

Palaeogeography and Facies Distribution in the Tertiary of Denmark and Surrounding Areas

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A short review of the stratigraphical terminology and nomenclature of the Danish Tertiary is presented. The Lower Paleocene (Danian) is lithologically similar to the Upper Cretaceous but has a more variable facies distribution, and is mainly restricted to the area north of the Fyn-Ringkøbing ridge. The Upper Paleocene (Selandian) is also variable in facies and consists mostly of glauconitic clays and marls. In the Eocene, volcanic ash, diatomites and extremely fine-grained clays were deposited. One of the still incompletely understood palaeogeographical peculiarities in the area during the Cretaceous to Oligocene is the predominance of sediments and faunas of open oceanic, and partly deep water type close to the Fennoscandian (Baltic) Shield. Possible explanations for this anomaly are discussed.

In the Upper Oligocene terrigenous clastic sand begins to appear in quantity, and the Miocene is dominated by an alternation between terrestrial/limnic sands with lignite, and marine, glauconitic and micaceous clays and sands. A Miocene drainage system from the east and north-east can be discerned, and it appears to be shifted towards the south during the Pliocene, possibly reflecting the uplift of the Atlantic margin of the Fennoscandian Shield. The mechanism and timing of this tectonic event is not completely understood, but it must have been of major importance for the palaeogeographical development of the region, and for the formation of the sedimentary basins.

It is concluded that sediment supply and facies were influenced mainly by biological and tectonic parameters, whereas climate played a less important role. The climate appears to have been tropical to sub-tropical in the region up to, and including, the Upper Miocene, with a rapid cooling during the Pliocene, culminating in the Pleistocene glaciations.

Except for minor fluctuations and Southern Sweden, the coastlines were roughly parallel and close to the present coasts of Norway and Sweden until the Miocene. Since then the area has been low, fluctuating between flats and shallow sea.

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Introduction

A glance at a map of the distribution of Tertiary strata around the North Sea (Fig. 1) shows that Denmark has a key position in this respect. Here the exposed Tertiary is closest to the productive areas in the northern part of the North Sea, and because of the structural trends, the development in Denmark can be extrapolated out into the off-shore region.

The Tertiary of Denmark, and surrounding regions, has been studied for a long time, and one would immediately suppose that these areas were known in detail. There are, however, restrictions which must be considered when evaluating the data from Denmark. Besides the imprecision inherent in the drilling methods used, there are two additional sources of error and inaccuracy.

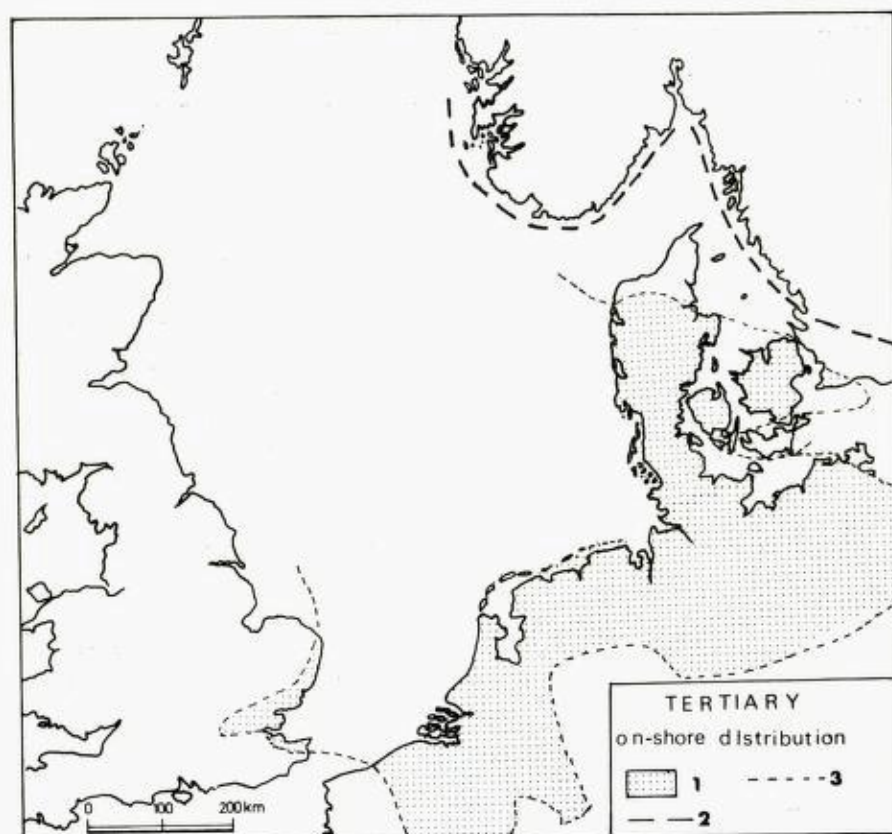


Fig. 1. The distribution of the Danish Tertiary in relation to the North Sea basins.

