Palynostratigraphy of the Lower Tertiary volcanics and marine clastic sediments in the southern part of the West Greenland Basin: implications for the timing and duration of the volcanism

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Volcanic rocks, forming hyaloclastites and subaqueous lava flows, were deposited intercalated with clastic sediments in a water-filled basin in West Greenland in the Early Tertiary. Three main stages of basin infilling occurred in the Disko–Nuussuaq area. The distribution of dinoflagellate cysts in the sediments shows that the basin was marine in the first stage and non-marine in the second stage of infilling. In the third stage the basin was displaced towards the south and was marginally marine.

The dinoflagellate cysts form a typical mid-Paleocene assemblage which may be correlated with the calcareous nannoplankton (NP) zonation. The stratigraphically lowest investigated localities are coeval with the uppermost part of nannoplankton zone NP4, whereas the overlying localities within the marine basin (first stage) may be correlated with NP5–6. The localities from the non-marine second stage cannot be correlated with the NP zonation because they do not contain dinoflagellate cysts. Localities from the third stage are coeval with NP7–8. Younger volcanics are subaerially deposited.

The total known range of the volcanics now falls within the NP3 to NP8 interval, giving a minimum duration for the main plateau-building stage of the volcanism of 4–6 million years.

The subaerial basalts have previously been found to be mainly reversely magnetised, with one normally magnetised sequence which can now be stratigraphically correlated with NP4, and thereby identified as anomaly 27.

The basalts in East Greenland started erupting during the NP9 zone, so that the volcanic activity in East Greenland largely succeeded that in West Greenland. In relation to the postulated mantle plume in the North Atlantic this means that the volcanic activity started in the peripheral part of the plume and only later switched to the central part.

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Introduction

The Tertiary volcanic province of West Greenland (Clarke & Pedersen, 1976) represents a major geodynamic event in the Baffin Bay – Davis Strait area in the early Tertiary, when volcanic products invaded and finally covered large areas of a continental rift basin which had developed from the mid-Cretaceous and onwards (Henderson *et al.*, 1976, 1981; Fig. 1). Contemporaneously with the volcanism a range of marine, limnic and fluviatile clastic sediments were deposited, some of which contain rich faunas and floras. Volcanic rocks are sometimes interspersed with sediments, bringing about the possibility of biostratigraphic dating also of the volcanic sequence. It has until now been difficult to establish a coherent picture of the timing of the volcan-

Rapp. Grønlands geol. Unders. 154, 13–31 (1992)

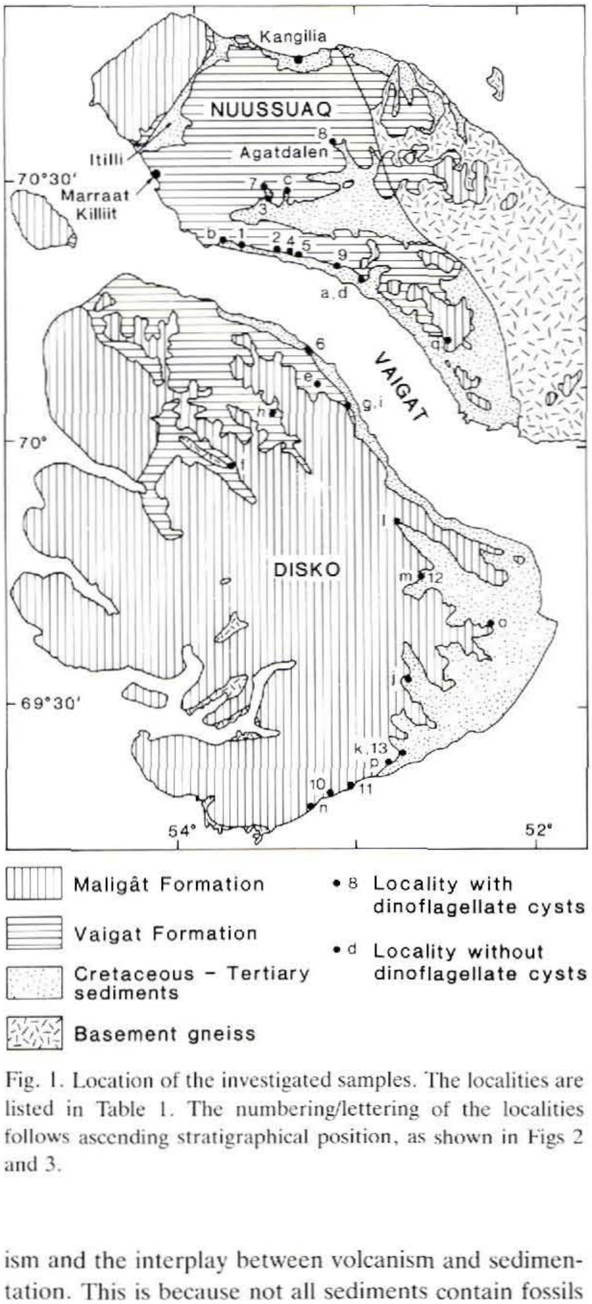


Fig. 1. Location of the investigated samples. The localities are listed in Table 1. The numbering/lettering of the localities follows ascending stratigraphical position, as shown in Figs 2 and 3.

ism and the interplay between volcanism and sedimentation. This is because not all sediments contain fossils suited for biostratigraphic work, and because many contacts between volcanic rocks and sediments are at best poorly exposed.

The formation of the volcanic rocks and the accumulation of clastic sediments in the West Greenland basin involved considerable movements of parts of the continental crust. In order to assess the geological evolution it is of particular importance to date and to estimate the time span during which the geological units in the region formed, and it is important to estimate uplift and subsidence relative to the sea level.

Absolute radiometric dating of the early volcanics is difficult because of the ultramafic and mafic nature of most of the volcanic products, and because some of the volcanics are strongly contaminated by reaction with the crust.

Palynological analysis of dinoflagellate cyst assemblages in clastic rocks deposited contemporaneously with the volcanic formations offers the possibility of determining the age and duration of the volcanism, and the distribution of marine and non-marine facies. For this reason seventy-one stratigraphically well-defined clastic rock samples ranging from mudstone and siltstone to sandstone, tuff and hyaloclastite have been subjected to palynological analysis.

Geology

The Tertiary volcanic formations on Nuussuaq and Disko comprise the Vaigat and Maligât Formations (Hald & Pedersen, 1975).

Slightly older and partly contemporaneous marine sedimentary formations comprise the Kangilia Formation in northern Nuussuaq (and probably also in western and southern Nuussuaq) described by Rosenkrantz (1970), Henderson *et al.* (1976) and Hansen (1980), and the Agatdal Formation (Rosenkrantz, 1970) in central Nuussuaq. The Upper Atanikerdluk Formation (Koch, 1959) in south-eastern and south-central Nuussuaq is considered mostly non-marine.

Vaigat Formation

The volcanism of the Vaigat Formation started from eruption centres in the north-western and western part of the region, either as mounds of pillow breccias and hyaloclastites erupting directly into an aqueous environment, or as thin fluid subaerial lava flows which spilled towards the east and north-east and eventually entered into a deep water-filled basin, presumably of tectonic origin. As corroborated by the results from this study, the basin was at least periodically marine; it covered large parts of western and central Nuussuaq and parts of northern Disko. The basin was delimited towards the east and south by large faulted blocks of Cretaceous clastic sediments. To the west and southwest the basin was confined by volcanic rocks which prograded eastwards and gradually narrowed the basin through infilling. When the subaerial lavas entered the water they were fragmented to hyaloclastite breccias and were deposited in huge fans. Individual foresets can be traced from the subaerial lava flow to the bottom of the basin, and the hyaloclastite fans may be compared to Gilbert deltas. The height of the foresets indicate

