K40/3. Fig. 8: K34.

Fig. 10: Selenopemphix nephroides Ben. Prep. 3878: K43/1-3, Sarsbukta loc. 5.

Figs. 11–15: Svalbardella cooksoniae Man. Sarsbukta loc. 5. Figs 11–12: Prep. 3880: O34/4. Fig. 13: Prep. 3353. Figs. 14–15: Prep. 3351.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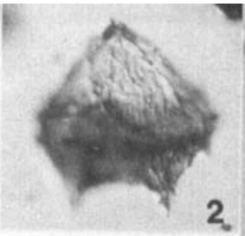
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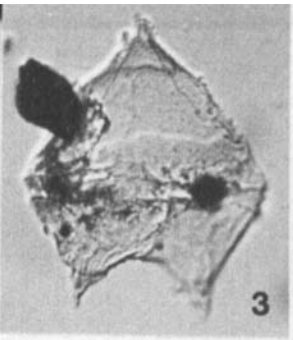
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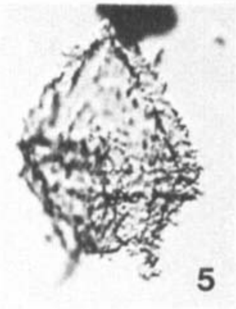
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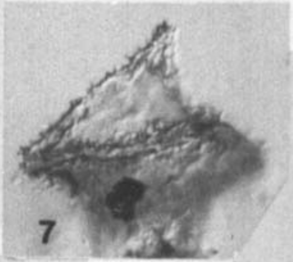
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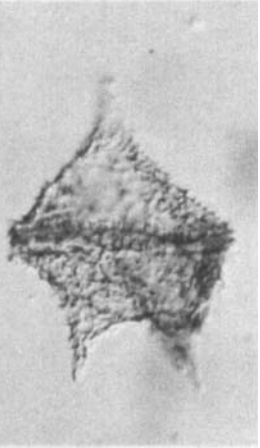
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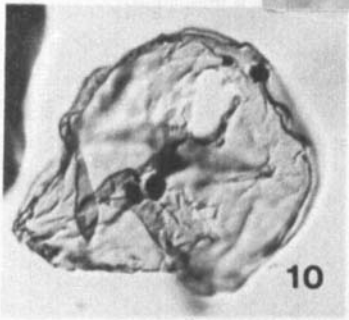
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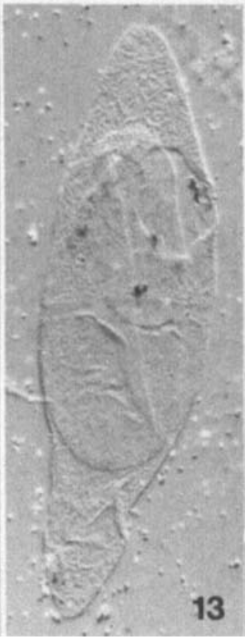
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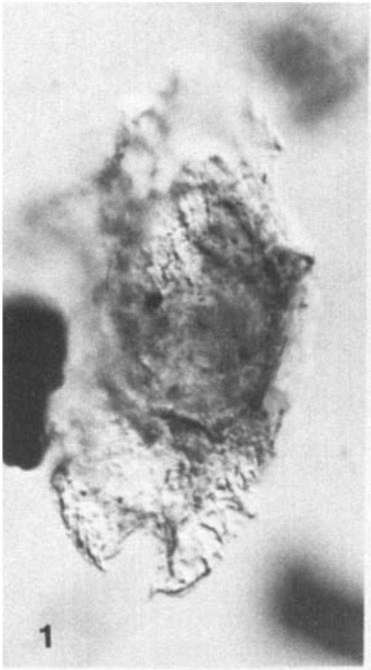
Plate 6