1. Areas where Tertiary strata are found (partly covered with Pleistocene and Holocene).
2. The generalized coast-line, from the end of the Lower Cretaceous to the Oligocene.
3. Approximate outcrop boundary of the Tertiary.

During the Pleistocene glaciations, thick ice-sheets invaded Danish territory, and to some extent ploughed up the soft Tertiary beds which lay on top of the thick sedimentary sequence. This has produced some spectacular tectonics, with intense folding and thrusting, which obscures contacts and make precise measurements of thickness rather difficult. The result is that the thicknesses given must be corrected, and the best ones are those which result from educated estimates made by experienced geologists. It would be easy to construct complicated patterns of distribution, but most of the information should not be taken at face value because of these sources of error.

Salt tectonics have deformed the soft Tertiary sediments, and on and around these structures the thickness may vary considerably (Madirazza 1968a, 1968b; Lind et al. 1972). This is partly due to original changes in thickness, and even in facies, because the salt structures were topographic features at the time of deposition. In other cases the changes in thickness may be due to differential compaction, to slumping or faulting due to post-depositional movements of the salt, and to solution features.

Most of the palaeontological and sedimentological work on the Danish Tertiary has traditionally been made on material from exposures. As mentioned above, the quality of the exposures — which at the surface have been overridden by the Pleistocene ice — is generally not good and an increasing amount of work is now carried out on material from drillings.

The bulk of the borings are short ones, for water or engineering studies (the most important ones in connection with construction of bridges). Even though most of these borings are short ones, and the information — especially in the older ones — is not always complete, they give an excellent coverage over almost all Denmark. They are all registered in the drilling archive of the Danish Geological Survey, where they form a wealth of useful information. The first maps with this kind of drilling data have been published (Andersen 1973), and will be an indispensable tool for the study of the geology of Denmark when they have been completed.

The deep drillings have been made in the search for hydrocarbons, and especially those made in the first phase of exploration (cf. Sorgenfrei & Buch 1964; Sorgenfrei 1966) must be used with considerable caution, since most of them were made on or near salt-structures where the Tertiary strata may have been deformed.

The new borings, made in the second phase of exploration, are better in this respect (Rasmussen 1973b, 1974), and are the key points in the description of the Danish Tertiary. Seismic studies, done in connection with the exploration, have not and cannot be used extensively in working out the detailed stratigraphy of the Tertiary, because of the low velocity contrast between the different formations. The only useful information obtained is the depth to the top of the carbonates (Danian, or where it is missing, the Maastrichtian).

Much of the work on the Danish Tertiary is done by the Geological Survey of Denmark, and most of the information used in this paper is based on the work of the Survey staff. It should also be noted that an enormous amount of information exists — mostly unpublished, and partly classified — in the Survey archives. The presentation given here is therefore incomplete, as part of the information has not been available. It should be regarded as a review of the present status of publicly available information.

Danian

Lithologically the Danian consists of carbonates, resembling those of the Upper Cretaceous (Ødum 1926; Brotzen 1948). Three main types are found: coccolite limestone, Bryozoan limestone and coral limestone. The coccolite limestone is an ooze, where planctonic foraminifera and coccolites dominate among the biotic constituents. It is the most common rock-type, especially in the central part of the basin.

The Bryozoan limestone is characterized by small bryozoan fragments. It grades into the coccolite facies through limestones with fewer bryozoans, floating in a coccolite ooze matrix. The most striking development is in the

bryozoan banks, elongate mound-like structures often occurring in large numbers with more or less parallel orientation. This rock typically has a high porosity, part of which is residing in the cavities within the bryozoan and other fossils, which are normally not filled diagenetically. The permeability varies widely, depending on the fracturing which seems to be related to the specific tectonic setting in the individual localities.

The formation of the bryozoan bank has been much debated, and has recently been studied by Cheetham (1971), Thomsen (1973a, 1973b) and Nielsen (1973). Thomsen (1973b) concludes that the banks have been formed in an environment with only weak water movement (currents below wave-base), and that they are authigenic and not the result of long-distance transportation of the bryozoan, which have apparently been fragmented biogenetically and not mechanically.

Such bryozoan carbonates are not uncommon on continental shelves in regions of slight supply of terrigenous sediments, and at depths of 100–400 m.

The coral limestone is found especially at Fakse, which, together with Stevns Klint nearby, is the type locality for the Danian. The limestone is no bioherm, but rather a type of coral thicket with a rich and varied fauna, but without algae. There are few good depth indicators, and none of wave activity. H. W. Rasmussen (1973) has indicated that some of the burrows found may belong to nocturnal animals seeking darkness during the day. This would imply that the coral thicket was in the photic zone, but more evidence is needed before a good estimate of the depth of deposition can be given. The spatial relationship to the bryozoan limestone indicates a similar, or perhaps slightly shallower depth, for the coral limestone.