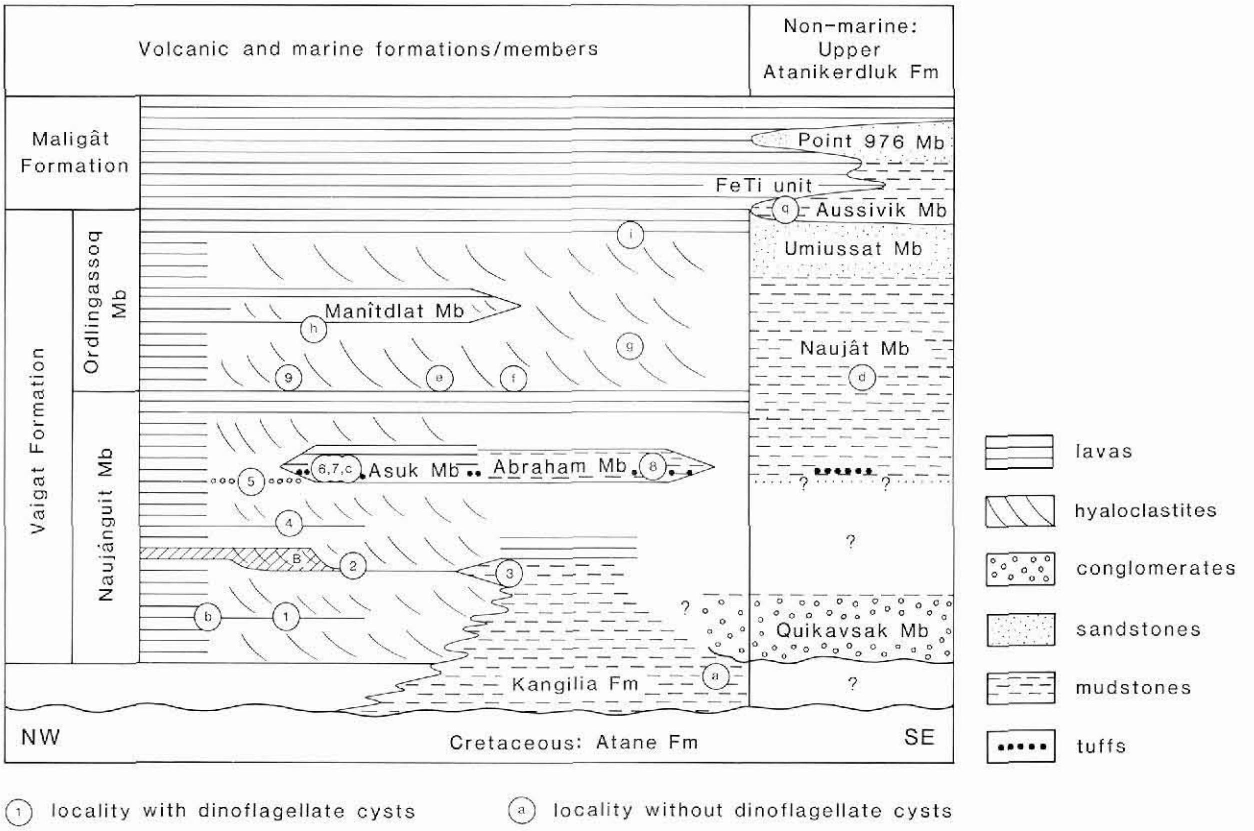


Fig. 2. Schematic NW–SE section through Nuussuaq and northern Disko, showing the stratigraphical position of the volcanic and sedimentary units. B = informal unit B. Abraham Member is part of the Agatdal Formation. Note that the strong element of progradation from NW to SE of the successive volcanic units cannot be shown properly; the units are shown superposed. The localities are shown in Fig. 1 and listed in Table 1.

water depths of up to 700 m (1:100 000 geological map sheets Agatdal and Qutdligssat; Dueholm & Pedersen, 1988). Through progradation of the fans the basin was filled out sidewards, with successively younger hyaloclastites deposited towards the east. The ultramafic lavas and hyaloclastites which constitute the major part of the Vaigat Formation contain a number of sequences of sediment-contaminated volcanic rocks which can be used as marker horizons. These can be recognised both as lavas, hyaloclastites and tuffs. It is thus possible to correlate sequences of subaerial lava flows to the time-equivalent shore zones and hyaloclastite deposits and sometimes further to the contemporaneous clastic non-volcanic sediments.

The Vaigat Formation is divided into two main units: the older Naujánguit Member and the younger Ordlingassoq Member (Fig. 2). These correspond to two stages of magmatic activity, each of which led to deposition of large amounts of material in the basin. These two major members enclose a few minor members which are characterised by distinct chemical compositions and restricted areas of distribution (Pedersen, 1985).

Rocks from the first stage of magmatic activity (Naujánguit Member) are widely distributed on northern Disko and in central and western Nuussuaq east of the Itilli (Itivdle) valley. The oldest known part of the volcanic sequence is exposed near the Itilli valley (Fig.1; 1:100 000 geological map sheet Agatdal; Henderson, 1975) but has not been studied in detail; unfortunately it occurs in a strongly faulted area. Within this part of the sequence an occurrence at Marraat Killiit of basalt conglomerate with matrix of fossiliferous marine limestone has yielded calcareous nannoplankton of the NP3 zone of Danian age (Jürgensen & Mikkelsen, 1974; Perch-Nielsen, 1973).

Younger parts of the Naujánguit Member are well exposed along the south coast of Nuussuaq and on Disko (Pedersen, 1985). Two sequences of contaminated volcanic products (informally named units A and

B) in the middle part of Naujánguit Member define stages of basin infilling in south Nuussuaq. A third contaminated sequence occurs in the upper part of the Naujánguit Member and has been defined as the Asuk Member (Pedersen, 1985). The lavas of Asuk Member are not as widespread as the Naujánguit Member; however they comprise unique igneous rocks with graphite and native iron, and this has allowed occurrences of tuffs in western and central Nuussuaq to be correlated with the Asuk Member (Pedersen *et al.*, 1989). Among these are tuff sequences in the marine siltstones of the Abraham Member of the Agatdal Formation. The marine basin was much narrowed at the end of Naujánguit Member time, and subaerial lava facies prevailed.

The second stage of magmatic activity in the Vaigat Formation was preceded by subsidence which enlarged the water-covered areas. This new basin was gradually filled with hyaloclastites and lavas of the Ordlingassoq Member, while the subsidence continued. The nearly total absence of dinoflagellate cysts in sediments within the Ordlingassaq Member volcanics demonstrated in the present work confirms that the water-filled basin during the second stage was almost entirely non-marine.

Maligât Formation

The upper volcanic formation, the Maligât Formation, consists mostly of thick, massive lava flows rather different from the usually thin lavas of the Vaigat Formation.

The Maligât Formation is thickest in central and western Disko where many eruption sites were probably situated. On Disko, it has been informally divided into three members (Fig. 3; Pedersen, 1975) of which the lowest, the Rinks Dal Member, is of concern here. When the lavas of the Maligât Formation started erupting a water-filled basin existed, which was confined to the west by the Disko Gneiss Ridge (Fig. 3), to the north by the old lava shield of the Vaigat Formation, and to the east by a low-lying fluvial plain, whereas the delimitation to the south is uncertain. During the formation of the lower part of the Rinks Dal Member this basin was filled in from the west and north-west by volcanic products, and by shales and sandstones from the east and south-east. Volcanic and sedimentary rocks are intercalated (Fig. 3). According to Larsen & Pedersen (1990) the lowest unit of the Rinks Dal Member in the basin consists of thick subaqueous lavas which often invaded the contemporary sediments to form sills (Fig. 3). A following 'pahoehoe unit' of hyaloclastite breccias and thin subaerial pahoehoe lavas made the infilling of the basin nearly complete. However, the lavas of the following unit, the 'FeTi unit', still show signs of encountering wet conditions and unconsolidated sediments in eastern Disko and eastern Nuussuaq, while being clearly subaerial in western Disko. In eastern Nuussuaq lavas of the 'FeTi unit' invaded shales of the Aussivik Member of the Upper Atanikerdluk Formation (Larsen & Pedersen, 1990; see Fig. 2). The younger lavas, from the upper part of Rinks Dal Mem-

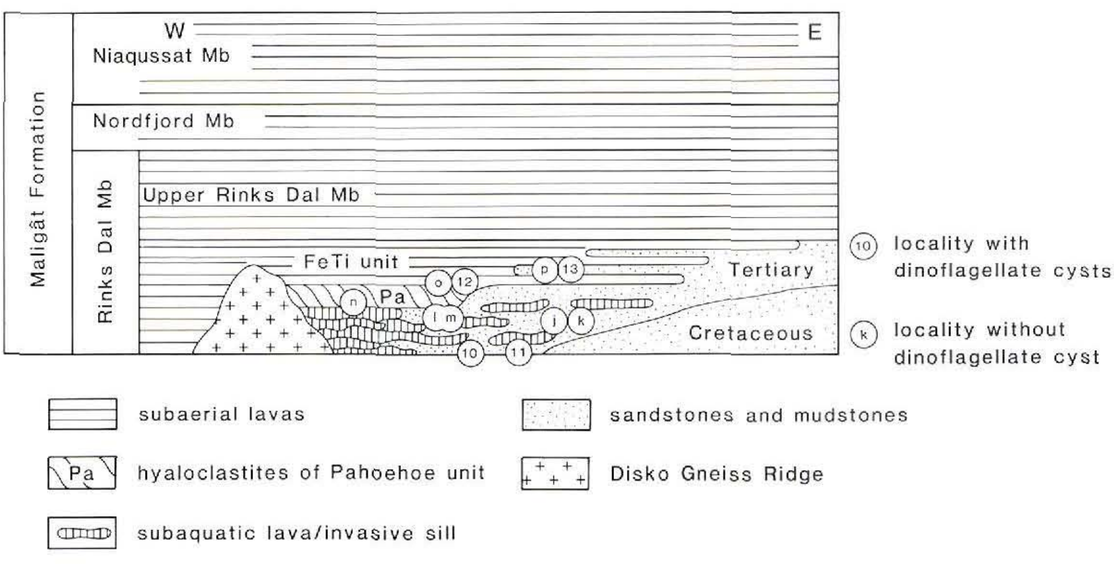


Fig. 3. Schematic W–E section through southern Disko, showing the stratigraphical position of the volcanic and sedimentary units. The localities are shown in Fig. 1 and listed in Table 1.

ber and the Nordfjord and Niaqussat Members, are all subaerial and flowed far to the east; they covered the old fluvial plain and eventually lapped onto the high crystalline basement in eastern Nuussuaq (Pedersen & Larsen, 1987).

Kangilia and Agatdal Formations

Marine deposited, dark laminated mudstones of Late Cretaceous to Early Tertiary age are well exposed at Kangilia on the north coast of Nuussuaq and reported as the Kangilia Formation (Rosenkrantz, 1970). The formation is followed across Nuussuaq (H. J. Hansen, 1970) and reported from southern Nuussuaq at Ataa (Koch, 1959) and from cuesta-like basins at Asuk on Disko (J. M. Hansen, 1980). Faulting at the Cretaceous–Tertiary boundary, erosional unconformities, coarse channellised conglomerates and sand-dominated units in this formation are reported from Ataata Kuua (Pulvertaft & Chalmers, 1990).