Fig. 1: Turbiosphaera cf. *T. filosa* Arch. Prep. 3890: R41/2, Gilsonryggen Fm. loc. 2.
Figs. 2–3: Glaphyrocysta exuberans (Defl. & Cooks.) Stover & Evitt. Prep. 3890: Gilsonryggen Fm. loc. 2. Fig. 2: N43/3. Fig. 3: M42/2–4.
Fig. 4: Thalassiphora pelagica (Eis.) Eis. & Gocht. Prep. 3878: DE37/1–3, Sarsbukta loc. 5.
Figs. 5–6: Palaeoperidinium pyrophorum (Ehrenb.) Sarj. Basilika Fm. loc. 4. Fig. 5: Prep. 3886: O42–43/3–4. Fig. 6: Prep. 3887: U36–37/1–2.
Figs. 7–9: ?Palaeoperidinium sp. Gilsonryggen Fm. loc. 1. Fig. 7: Prep. 4383: O34. Figs. 8–9: Prep. 4385: J34.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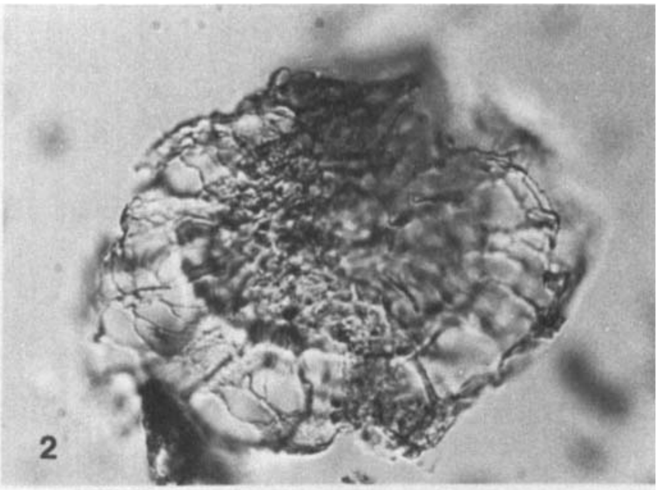
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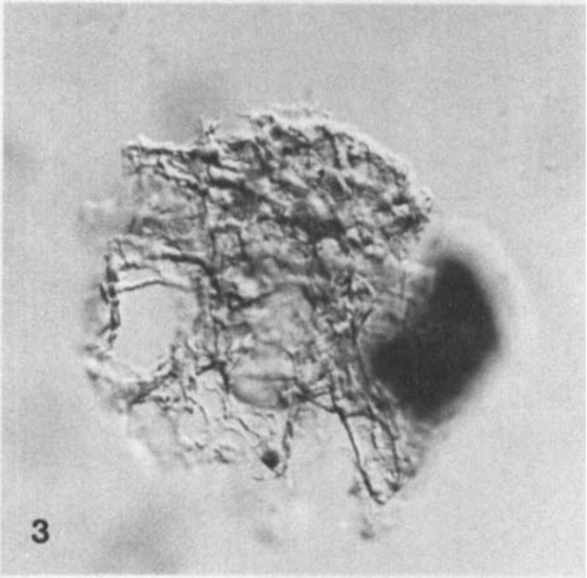
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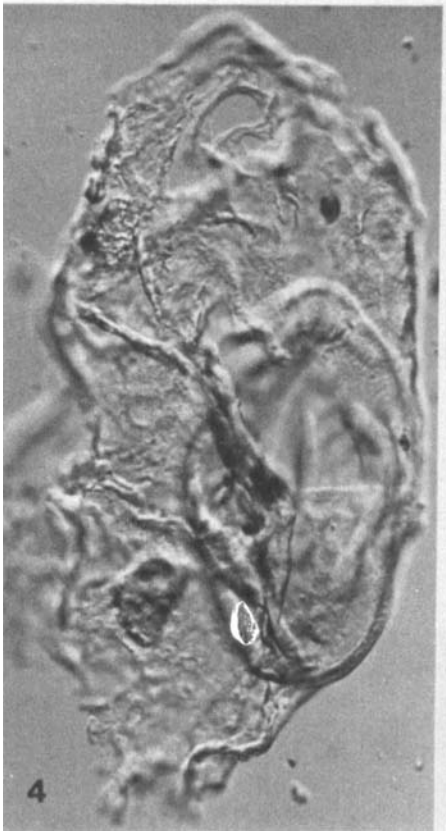
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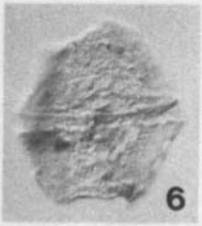
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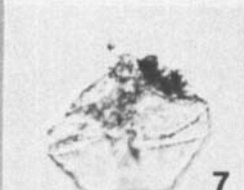
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