At one locality on the Fyn–Ringkøbing High, Klintholm, the bryozoan limestone is somewhat differently developed. It is more coarse-grained and well-washed, and the grain-size distribution both of the bryozoan fragments and of other fossils is different from that of the bryozoan banks. This may imply shallower depths, perhaps even above wave-base, and is consistent with the position of this locality (and Fakse) on the Fyn–Ringkøbing High.

The Danian is resting on the Maastrichtian with a slight disconformity. Detailed studies indicate that the disconformity was a double, or even multiple one, which stops in the sedimentation, with some erosion, or at least the formation of intensely burrowed 'hard-grounds'. It is not known if this represents a total emergence above sea level, or only a period of submarine non-sedimentation, but anyhow it indicates a shallower water depth.

Thomsen (1974) has recently shown that the presumed thick, Danian, bryozoan limestone on the northern flank of the Fyn–Ringkøbing Ridge really is of Maastrichtian age. Such bryozoan limestones of Upper Maastrichtian age have been known, but only as thin and local developments. Our present knowledge indicates that the Maastrichtian is developed in bryozoan limestone facies on the ridge, which was therefore a topographic high, exposed to slight currents but probably not to wave activity.

The Danian seems to be missing on the ridge itself, but occurs as a thin

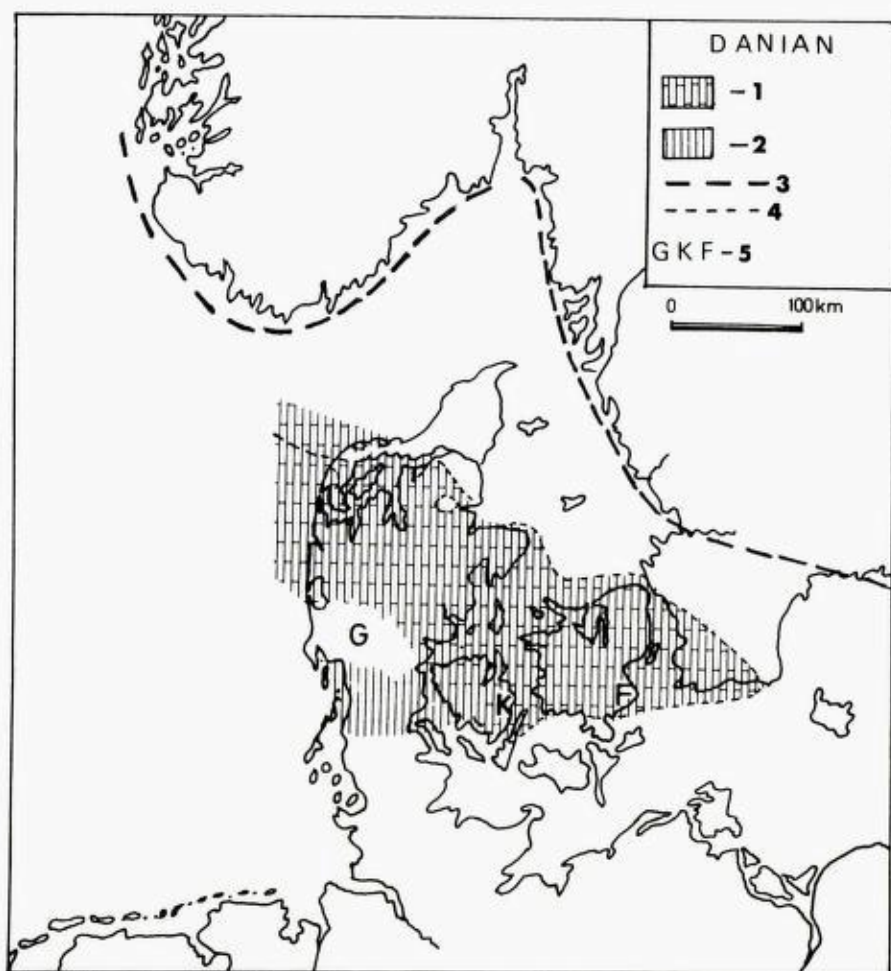


Fig. 2. The palaeogeography of the Danian.

1. Normal Danian represented.
2. Only thin Danian IV represented.
3. Generalized coast-line.
4. Outcrop boundary.
5. Important localities (G - Grindsted, F - Fakse, K - Klintholm).

sliver on the southern flank or in a special, shallower facies (at Klintholm) which differs from the ordinary bryozoan limestone, both in faunal composition and granulometry.