In central Nuussuaq, the Kangilia Formation is overlain by the marine Agatdal Formation, comprising several members of sandstones and shales (Rosenkrantz, 1970). Tuff layers are found in the shales of the Abraham Member.

Upper Atanikerdluk Formation

Koch (1959) established the Upper Atanikerdluk Formation which comprises non-marine clastic sediments grouped into five members, all of which have type localities in south-east Nuussuaq. The Upper Atanikerdluk Formation unconformably overlies delta deposits of the Cretaceous Atane Formation or, locally, marine mudstones of the Kangilia Formation. The Atane Formation is Cenomanian in the Atanikerluk area (Pulvertaft, 1987) and latest Santonian to earliest Campanian in Paatuut (Pautût) (Olsen & Pedersen, 1991).

The Upper Atanikerdluk Formation (Fig. 2) comprises a basal, strongly erosive conglomeratic unit (Quikavsak Member) overlain by two coarsening upward sequences. The first of these comprises black shales of the Naujât Member grading up into fine-grained sandstone of the Umiussat Member. The next sequence comprises black shales of the Aussivik Member capped by heterolithic, fine-grained sandstone of the Point 976 Member. The lack of dinoflagellate cysts and the very low sulphur/carbon ratios in the black shales of both the Naujât and the Aussivik Members indicate that both shale units are lacustrine. This is supported by a palynological study carried out by Hjortkær (1991). Her results indicate that the Upper Atanikerdluk Formation is of mid-Paleocene age. The samples are characterised by an assemblage of spores and pollen dominated by a coniferous element represented by various forms of inaperturate pollen. This is in close agreement with the description of Manum (1962) of the microfossils of Ellesmere Island and Spitsbergen (Hjortkær, 1991). The coarsening upward sequences are interpreted as gradual infilling of lake basins which attained their maximum depth initially.

Correlation with the volcanic units is not yet very precise (Fig.2 and 3); however at least parts of the Naujât Member seem to correlate with the Ordlingassoq Member of the Vaigat Formation, whereas at least some of the Aussivik Member is time-equivalent to the 'FeTi unit' of the Maligât Formation (Larsen & Pedersen, 1990).

Sedimentary history

The oldest Tertiary sediments are included in the marine Kangilia Formation. Prior to deposition of the Kangilia Formation a marine transgression took place. At Ataa the Kangilia Formation is erosively cut by the coarse fluvial Quikavsak Member which elsewhere has eroded into the Cretaceous Atane Formation. A marine intercalation in the Quikavsak Member is reported by Koch (1959), and J. M. Hansen (1980) noted a rich trace fossil assemblage in the top of the Quikavsak Member at Ataa. However, in south-eastern Nuussuaq and eastern Disko the sediments overlying the Quikavsak Member appear to be almost entirely non-marine, and they are referred to the Upper Atanikerdluk Formation.

Three following phases of lake sedimentation are recognised. The first drowned the Quikavsak Member, and while hyaloclastite breccias of the Ordlingassoq Member were infilled from the west and north-west the black shales of the Naujât Member were deposited in eastern Nuussuaq. The Naujât Member constitutes an upward coarsening sequence which passes up into the Umiussat Member.

A second lake phase may be represented by shales in southern Disko, invaded by subaquous lavas/sills of the lowest Rinks Dal Member of the Maligât Formation. There were contemporary marine incursions into this basin (see later).

The third lake phase is represented in the sedimentary column by the black shales of the Aussivik Member in south-east Nuussuaq, and possibly also by the lacustrine shale sequence at Pingo, eastern Disko (Pedersen, 1989).

Sample selection

The samples selected for palynological analysis are from stratigraphically well defined units and are nearly all from sediments in close association with volcanic rocks. The sample localities are shown on the map (Fig. 1), and the stratigraphic positions of the samples are shown in Figs 2, 3 and Table 1. Priority was given to samples for which there was some probability that they were deposited in marine or brackish environments; in addition some supposed non-marine samples were checked.

The study is geographically restricted to areas where the authors have performed field work; the expected marine facies of the lower Vaigat Formation in northern and western Nuussuaq is therefore not included. Also, the areas with subaerial lavas in western Disko are excluded.

Results

Organic matter

In total 71 samples of fine-grained, shaly sediments from the Tertiary strata of Nuussuaq and Disko have been prepared palynologically. The contents of organic matter show very characteristic variations, and the composition of the organic content can easily be classified within six facies most of which are sharply delineated. The facies classification of the investigated samples is shown in Table 1.

Facies 1 and 2 are characterised by mixed contents of organic debris which is almost entirely of terrestrial origin. Facies 1 has a prominent fraction of fungal remains, *Botryococcus* sp. and *Ulvella nanae* which generally is absent or rare in facies 2. Dinoflagellate cysts have not been recorded from facies 1, and only in two cases (localities 12 and 13) from facies 2, and trilete spores are locally frequent. These two facies can be subdivided by more detailed work.

Facies 3 contains terrestrially derived organic matter which is strongly dominated (60–95%) by bisaccate pollen. Lumps of 20–40 aggregated pollen occur. Dinoflagellate cysts have been recorded from this facies.

Facies 4 comprises organic matter that is dominated (50–95%) by brown and black woody material and coaly grains. Dinoflagellate cysts occur in this facies and there is gradual transition to facies 1 and 2.

Facies 5 is characterised by a poor organic content of black rounded carbonised grains associated with few palynomorphs of dinoflagellate cysts or trilete spores. Iron sulphides are characteristically frequent in this facies.

Facies 6 is noteworthy for the dominance of resin-like material which also could be degraded bitumen or possibly very sapropelised algal material. Samples rich in wood with large resin content appear only partly similar after preparation, and further studies are necessary before any final conclusions about the origin of the material can be drawn. Dinoflagellate cysts and sporomorphs occur infrequently within this facies.

A small group of samples turned out to be strongly thermally degraded by local intrusions or barren of organic material (Table 1).

Distribution of the organic facies

The number of analysed samples is small compared to the thickness of the Tertiary strata and to the extension of the sedimentary basin, the Nûgssuaq Embayment. None the less, a consistent pattern of regional and stratigraphical distribution of the six organic facies appears and reflects variations in geological, depositional environments.

Facies 1 and 2 occur in the fluvial and lacustrine deposits of the Upper Atanikerdluk Formation and in brackish to locally marine deposits of the Vaigat and Maligât Formations with occasional marine palynomorphs. The bisaccate pollen facies (3) is mainly associated with specific sedimentary levels of deep basin sedimentation in the Vaigat Formation and locally with fluvial and lacustrine deposits. Typically, facies 1 & 2 occur mainly in the sediments along the eastern and southern basin margins whereas organic facies 3 is frequent in the deep basin among the hyaloclastites. The dominance of bisaccate pollen in facies 3 indicate specific transportation and sorting effects, and the sporomorphs were possibly windblown or floating before deposition in the central basin (cf. Davis & Brubaker, 1973).

Facies 4 of woody material is associated with marine sediments in the Vaigat Formation and probably reflects transportation and sorting effects from land to sea. Similar facies occurs in the Kangilia Formation (Hansen & Gudmundsson, 1979).

Facies 5 of coaly grains and iron sulphides occurs in marine sediments between hyaloclastite breccias of the informal unit B of the Naujánguit Member (loc. 3) and in tuffs with sulphide, traces of native iron and graphite from the Asuk Member and Agatdal Formation (locs 7, c, 8).

Facies 6 is mainly associated with 'basinal bottom levels' eroded and overlain by subaquatic hyaloclastite breccias. One sample of partly comparable composition occurs in lacustrine to fluviatile sediments at loc. j on Disko. The origin is not fully understood.

The marine microflora and organic facies 4, 5 and 6 are basically confined to the lower volcanic part of the Tertiary sequence, the Naujánguit Member of the Vaigat Formation. Time-equivalent clastic sedimentation is basinal mud supposedly of the Kangilia Formation.

Distribution of marine and non-marine facies

The sedimentary facies distribution indicates that subsidence of the basin formed a sediment starved marine basin where most sediments including the terrestrial organic matter were trapped along the eastern and southern margins. The most distal deposited phytoclasts of brown and black woody material (facies 4) or rounded carbonised grains (facies 5) occur in the deepest deposited sediments associated with the bottom sets of hyaloclastites plunging down-slope into the basin from the western margin. Facies 5 may well be derived from graphite, native iron and sulphides in the associated volcanic rocks.

All the investigated sediment localities in the Naujánguit Member of the Vaigat Formation yielded dinoflagellate cysts except loc. b, a siltstone horizon between subaerial lavas adjacent to the palaeo-shoreline. It can be concluded that the water-filled basin at this time was marine. The marine sediments include the Abraham Member of the Agatdal Formation.

The early marine basin was filled by volcanics and sediments and was succeeded by another basin with a geological setting similar to the marine precursor. This second basin was filled by volcanics of the Ordlingassoq Member of the Vaigat Formation. None of the investigated sediment localities in the Ordlingassoq Member yielded dinoflagellate cysts except loc. 9 at the lowest stratigraphical level. Volcanic eruptions probably sealed the connection to the sea towards north-northwest (Pedersen, 1989). The Naujât Member is most probably at least partly time-equivalent with the volcanics and sediments of the Ordlingassoq Member. No dinoflagellate cysts were found in the analysed samples of the black shales of the Naujât Member. This supports previous interpretations of this shale as lacustrine deposited (Koch, 1959; Schiener & Leythaeuser, 1978; Pedersen, 1987). It can be concluded that the water-filled basin at this time was dominantly non-marine; the few dinoflagellate cysts from loc. 9 may be redeposited or the basin initially changed from marine to non-marine.

Several localities with sediments intercalated with subaqueus lavas, sills and hyaloclastites in the Rinks Dal Member of the Maligât Formation on Disko were investigated. Four localities yielded dinoflagellate cysts, and the depositional environment was apparently marginally marine or affected by short-lived marine influxes. Contemporaneous shales of the Aussivik Member of the Upper Atanikerdluk Formation in southern Nuussuaq contain no dinoflagellate cysts (Fig. 2). The marine influxes at this late stage entered the basin from the south, in accordance with the shape of the basin outlined by Larsen & Pedersen (1990).

The rather clear difference in organic facies of the deep marine and limnic basins may reflect the difference in salinity and density of the water, or flocculation of small particles in saline waters. However, this is very speculative and more detailed and precise data are necessary for any conclusions.

Biostratigraphy

The dating of the Tertiary strata in the Disko – Nuussuaq region is historically based on the rather patchy occurrence of marine macrofossils. Rosenkrantz (1970) suggested Early and Late Danian ages for parts of the sedimentary strata, and similar results were obtained on the basis of foraminifera (H. J. Hansen, 1970) and coccoliths (Perch-Nielsen, 1973; Jürgensen & Mikkelsen, 1974). The complex interbedding of sediments and volcanic extrusives, combined with significant lateral variation in depositional environment from fluvial/lacustrine to marine settings, introduced severe problems for the interpretation of a coherent stratigraphy. Petroleum exploration on the West Greenland shelf in the 1970s focused new interest on the onshore exposures of Cretaceous – Tertiary strata, and palynological biostratigraphy was introduced to the region.

Unfortunately, most of this geographically extensive and stratigraphically detailed work has never been published and is partly available only as internal reports in oil companies or GGU and as an unpublished thesis (Ehman *et al.,* 1976; Croxton, 1978; Hansen, 1980). However, these works with their correlation problems, and the combined conclusions that can be drawn from them, are presented in detail by Pulvertaft (1987). Croxton (1976, 1980) published selected, specific palynological subjects.

The dinoflagellate cyst assemblages. The complete, recorded assemblage of dinoflagellate cysts (Fig. 4) is a typical mid-Paleocene association. The recorded association is never rich in specimens and species and the diversity decreases upwards. The stratigraphical distribution of species is broadly comparable to the formal, mid-Paleocene, dinoflagellate cyst stratigraphies of Hansen (1980) and Heilmann-Clausen (1985).

The main assemblage is characterised by *Cerodinium*

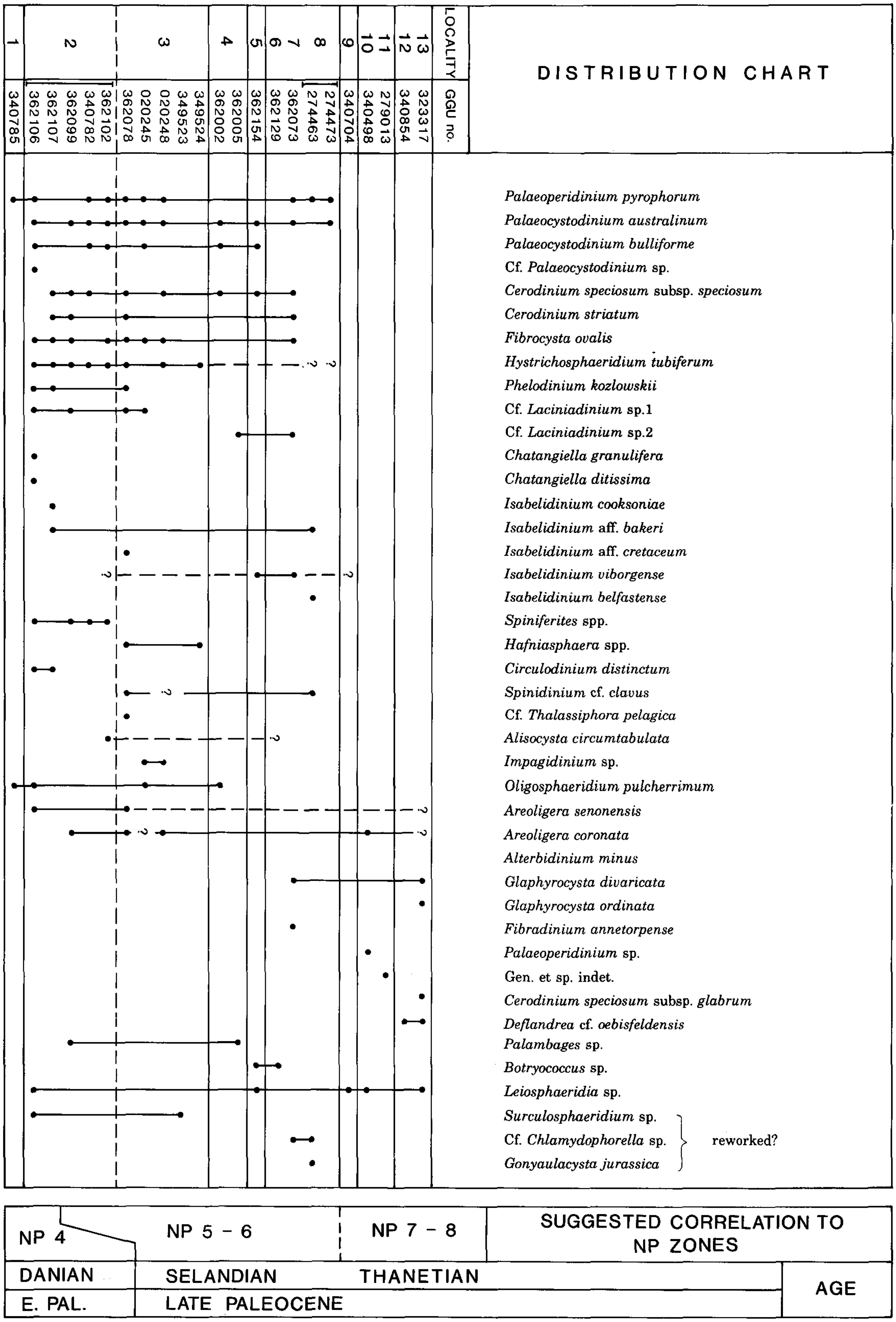
Table 1. Investigated localities: stratigraphic position, location, samples, dinoflagellate cyst contents and palynofacies

Loc. no.	Latitude °N	Longitude °W	Alt. m	Sample no.	Dinoflag. cysts	Palynofacies
Kingittoq. Mudstones invaded by FeTi unit lavas, Rinks Dal Mb						
q	70°12.75′	52°28.6′	1095	362225	-	2
q	70°12.80′	52°28.7′	993	362221	-	2/3
Marraat qaqqaat. Sediments between FeTi unit lavas, Rinks Dal Mb						
p	69°23.55′	52°50.7′	645	326417	-	e
p	69°23.35′	52°51.3′	570	326413	-	e
Tuapaat. Sediments between FeTi unit lavas, Rinks Dal Mb						
13	69°25.10′	52°42.6′	650	323317	+	2
Frederik Lange Dal. Siltstones between pahoehoe unit and FeTi unit lavas, Rinks Dal Mb						
12	69°45.25′	52°36.8′	660	340854	+	2
12	"	"	657	340855	-	2
Peak 1123 m. Thin siltstone horizon between pahoehoe unit and FeTi unit, Rinks Dal Mb						
o	69°39.20′	52°15.5′	670	362345	-	pm
Ippik. Sediment schlieren within pahoehoe unit breccias, Rinks Dal Mb						
n	69°18.15′	53°16.1′	215	157253	-	1
Frederik Lange Dal. Siltstones below pahoehoe unit, Rinks Dal Mb. Underlain by sediments without volcanics						
m	69°45.65′	52°36.9′	480	340840	-	2/3
Kvandalen. Siltstones below pahoehoe unit; contain nucula *sp. Boulders in river bed. Underlain by sediments without volcanics*						
l	69°50.20′	52°45.9′	*c.*500	362163	-	2/3
l	"	"	*c.*500	349554	-	1
l	"	"	*c.*500	340870	-	1
Tuapaat. Mudstones with sills from lower part of Rinks Dal Mb						
k	60°25.10′	52°39.8′	485	323318	-	3
k	"	52°39.3′	450	323319	-	pm
k	69°24.80′	52°42.6′	460	323315	-	1
k	69°24.75′	52°42.4′	410	323314	-	3
Laksedalen. Mudstones on top of large sill from lower part of Rinks Dal Mb						
j	69°31.8′	52°40.7′	370	362306	-	1
j	"	"	370	362305	-	6
j	"	52°40.5′	335	362282	-	pm
Niuluut. Shale clasts in subaqueous volcanic breccia from lower part of Rinks Dal Mb						
11	69°20.10′	53°3.3′	2	279022	-	3
11	69°20.05′	53°4.5′	5	279013	+	3
Assoq. Mudstones with tuff layers, between subaqueous lavas from lower part of Rinks Dal Mb						
10	69°19.30′	53°9.6′	50	340500	-	3
10	"	"	18	340498	+	3
10	"	"	5	340490	-	pm
Qullissat. Thin conglomerate horizon between Vaigat Fm and Maligât Fm						
i	70°05.55′	53°05.9′	890	156731	-	2
Kuugannguaq. Mudstones between breccias from Ordlingassoq Mb						
h	70°04.45′	53°32.1′	500	264089	-	3
Qullissat. Mudstones between breccias from Ordlingassoq Mb						
g	70°05.05′	53°04.8′	550	156728	-	2
g	70°04.75′	53°04.4′	480	156750	-	3
Stordal. Mudstones at bottom of breccia basin. Ordlingassoq Mb. Same level as 9 and e						
f	69°55.90′	53°44.2′	400	264020	-	2
Qorlortorsuaq. Mudstones at bottom of breccia basin. Ordlingassoq Mb. Same level as 9 and f						
e	70°07.90′	53°16.3′	485	349552	-	1
e	70°07.25′	53°15.3′	540	138338	-	3
e	"	"	540	138334	-	2

Table 1. Cont.