The Danian is subdivided either by planctonic foraminifera (cf. Berggren 1962, 1971; Bang 1969, 1973; Hansen 1970; Bang, in Rasmussen 1972), by coccoliths (Perch-Nielsen 1971), or by echinid spines (cf. Brotzen 1959). The methods are in general agreement, even though there are some discrepancies. Of the four biostratigraphical zones, only the uppermost one (Danian IV) is found on the southern flank of the Fyn-Ringkøbing Ridge (Fig. 2), and this period represents the greatest extent of the Danian transgression.

Selandian

In contrast to the Danian, the Selandian consists of clays with minor quantities of glauconite sand and marls (Gry 1935; Müller 1937). The detailed distribution of facies is not known, but the greatest variety of facies is found in the east, on Sealand. Here the basal beds are glauconite sand (Lellinge Greensand) followed by marl (Kerteminde Marl). Upwards the clays are poorer in carbonates, and grade imperceptibly into the unfossiliferous carbonate-free clays forming the transition to the Eocene.

Further west, the basal beds are thinner and less varied, and the bulk of the sequence consists of marls and clays with very little coarse-grained terrigenous components, and a decreasing carbonate content towards the top. The detailed stratigraphy of this interval is not known, but it is not altogether unfossiliferous. Foraminifera preserved as pseudomorphs of clinoptilolite (Hansen & Andersen 1969) in one of the localities, indicate that at least part of this sequence really belongs in the Palaeocene.

The Selandian sedimentation seems almost unaffected by movements of the Fyn-Ringkøbing High, but in the absence of detailed studies it is not definitely known if the basal beds on the high are younger than those in the basin. The age difference seems to be small.

The mollusc fauna of the Selandian is fairly well known from a series of older papers, e.g. by Ravn, but the modern biostratigraphy is based mostly on the foraminifera, and the nannofossils (Hansen 1968, Bang 1973).

The boundary towards the Danian is not only a sharp lithological one, but the basal Selandian is often resting on an eroded Danian, where the upper part is missing. In the basal beds of the Selandian there are reworked fossils of Maastrichtian age, indicating that the erosion cut down right through the Danian. This can be explained by assuming a Danian/Selandian faulting, creating fault escarpments on which rapid erosion took place. The vertical components of the faulting exceeded the thickness of the Danian (≈ 250 m.). The direction of the faults is not known, but it was probably parallel to the basin and high (NW-SE). Most of the erosion probably took place below sea level. There are also indications of a certain topography in the pre-Selandian carbonate surface, probably a result of the same erosion.

The Selandian has been studied in less detail than the Danian, and much remains to be done on the detailed stratigraphy. The description given by Gry (1935) is the main source for the sedimentology and for the older literature.

Eocene

The Selandian grades imperceptibly into the Eocene, and because of the lack of fossil evidence it may be difficult to define the boundary precisely.

The practical boundary is therefore taken at the base of the volcanic ash series in the Moler Formation and its lateral equivalents. This formation is

restricted to the basin in the northernmost outcrop of the Eocene, but the lower Eocene Røsnes and Lillebelt Formations are distributed all over that part of Denmark where the Eocene is found; very little in the way of systematic changes in facies has been observed.

There are some doubts as to where the boundary between the Palaeocene (Selandian) and Eocene should be placed in the North Sea area. Particularly in the subsurface geology, there is a tendency to place the boundary above the volcanic ash beds. The boundary used here is the traditional Danish one, which is convenient lithologically and supported by micropalaeontological evidence (Dinesen 1973).

The well known volcanic ash beds were the subject of the classical monograph by Bøggild (1918), and have later been studied by e.g., S. A. Andersen (1937) and Norin (1940). Most of the layers are of basaltic composition, but a few acid ones are also found. Studies of the thickness of the individual beds (which may, however, change due to compaction and tectonic deformation (cf. Madirazza & Fregerslev 1969)) and the granulometry indicate a northerly or north-westerly source for the ash and a distance to this source of 100–200 km, or perhaps less. The ash beds are known throughout the North Sea but are thickest and best preserved in the Moler Basin in North Jutland (Fig. 3). This has probably been substantiated by the finding of a magnetic structure, interpreted as a basaltic volcanic cone, off Kristiansand in the Skagerrak (Sharma 1970). Basaltic rocks, presumably in situ and intrusive into Jurassic strata, have been dredged further to the east (Noe-Nygaard 1967).

The 'Skagerrak Volcano' has not yet been positively identified by seismic studies, and it is not known with certainty if the magnetic anomaly is really a basaltic volcano, or whether it was one or more centres of volcanic activity in the Skagerrak in the early Eocene.