Loc. no.	Latitude °N	Longitude °W	Alt. m	Sample no.	Dinoflag. cysts	Palynofacies
Ataa. Naujât Mb. mudstones below Ordlingassoq Mb. breccias						
d	70°19.35′	52°57.5′	710	340319	-	2
Tupaasat. Mudstones at bottom of breccia basin; new transgression. Same level as e and f (845, 809, 700 m). Uppermost Naujánguit Mb, between lavas (805 m)						
9	70°20.80′	53°02.6′	700	340728	-	1
9	70°21.25′	53°05.3′	809	340704	+	3
9	70°21.55′	53°11.0′	845	362018	-	6
9	"	"	805	362024	-	6
Agatdal. Mudstones and cement stones with graphite andesite tuff layers. Abraham Mb. Equivalent level to 6, 7 and c						
8	70°35.45′	53°08.4′	518	274477	-	e
8	70°35.65′	53°08.5′	502	274473	+	5
8	"	"	495	274463	+	5
8	70°35.45′	53°08.4′	510	274483	-	2
8	"	"	510	274482	-	5
Qilakitsoq. Sediment basin with redeposited graphite andesite tuff layers. Equivalent level to 6, 7 and 8						
c	70°29.75′	53°25.4′	905	362086	-	5
c	"	"	904	362087	-	5
Ilugissoq. Sediment basin with redeposited graphite andesite tuff layers. Equivalent level to 6, c and 8						
7	70°30.35′	53°34.7′	1176	362066	-	5
7	"	"	1151	362073	+	5
Asuk. Sediment with fossil wood between pillow lavas from Asuk Mb. Equivalent level to 7, c and 8						
6	70°11.95′	53°18.2′	15	362129	+	4
6	"	"	8	362133	-	4
Between Nuuk Killeq and Nuuk Qiterleq. Conglomerate horizon within hyaloclastites from Naujánguit Mb						
5	70°22.20′	53°17.6′	733	362156	?	3
5	"	"	733	362154	+	3
Between Nuuk Killeq and Nuuk Qiterleq. Mudstones with hyaloclastites at bottom of breccia basin, Naujánguit Mb						
4	70°22.33′	53°21.7′	573	362005	+	4
4	70°22.30′	53°22.4′	570	362002	+	5
Ilugissoq. Hyaloclastites from Nuajánguit Mb with mudstones and corals at 620 m; mudstones at c. 700 m						
3	70°29′	53°33′	*c.*700	349524	+	5
3	"	"	*c.*700	349523	+	5
3	"	"	620	20248	+	5
3	"	"	620	20245	+	5
3	"	"	620	362078	+	4
Nuuk Killeq. Mudstones at bottom of breccia basin, Naujánguit Mb. Same level as loc. 3						
2	70°22.35′	53°30.1′	176	362103	-	6
2	70°22.25′	53°30.0′	125	362102	+	4
2	"	"	120	340782	+	4
2	"	"	120	362099	+	4
2	"	"	116	362107	+	6
2	"	"	113	362106	+	4
Nuusap Qaqqarsua. Mudstones at bottom of breccia bassin, Naujánguit Mb						
1	70°23.30′	53°44.6′	228	340786	-	4
1	"	"	227	340785	+	4
Nuusap Qaqqarsua. Siltstones between lavas from Naujánguit Mb, subaerial, near-shore.						
b	70°24.75′	53°51.9′	842	362277	-	e
b	"	"	842	362276	-	e
Ataa. Thick sediment sequence, assumed Kangilia Fm						
a	70°19.9′	53°01.1′	490	340340	-	2
a	70°19.7′	53°01.6′	317	340331	-	2
a	"	"	301	340328	-	1

The locations are shown in Figs. 1-3. Locations with samples that yielded dinoflagellate cysts are numbered. Locations with samples that did not yield dinoflagellate cysts are lettered.
The palynofacies 1-6 are described in the text. pm = postmature, e = empty.
The samples are arranged with increasing stratigraphic height; however, some localities represent equivalent levels as indicated.



DISTRIBUTION CHART
LOCALITY
1 2 3 4 5 6 7 8 9 10 11 12 13
GGU no.
340785 362106 362107 362099 340782 362102 362078 020245 020248 349523 349524 362002 362005 362154 362129 362073 274463 274473 340704 340498 279013 340854 323317
Palaeoperidinium pyrophorum
Palaeocystodinium australinum
Palaeocystodinium bulliforme
Cf. Palaeocystodinium sp.
Cerodinium speciosum subsp. speciosum
Cerodinium striatum
Fibrocysta ovalis
Hystrichosphaeridium tubiferum
Phelodinium kozlowskii
Cf. Laciniadinium sp.1
Cf. Laciniadinium sp.2
Chatangiella granulifera
Chatangiella ditissima
Isabelidinium cooksoniae
Isabelidinium aff. bakeri
Isabelidinium aff. cretaceum
Isabelidinium viborgense
Isabelidinium belfastense
Spiniferites spp.
Hafniasphaera spp.
Circulodinium distinctum
Spinidinium cf. clavus
Cf. Thalassiphora pelagica
Alisocysta circumtabulata
Impagidinium sp.
Oligosphaeridium pulcherrimum
Areoligera senonensis
Areoligera coronata
Alterbidinium minus
Glaphyrocysta divaricata
Glaphyrocysta ordinata
Fibradinium annetorpense
Palaeoperidinium sp.
Gen. et sp. indet.
Cerodinium speciosum subsp. glabrum
Deflandrea cf. oebisfeldensis
Palambages sp.
Botryococcus sp.
Leiosphaeridia sp.
Surculosphaeridium sp.
Cf. Chlamydophorella sp.
Gonyaulacysta jurassica
reworked?
NP 4
NP 5 - 6
NP 7 - 8
SUGGESTED CORRELATION TO NP ZONES
DANIAN
SELANDIAN
THANETIAN
AGE
E. PAL.
LATE PALEOCENE

speciosum subsp. *speciosum* (Alberti) Lentin & Williams, 1987, *Cerodinium striatum* (Drugg) Lentin & Williams, 1987, *Palaeocystodinium australinum* (Cookson) Lentin & Williams, 1976, *Palaeocystodinium bulliforme* Ioannides, 1986, *Palaeoperidinium pyrophorum* (Ehrenberg) Sarjeant, 1967, and *Hystrichosphaeridium tubiferum* (Ehrenberg) Davey & Williams, 1966, which are present in most samples though not necessarily the most frequent species (Figs 5, 6). The lower part of this assemblage is further characterised by genera and species of more Cretaceous than Tertiary affinity i.e. *Chatangiella*, *Isabelidinium* and *Phelodinium* (Fig. 6).

A poor assemblage, recorded only from Disko (locs 10–13) deviates from the main assemblage and is clearly slightly younger. The assemblage is characterised by *Cerodinium speciosum* subsp. *glabrum* (Gocht) Lentin & Williams, 1987 and *Deflandrea* cf. *oebisfeldensis* Alberti, 1961 (Fig. 5).

The age of the dinoflagellate cyst assemblages. The lower parts of localities 2 and 3 contain *Phelodinium kozlowskii* (Gorka) Lindgren, 1984 (top NP4; Williams & Bujak, 1985) apparently associated with the first appearance of *Cerodinium speciosum* subsp. *speciosum* (first occurrence in presumed uppermost NP4 or lowermost NP5 in Denmark; Hansen, 1980; Heilmann-Clausen, 1985; Thomsen & Heilmann-Clausen, 1985). A larger overlap of these two species is indicated in the section at Kangilia (Hansen, 1980) suggesting either that *C. speciosum* subsp. *speciosum* could occur stratigraphically lower than at localities 2 and 3 or that the sequence here is condensed compared to the sequence at Kangilia.

In the wells offshore eastern Canada (Williams & Bujak, 1985) *C. speciosum* is claimed to range down to the base of NP3, and this is apparently also the case in the Kangilia section where *C. speciosum* is present well below the two tuff-layers (Hansen, 1980) of which the youngest one contains a mid to upper NP3 coccolith assemblage (Jürgensen & Mikkelsen, 1974; E. Thomsen, personal communication, 1990). The tuff-layers indicate that extrusive volcanic activity had started.

A stratigraphical equivalence to (upper) NP4 is suggested for the lower part of localities 2 and 3. This is in good accordance with the NP3 coccolith assemblage in the stratigraphically lower level represented by the volcanic conglomerates at Marraat Killiit (Jürgensen & Mikkelsen, 1974).

The age of the lower part of localities 2 and 3 is then latest Early Paleocene (i.e. Late Danian). This indicates that the Lower – Upper Paleocene boundary is located approximately within the sections of localities 2 and 3 (Fig. 4). However, there are problems with the definition/identification of this boundary and with the precise correlation from the stratotypes to the nannoplankton stratigraphy. The Lower Paleocene is here regarded as synonymous with the Danian and the Upper Paleocene with the Selandian and Thanetian. Thomsen & Heilmann-Clausen (1985) concluded that the Danian–Selandian boundary is very close to the NP4 to NP5 boundary, with the top Danian in the uppermost NP4 or the lowermost NP5. The basal Selandian is in NP5 (Perch-Nielsen, 1979). This is in contrast to the position of the boundary in uppermost NP3 indicated by Harland *et al.* (1989) but close to the uppermost NP4 position suggested by Berggren *et al.* (1985) and depicted here in Fig. 7.