The Diatomites of the Moler Basin are richly fossiliferous, with a varied fish fauna dominated by oceanic, open water forms (Bonde 1966), plant fragments and wind-blown insects indicating forest conditions (Henriksen 1934; J. P. Andersen 1947; Heie 1970) on a neighbouring land, presumably situated to the north. Because of the distribution pattern of the volcanic ash, the prevailing winds must have come from the north and north-west.

The microfossils are dominated by diatoms (Stolley 1899), spores and pollen, with radiolarians and archeomonadids (Deflandre 1932) as minor constituents. Calcareous forms are normally absent, and benthonic fauna (ophiurids and a few molluscs) are restricted to a few bioturbated bedding planes.

The Moler diatomite biota was therefore dominantly planctonic with no bottom fauna, except in some few special cases. This is so striking that it cannot be due solely to lack of nutrients, but must be attributed to lack of oxygen in the bottom waters. The rather high content of organic matter, and the usually completely preserved fossils (fishes and insects) indicating absence of scavengers also support this.

The Moler diatomite contains some carbonate concretions and bands

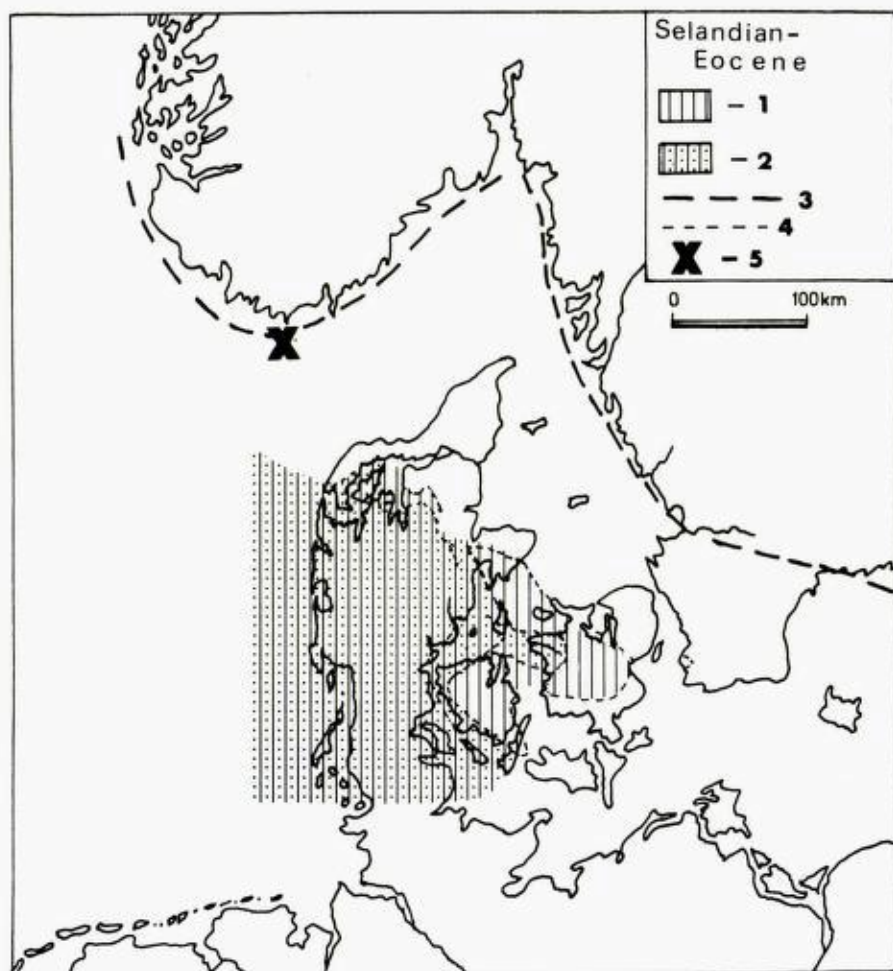


Fig. 3. The palaeogeography of the Selandian and Eocene.

1. Areas where only Selandian is represented.
2. Areas where both Selandian and Eocene are represented.
3. Generalized coast-line.
4. Outcrop boundary.
5. Presumed location of the Skagerrak volcano (geophysical anomaly).

(cement-stone) which are finely laminated like the rest of the diatomite, with the exception of the few bioturbated beds mentioned above.

There are two opposite views about the sedimentation rate of the diatomite. Bonde (1973) suggests that the lamination represents annual varves, indicating a high production rate of organic material, and consequently high net sedimentation rate (ca. 1000 mm/1000 years) in a short period (ca. 60,000 years). Sharma's studies (1969) of the magnetic reversals of the volcanic ashbeds indicate a much longer time for the duration of the formation, approximately 3 mill. years, given an average net sedimentation rate of only 20 mm/1000 years. Both models are compatible with the fact that there are

over 130 well-defined ash beds in the sequence, and with the observations on sedimentation rates of similar recent sediments.

Sharma's model is most extreme, requiring sedimentation rates of oceanic type, indicating low nutrient supply and restricted organic production. No breaks have been detected in the sequence to explain the low sedimentation rate, and it would be surprising if the Eocene 1 (of which the Moler formation is a part) had a duration of over 3 mill. years.

Bonde's model requires a rich nutrient supply and high organic productivity, and is compatible with sedimentation rates found in such environments today. The anaerobic bottom conditions also indicate a high organic productivity in the surface water, rather than a low one. In the clays, which are the lateral equivalent to the Moler with the same volcanic ash beds, Bonde's model would give a net average sedimentation rate of about 200 mm/1000 year, which seems to be realistic. If this sedimentation rate were typical of the similar sediments in the rest of the Eocene in Denmark, the sequence would have been several times thicker, and a consequence of Bonde's model is that less than 1/6 of the Eocene is represented as continuous sediments in Denmark. The lower sedimentation rate implicit in Sharma's model would — under the same assumptions — give an unrealistically long time interval for the Eocene.

The Eocene above the volcanic ash beds (and the lateral equivalents of the Moler) has a rather poor macrofauna — some fishes, molluscs and trace fossils. The microfossils are much better represented, and the foraminifera have been studied by Dinesen (1972, 1973) and the coccoliths by Perch-Nielsen (1971). There are also numerous hystricospaerids, diatoms and other siliceous microfossils.

In contrast to the Lower Eocene, which is uniformly distributed, the Upper Eocene is most completely developed in the North Jutland basin (Fig. 4), whereas only the lower part is found in the Fyn-Ringkøbing ridge (cf. Dinesen 1973).

The development of the Eocene, and partly also the Selandian (Upper Paleocene), poses some interesting paleogeographical questions which are important to the understanding of the development of the Danish Tertiary.

The sediments are normally extremely fine-grained, with more than 70–80% less than $2\ \mu$, and often more than half below $0.2\ \mu$. Coarse clastic material is extremely sparse, the small coarse fraction consisting almost exclusively of organic remains or products of diagenetic processes. The sedimentation rate (calculated from the number of microfossils, particularly hystricospheres, and the ash beds — see above) is very low, at least for many beds.

The fauna consists mostly of microfossils; three types of foraminifer-faunas occur (Dinesen 1972), one dominated (75–90%) by planctonics, one with almost exclusively agglutinating, benthonic types, and a third dominated by calcareous, benthonic ones, but often with a much higher content of planctonics than in the present North Sea. The details of the successions of these faunal assemblages in the individual sections are not known, but a general review has been given by Dinesen (1972).