The main assemblage of the upper parts of locs 2 and 3 and of locs 4–8 is comparable to the dinoflagellate cyst zones 2 and 3 in Denmark of Heilmann-Clausen (1985), which together with zone 4 are correlated with NP5 to NP8, and to the *C. speciosum* Zone in Denmark and West Greenland of Hansen (1980). However, the index species of zone 3 (Heilmann-Clausen, 1985) has not been found in this study. A subdivision of this interval can be made on the basis of dinoflagellate cysts, as discussed below, but the correlation with the NP zones is not very precise. However, it can be concluded that the age of the main assemblage and the strata in localities 2 (upper part), 3 (upper part), 4, 5, 6, 7 and 8 is early Late Paleocene.

The last occurrences of *Cerodinium speciosum* subsp. *speciosum*, *Cerodinium striatum*, *Palaeocystodinium australinum*, *Palaeocystodinium bulliforme* and *Palaeoperidinium pyrophorum* in localities 5, 6, 7, and 8 (Fig. 4) are comparable with the boundary between dinoflagellate cyst zones 2–3 and 4 in Denmark of Heilmann-Clausen (1985) and with a level in the upper *C.* (*D.*) *speciosum* Zone (Hansen, 1980). This level is probably equivalent to the boundary between NP6 and NP7 (Hansen, 1980). The last occurrences of these species in the Upper Paleocene are widely used as stratigraphical markers in the North Atlantic and NW European regions. The suggested correlations of this level to the NP zones vary however and are uncertain. The boundary is therefore marked with a broken line in Fig. 4.

The *C. speciosum* subsp. *glabrum* / *D.* cf. *oebisfeldensis* assemblage from locality 13 at Tuapaat, Disko, is

Fig. 4. Distribution of dinoflagellate cysts and other algae in Tertiary sediments from Disko and Nuussuaq, West Greenland. The occurrence of a species is marked by a black dot whereas doubtful occurrences/identifications are marked with questionmarks. Localities 1–13 are geographically and stratigraphically located on Figs 1–3 and listed in Table 1.

comparable to dinoflagellate cyst zone 5 of Heilmann-Clausen (1985) which is equivalent to NP9. However, the low diversity and absence of marker species make correlation uncertain and *D. oebisfeldensis* appears already in NP7 in the wells offshore eastern Canada (Williams & Bujak, 1985).

The most widespread and characteristic level in Upper Paleocene dinoflagellate cyst biostratigraphy is the first appearance of the *Wetzeliella* – group *(Apectodinium)* near the boundary between NP8 and 9 (Costa & Downie, 1976, 1979; Hansen, 1980; Heilmann-Clausen, 1985; Williams & Bujak, 1985). This level has not yet been recorded in the Tertiary sediments of Disko–Nuussuaq (Croxton, 1978; Hansen, 1980). The youngest sediments may therefore not reach above NP7–8, at least not in a marine facies, and the age of the upper strata is therefore mid-Late Paleocene, contemporaneous with the type Thanetian (Fig. 7).

Very few clearly reworked specimens have been recorded. A specimen of *Gonyaulacysta jurassica* (Deflandre) Sarjeant, 1982 (Fig. 5,H), from loc. 8 in Agatdalen suggests reworking of Middle to Upper Jurassic sediments which, however, are not recognised in this region or within considerable distances. However, Haughton (1860) reported a Jurassic bivalve from a sea-bottom sample at an approximate position south of Disko (Denham, 1974). This very isolated occurrence has not been verified by later studies, but is in accordance with the here reported occurrence of some few Jurassic dinoflagellate cysts.

Biostratigraphical correlation within the Disko–Nuussuaq area. The NP3 coccolith assemblage, *Chiasmolithus danicus* Zone, forms a fairly good correlation level from the basalt and conglomerate at Marraat Killiit at a very low level in the Vaigat Formation (Jürgensen & Mikkelsen, 1974), via the 'Sonja lens' in the Agatdal Formation, Agatdalen in central Nuussuaq (Perch-Nielsen, 1979) to the 'second' tuff bed in the Kangilia Formation at Kangilia on the north coast of Nuussuaq (Jürgensen & Mikkelsen, 1974) (Fig. 1).

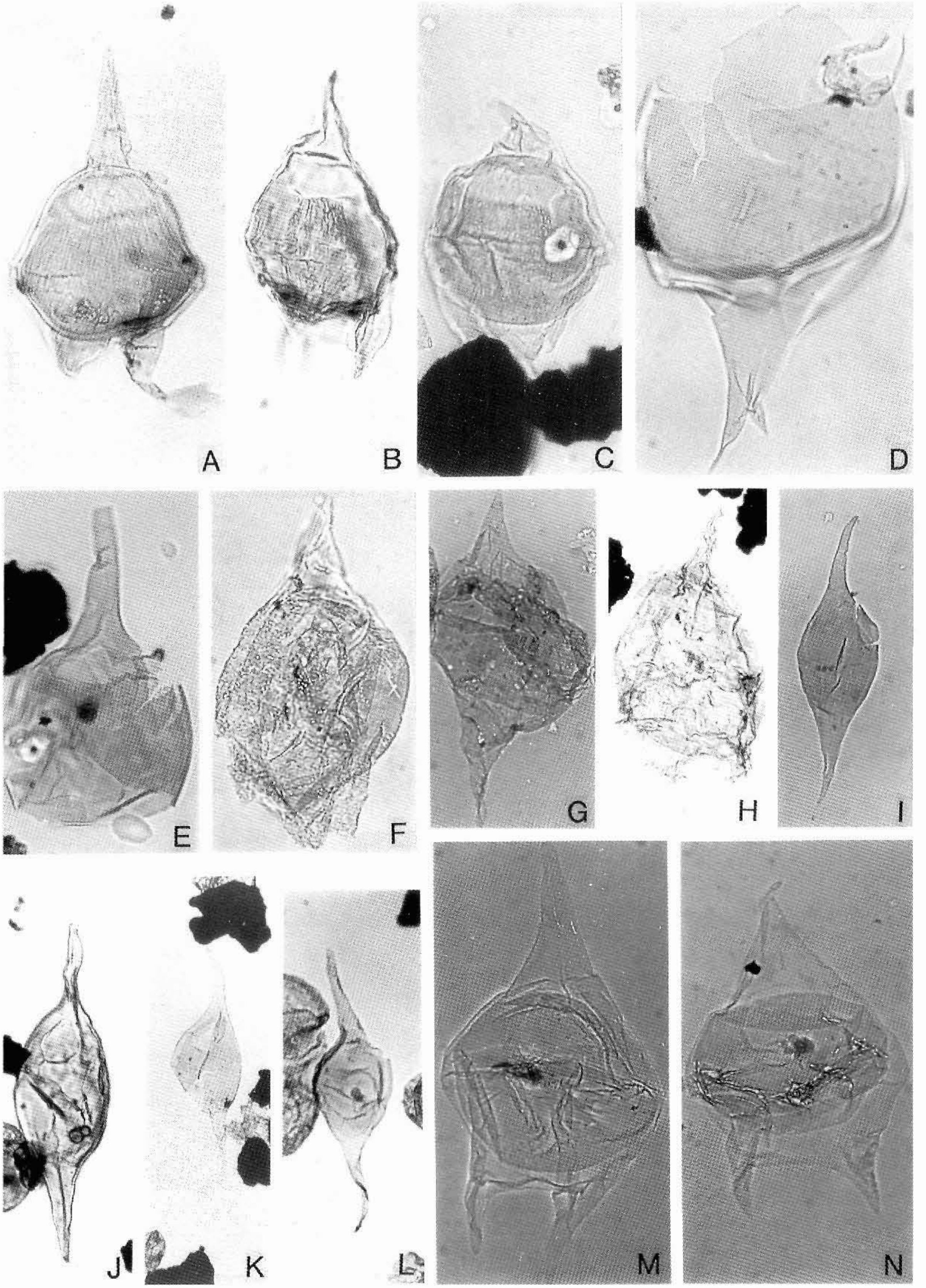
The indicated NP4 – NP5 boundary is found at locality 2 on the south coast of Nuussuaq in shales with hyaloclastite sand layers below hyaloclastites, and at locality 3 in central Nuussuaq in shales reworked by hyaloclastites (Figs 1, 2). In both cases the overlying/reworking hyaloclastites belong to informal unit B in the middle part of the Naujánguit Member of the Vaigat Formation (cf. Fig. 2). Unit B thus belongs to the lowermost part of NP5.

The suggested NP5+6 – NP7+8 boundary between localities 8/9 and 10 (Fig. 4) cannot be placed in the field because there is a big palynostratigraphical hiatus between these two localities. This hiatus comprises the upper half of the Vaigat Formation: the Ordlingassoq Member, from which only the lowest locality (loc. 9) yielded a few non-diagnostic dinoflagellate cysts. The highest level in the Vaigat Formation which can be correlated to a nannoplankton zone is the Asuk Member (Fig. 2).

Localities 10 to 13 have a dinoflagellate cyst assemblage that is younger than that of localities 1–8 and is correlated to NP7–8. Localities 10 to 13 are all situated in the Maligât Formation on eastern and southern Disko (Fig. 3), in the lower and middle part of the Rinks Dal Member.