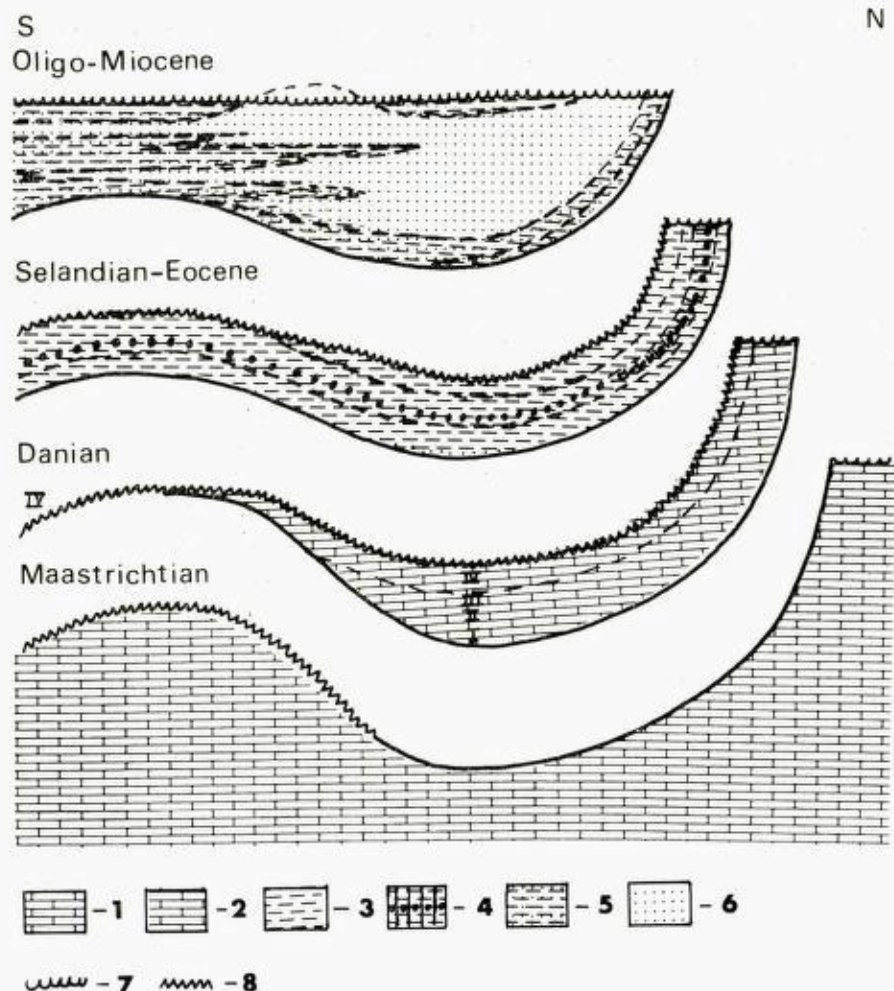


Fig. 4. Diagrammatic, exaggerated section through the North Jutland Basin and the Fyn-Ringkøbing High. The thicknesses are only approximate.

1. Chalk (mostly coccolith ooze carbonates).
2. Bryozoan carbonates of chalk type.
3. Fine-grained clays.
4. Diatomite, with volcanic ash beds.
5. Micaceous clays.
6. Sand and silt with lignite.
7. Truncation of beds due to glacial erosion.
8. Major surface of erosion or non-deposition.

Taken at face value, these data would indicate very deep and partly cold water. The carbonate-free sediments with agglutinating faunas recall those deposited below the compensation depth. An unsuspecting student would most likely refer some of the samples from the Danish Eocene to abyssal sediments in an oceanic basin. Since it is geologically improbable that the Danish basin was more than 2000 m deep in the Eocene, one must conclude that the sediments mimic abyssal, oceanic sediments in a way which reflects rather unusual geological and oceanographic conditions.

The two important questions are: (i) why did not the Fennoscandian Shield yield any appreciable amount of terrigenous clastics to the basin (it did up to the lower Cretaceous, and from the Oligocene on) ?; and (ii) what kind of oceanographic model can explain the peculiar faunas and sediments?

(i) The amount of clastics coming from a land area will depend on the relief and the run-off. Most of the Shield probably had a low relief, such as today, or even lower, but some geomorphological studies (Gjessing 1967) indicate that at least parts of Norway had a moderate relief even in the Mesozoic. Under the prevailing subtropical climate, considerable amounts of weathering products would be delivered even from a low-relief area. If the Shield were at least partly covered by shallow sea, currents generated by wind and tides would certainly transport more and coarser material into the basin.

It is difficult to estimate the amount and the seasonality of the run-off. It has been suggested that the area was an arid one, but that would be difficult to explain meteorologically at these (palaeontological) latitudes, even if the climatic belts were displaced and more diffuse than now. Under arid conditions, in the absence of a vegetation cover the weathering products would be more mobile, and arid regions normally are also centres of high pressure, which would give considerable eolian sedimentation into adjoining basins. Sediments which could be identified as eolian have not been observed in the Danish Eocene.

The presence of a rich insect fauna, indicating forest conditions (J. P. Andersen 1947, Bonde 1973), in the diatomite beds in the basin supports an interpretation with a coast-line close by, or nearer than the present one, and the land area covered with a permanent vegetation cover in a subtropical, at least partly, humid climate.

The same lack of terrigenous clastics is found in the Upper Cretaceous and Danian, when carbonate sediments prevailed. In one instance, at Åsen, north of Ivosjön in Scania, there are indications of mangrove-swamp-like conditions. Here, at the extreme limit of the maximal Campanian transgression, the thin marine beds resting on kaolinitic clay with plants contain oysters which were attached to roots or branches, such as one finds in mangrove swamps to-day (Kegel Christensen, pers. comm.). If the estuaries during this period were characterized by mangrove swamps (or similar vegetation), the terrigenous sediments would be effectively filtered away and only put into recirculation when the 'filter' broke down for climatic and/or tectonic reasons in the Oligocene.

It is dangerous to generalize from one single locality, but the best model to explain the lack of terrigenous deposits in the period from the end of the Middle Cretaceous to the Lower Oligocene in our area seems to be that the land area had a low relief, a thick and permanent vegetation cover, moderate run-off rather evenly distributed over the year, and with mangrove swamps or similar vegetation operating as filters in the estuaries. The oceanographic model to explain this situation must be one which explains the seemingly deep and cold water, under conditions giving low sedimentation rates close to the continent, and under a subtropical climate.

In the Lower Eocene London Clay, there is also a discrepancy between the plant remains washed in from land, indicating a tropical to subtropical climate, and the marine invertebrate bottom fauna which appears to indicate cooler conditions.