In conclusion, the lower part of the Naujánguit Member corresponds to NP3–4 (Danian), and most of the upper part of the Naujánguit Member, up to and including the embedded Asuk Member, corresponds to NP5–6 (Selandian). The uppermost part of the Naujánguit Member and the whole of the Ordlingassoq Member may correspond to either NP5–6 or NP7–8, Selandian or Thanetian. The lower and middle part of the Rinks Dal Member correspond to NP7–8, Thanetian, whereas the upper part of the Rinks Dal Member and the Nordfjord and Niaqussat Members (Fig. 3) cannot be correlated.

Fig. 5. A: *Cerodinium striatum*, MGUH 21052 from GGU 362107. B: *C. striatum*, MGUH 21053 from GGU 362078. C: *Cerodinium speciosum* subsp. *speciosum*, MGUH 21054 from GGU 20248. D: *Palaeocystodinium bulliforme*, MGUH 21055 from GGU 360002. E: *P. bulliforme*, MGUH 21056 from GGU 362102. F: *P. bulliforme*, MGUH 21057 from GGU 362102. G: *P. bulliforme*, MGUH 21058 from GGU 352154. H: *Gonyaulacysta jurassica*, MGUH 21059 from GGU 274463. I: *Palaeocystodinium australinum*, MGUH 21060 from GGU 352164. J: *P. australinum*, MGUH 21061 from GGU 362106. K: *P. australinum*, MGUH 21062 from GGU 362073. L: *P. australinum*, MGUH 21063 from GGU 362078. M: *Cerodinium speciosum* subsp. *glabrum*, MGUH 21064 from GGU 323317. N: *Deflandrea* cf. *oebisfeldensis*, MGUH 21065 from GGU 323317. Please note that all specimens are enlarged approximately 500 times except the specimens of *Palaeocystodinium* in I to L which are enlarged approximately 250 times.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Discussion

Duration and timing of the volcanism

The volcanic sequence in West Greenland comprises a unique geological setting where subaerial lavas can be followed laterally into hyaloclastites in a marine basin. The marine sediments contain dinoflagellate cyst assemblages that can be correlated to marine nannoplankton zones, whereas the coeval subaerial lavas show magnetic reversal zones. This setting allows an estimate of the duration and timing of the volcanism, and a suggestion for identification of the magnetic reversal zones present. Absolute ages can only be assigned to the sequence with much uncertainty because the various time scales in use do not agree on the ages of, e.g. standard biozones.

As outlined above, we have correlated the marine strata of the area to the NP3–NP8 zones. These zones were deposited during a time span given as four to six million years (Berggren *et al.*, 1985; Harland *et al.*, 1989). This is then the minimum duration of the main plateau-building volcanic phase in West Greenland (Fig. 7).

In comparison, other plateau basalt sequences are considered to have formed in similar or shorter time periods. In the North Atlantic basalt province the extrusion of the known part of the Faeroes basalts seems to have lasted 5–6 million years (Waagstein, 1988), whereas the basalts in East Greenland were mainly formed within 3 million years (Soper *et al.*, 1976; also discussed in Berggren *et al.*, 1985). The Deccan traps have been claimed to have formed very rapidly, even in less than one million years (Courtillot *et al.*, 1986).

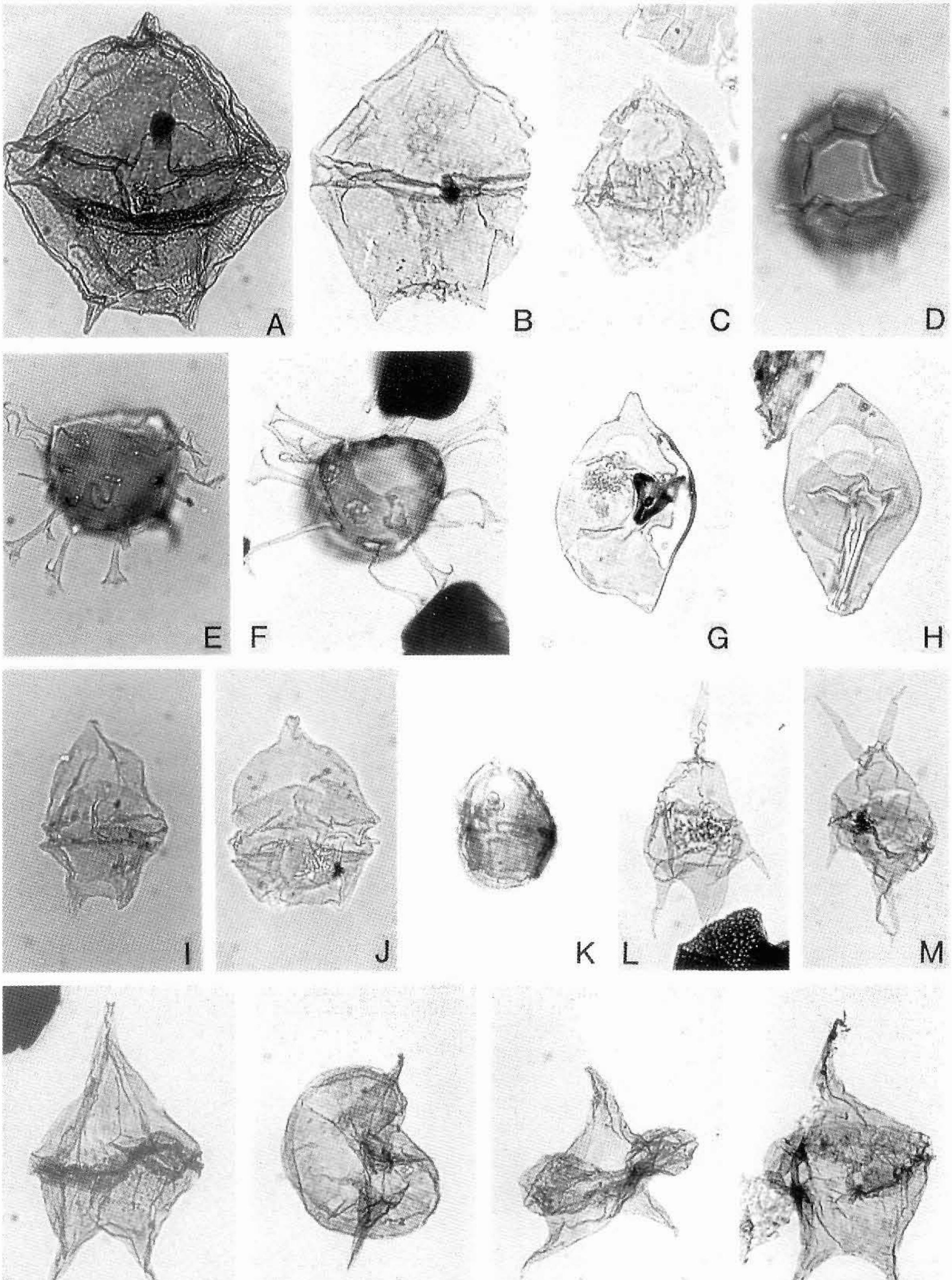
The relatively long duration of the volcanism in West Greenland is especially remarkable when the picritic character of the Vaigat Formation is considered. A minimum duration for the picrite volcanism (i.e. the Vaigat Formation only) of 3 million years can be obtained by assuming that all of the Ordlingassoq Member correlates to NP5–6 (Fig. 7). The high input of heat necessary to generate the picrites was apparently sustained over this period, and no 'density traps' preventing the picrites from being erupted (Cox, 1980) were established.

The palaeomagnetism of the subaerial basalts on Disko and Nuussuaq has been investigated by Kristjansson & Deutsch (1973), Deutsch & Kristjansson (1974), Athavale & Sharma (1975), and Hald (1977). Their results are summarised in Fig. 7 that also shows which parts of the basalt sequence that are covered by these investigations. Most of the basalts are reversely magnetised, but a sequence of normally magnetised lavas occurs in the Naujánguit Member on both Disko (Athavale & Sharma, 1975) and Nuussuaq (Hald, 1977) at the same stratigraphic level. Athavale & Sharma (1975) tentatively referred this sequence to anomaly 25.

The normally magnetised lava sequence is situated stratigraphically somewhat below informal unit B in the Naujánguit Member. It is therefore below the NP4–NP5 boundary and thus belongs in NP4 or perhaps in NP3 (Fig. 7). Following Berggren *et al.* (1985) anomaly 27 occurs within NP4 and anomaly 28 in the bottom of NP3. We suggest that the normally magnetised lava sequence is anomaly 27. It is unlikely to be anomaly 28 because this solution leaves no 'room' for reversely magnetised NP3 basalts at lower levels, and it also implies that anomaly 27 has to be absent. On the other hand the anomaly 27 solution fits all the data (Fig. 7).

Anomaly 26 lies at the boundary between NP6 and NP7 and should thus be present on Disko and Nuussuaq. We can think of three possible reasons why it has not been found: (1) It is situated in the unsampled lower part of Ordlingassoq Member, (2) The sampling in the upper Ordlingassoq and lower Rinks Dal Members has not been sufficiently closely spaced, (3) No lavas were produced during anomaly 26. The first possibility is considered the most likely; it can be tested by further work. It implies that the reversely magnetised upper part of the Naujánguit Member belongs to magnetochron 26R, whereas the upper Ordlingassoq and the Rinks Dal Members belong to magnetochron 25R (Fig. 7).

Fig. 6. A: *Palaeoperidinium pyrophorum*, MGUH 21066 from GGU 20248. B: *Palaeoperidinium* sp. MGUH 21067 from GGU 340498. C: *Spinidinium* cf. *clavus*, MGUH 21068 from GGU 362078. D: *Impagidinium* sp., MGUH 21069 from GGU 20248. E: *Hystrichosphaeridium tubiferum*, MGUH 21070 from GGU 20248. F: *H. tubiferum*, MGUH 21071 from GGU 20248. G: *Isabelidinium cooksoniae*, MGUH 21072 from GGU 362107. H: *Isabelidinium* aff. *bakeri*, MGUH 21073 from GGU 362107. I: *Isabelidinium viborgense*, MGUH 21074 from GGU 352164. J: *I. viborgense*, MGUH 21075 from GGU 362073. K: *Alisocysta circumtabulata*, MGUH 21076 from GGU 362102. L: Gen. et sp. indet., MGUH 21077 from GGU 279013. M: Gen et sp. indet., MGUH 21078 from GGU 279013. N: *Phelodinium kozlowskii*, MGUH 21079 from GGU 362078. O: *P. kozlowskii*, MGUH 21080 from GGU 362078. P: *P. kozlowskii*, MGUH 21081 from GGU 362078. Q: *P. kozlowskii*, MGUH 21082 from GGU 362078. Please note that all specimens are enlarged approximately 500 times.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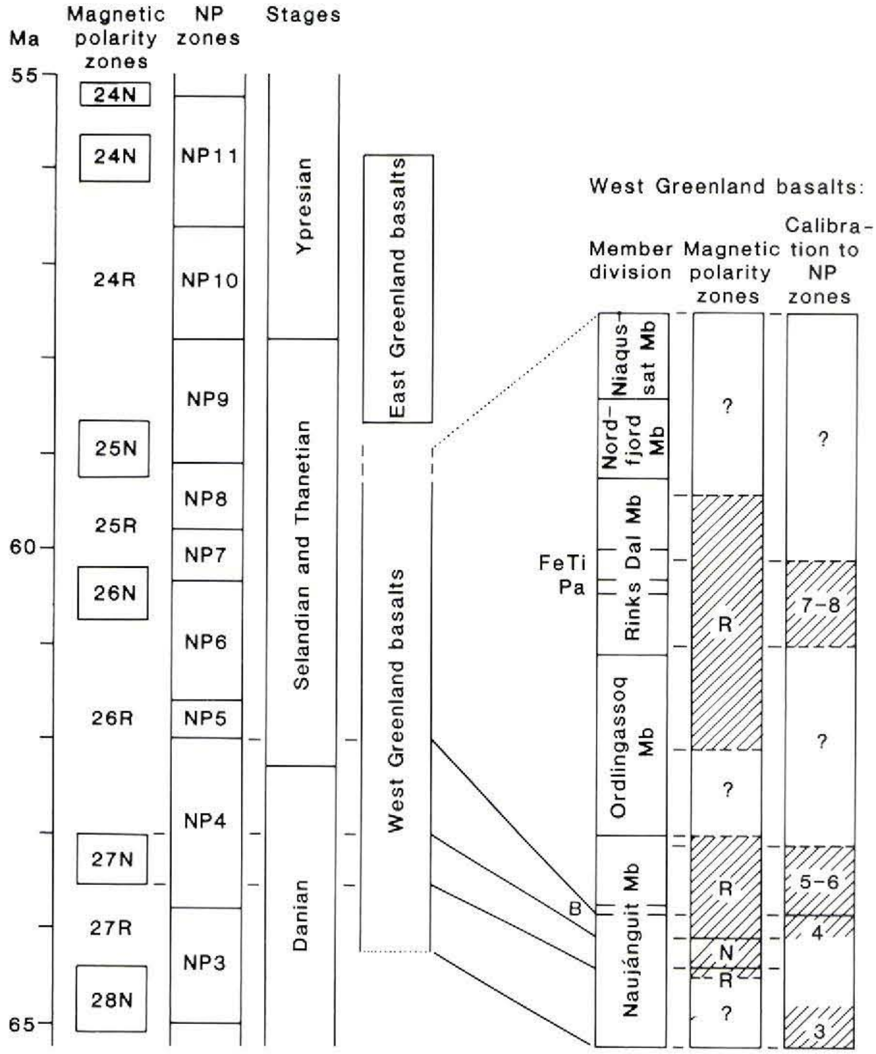

Fig. 7. Correlation between magnetic polarity zones and marine nannoplankton (NP) zones. Left: After Berggren *et al.*, 1985. Right: West Greenland basalts. Note that the absolute age scale (far left) is not well calibrated, and no absolute ages can be assigned to the basalts. R = reversed magnetic polarity, N = normal magnetic polarity, ? = not known, FeTi = FeTi unit in Rinks Dal Member, Pa = pahoehoe unit in Rinks Dal Member, B = informal unit B in Naujánguit Member.

Timing in relation to other parts of the North Atlantic basalt province

The volcanism in the Early Tertiary began at different times in different parts of the North Atlantic. West Greenland was among the first areas to start, in Middle Danian time (NP3). Apart from West Greenland, volcanics of Danian age, and older, are only known with certainty from the Porcupine Seabight Basin west of Ireland (Tate & Dobson, 1988). The magmatism in the British part of the province also started fairly early, around 63 Ma according to K-Ar dating summarised by Mussett *et al.* (1988). This is Danian according to both Berggren *et al.* (1985) and Harland *et al.* (1989).

The start time of the volcanism in the Faeroe Islands is not known with certainty because the bottom of the lava pile has not been penetrated by drilling. The lowest drilled basalts are placed in magnetochron 26R by Waagstein (1988).

In East Greenland, the extrusion of basalts began in magnetochron 24R, during deposition of NP9 (Soper *et al.*, 1976). At this time the main stage of plateau-building volcanism in West Greenland was terminated so that, with the possibility of some minor overlap in time, the centre of the volcanic activity actually switched from West to East Greenland (Fig. 7).

The volcanism and continental break-up of the North Atlantic in the Early Tertiary has been interpreted as being the effect of a hot mantle plume centred beneath East Greenland, with a plume head radius of *c.* 1200 km (White & McKenzie, 1989). The timing relations summarised above indicate that the volcanic activity began at the periphery of the plume (West Greenland and Scotland) and not over the central part. Furthermore, the 'peripheral' asthenosphere in West Greenland was able to produce very large volumes of hot picrite magma. These differences in timing and character of the volcanic products in different parts of the North Atlantic indicate that the structure and tectonics of the lithosphere over the plume exerted a considerable control over the volcanism.

Conclusions

Palynological investigations of clastic sediments coeval with volcanic rocks of the West Greenland Basin have demonstrated a systematic geographical and stratigraphical distribution of organic facies and dinoflagellate cysts.

The organic matter of the samples can be classified within six facies which are related to the sedimentary environment. They vary from a dominance of terrestrial organic debris in fluvial and lacustrine to brackish deposits, to resin-like material, coaly rounded grains or black and brown woody material in bottom deposits of the deep water-filled basin.

The dinoflagellate cyst assemblage is of a typical mid-Paleocene composition and shows a stratigraphical variation which indicates an Early Paleocene (Late Danian) to Late Paleocene (Selandian and Thanetian) age by correlation especially to areas from offshore East Canada and Denmark. This correlation also suggests equivalence to the standard calcareous nannoplankton zones NP4 to NP7–8.

The water-filled basin with hyaloclastites of the lower and middle part of the Naujánguit Member of the Vaigat Formation was marine, and partly contemporaneous with the sedimentary Kangilia Formation. Subaqueous volcanic rocks and tuff sequences from the Asuk Member within the upper part of the Naujánguit Member are also marine, and are contemporaneous with the Abraham Member in the upper part of the marine Agatdal Formation. The lowest investigated levels in the Naujánguit Member corresponds to nannoplankton zone NP4. The upper part of the Naujánguit Member corresponds to NP5–6.

The water-filled basin with hyaloclastites of the Ordlingassoq Member of the Vaigat Formation was lacustrine and partly contemporaneous with the lacustrine Naujât Member of the Upper Atanikerdluk Formation. Because of the non-marine character of the basin, the Ordlingassoq Member cannot be placed in a NP zone.

The water-filled basin that existed during the emplacement of the volcanic rocks of the Rinks Dal Member of the Maligât Formation was mostly non-marine. However, marginally marine conditions existed in southern Disko. This part of the sequence corresponds to NP7–8. The overlying part of the Maligât Formation cannot be correlated to the NP zone system because the lavas are subaerial.

Earlier work has demonstrated the presence of coccoliths of a NP3 assemblage in the stratigraphically lowest parts of the volcanic sequence, not covered here. The presently known stratigraphical range for the volcanics is thus equivalent to NP3–NP8, giving a minimum duration of 4–6 million years for the main plateau-building stage of the volcanism. Absolute ages cannot be assigned to the sequence because the various time scales in use do not agree.

Palaeomagnetic investigations of the subaerial lavas have found that most are reversely magnetised, with one normally magnetised sequence within the Vaigat Formation. This sequence can now be stratigraphically placed just below the NP4–NP5 boundary. Following Berggren *et al.* (1985) it can thereby be identified as anomaly 27. Anomaly 26 within NP6+7 should be present but has not been found.

Whereas the basalts in West Greenland were mainly erupted within the interval of NP3–NP8, the basalts in East Greenland started erupting during deposition of NP9, so that the volcanism switched from West to East Greenland. In terms of the postulated mantle plume in the North Atlantic, centred beneath East Greenland and with a radius of 1200 km, this means that the volcanism would have started in the peripheral parts of the plume and only later switched to the central part. This is only conceivable in terms of substantial lithospheric control of the volcanism.

Acknowledgements. The field work was partly supported by the Danish Natural Science Research Council. Søren Floris kindly put his field diaries and samples at our disposal.

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