To explain the diatomitic rocks in the centre of the basin, Bonde (1973) suggested a model with winds from the north (suggested by the distribution pattern of the volcanic ash) creating a surface current. Deflected by the Coriolis force, this would lead to upwelling of cold water. A more westerly placed counter-current would deprive the base of nutrients. This hypothesis provides a logical explanation for the conditions observed, even if the upwelling takes place farther from the continental margin than in most modern upwellings. It supposes that conditions along the Norwegian coast were compatible with the model (with a marked N-S current along the coast), and this can certainly be tested by studies of the Eocene beds on the continental shelf of Norway.

It should be noted that this model is different from normal upwellings as it will bring cold water, not from the oceans, but from the deep-water layers of the shelf. These waters are normally less rich in nutrient than upwelling deep-ocean water. The model may therefore be better to explain the normal situation in the Selandian and Eocene, rather than the presumably short episode ($\approx 60,000$ years) during which time the diatomite was formed, when parts of the basin probably received a rich supply of nutrients.

Oligocene

Comparatively little work has been done on the Danish Oligocene. The most recent work, with references to earlier literature, is found in Larsen & Dinesen (1959), Christensen (1969) and Christensen & Ulleberg (1973, 1974).

The Lower Oligocene appears to be totally missing, and the Middle Oligocene is found mostly in the basin. The sequence consists mostly of clays with the Viborg Formation at the base, sometimes with glauconitic basal beds (the Grunfør Formation) lying with a marked lithological boundary and a considerable and variable hiatus upon the Eocene Søvind Formation. The succeeding Branden Formation is lithologically similar, but the higher Cilleborg and Sofienlund Formations have an increasing content of silt and sand towards the top.

On the Fyn-Ringkøbing Ridge, the whole of the Oligocene is missing; towards the north and west a more complete sequence is found, with more littoral sediments in the south-east.

The biostratigraphy is not completely known, but recent studies by Christensen & Ulleberg (1973, 1974) indicate that the faunas known at present represent only few zones (such as Ruppel 2), whereas others either are missing or are not yet identified.

The Middle Oligocene forms the base of the Upper Tertiary in the Danish stratigraphic terminology. In sharp contrast to the fine-grained clays of typical

marine origin in the older Tertiary, the Oligo-Miocene presents a more varied picture, with sands, silts, micaceous clays and lignites, partly of fresh water and partly of marine origin.

In the Oligocene it is possible to discern the contours of a coast-line, even if littoral sediments are missing in the basin. The clay minerals show a zonation similar to that found parallel to recent coast-lines on a continental shelf (Christensen 1969). From this it is possible to reconstruct a N-S trending coast-line through Kattegat turning westwards in N. Jutland. It is difficult to estimate the exact distance to the shore-line, but from sedimentological and ecological data it is reasonable to expect it to have been at or just west and south of the present coast of Sweden and S. Norway.

The position of the coast-line is difficult to define in the Danian to Eocene, since no direct evidence of proximity to a landmass is found in the sediments from this time interval. The sum of the geological evidence indicates that the generalized shore-line was fairly stable from the end of the Lower Cretaceous to the Oligocene, along and close to the present coast of S. Sweden and S. Norway (Fig. 5).

Considering the good exposures and the minute remains of older transgressions (Middle Cambrian and Campanian) which have been discovered along the west coast of Sweden, widespread Tertiary transgressions on to the Shield would certainly have left some traces. Geomorphological studies (Gjessing 1967) also support the idea that the landscape of S. Norway is an old, pre-Pleistocene or even pre-Tertiary one.

The geological mechanism governing this stable boundary between the Precambrian shield, which is now mostly on land, and the sediment area, which is mostly submerged also today (with Denmark as the most notable exception), is still imperfectly understood. Høltedahl (1953, 1960), who first pointed out this important boundary, suggested simple faulting or flexures (Høltedahl 1970). Geophysical studies have failed to show major faults, even if minor ones are common both in the Kattegat and in the Skagerrak. The old structural lines in the Precambrian are often parallel to the 'Høltedahl-line', and at least in S. Norway there is a spectacular fault system paralleling the coast which has been active intermittently from the Precambrian to the Pleistocene. The tectonic movements along the Høltedahl-line were probably rather complicated in detail, and in chronology. They may have been comparatively 'plastic' deformations of flexure-type, alternating with sharply defined faulting, both in time and space. In a transitional area like Denmark, there are complicating elements such as the Fyn-Ringkøbing High and the comparatively high Precambrian area in northernmost Jutland, and the tectonic development was certainly not simple.

The development of the North Jutland basin and the structure of the region strongly suggest that this shield-basin boundary is an old and regular, large-scale feature, probably related to movements along neighbouring plate boundaries. The actual coast-line may have fluctuated somewhat, but basically the Shield was an area of erosion and uplift where ephemeral sediments were

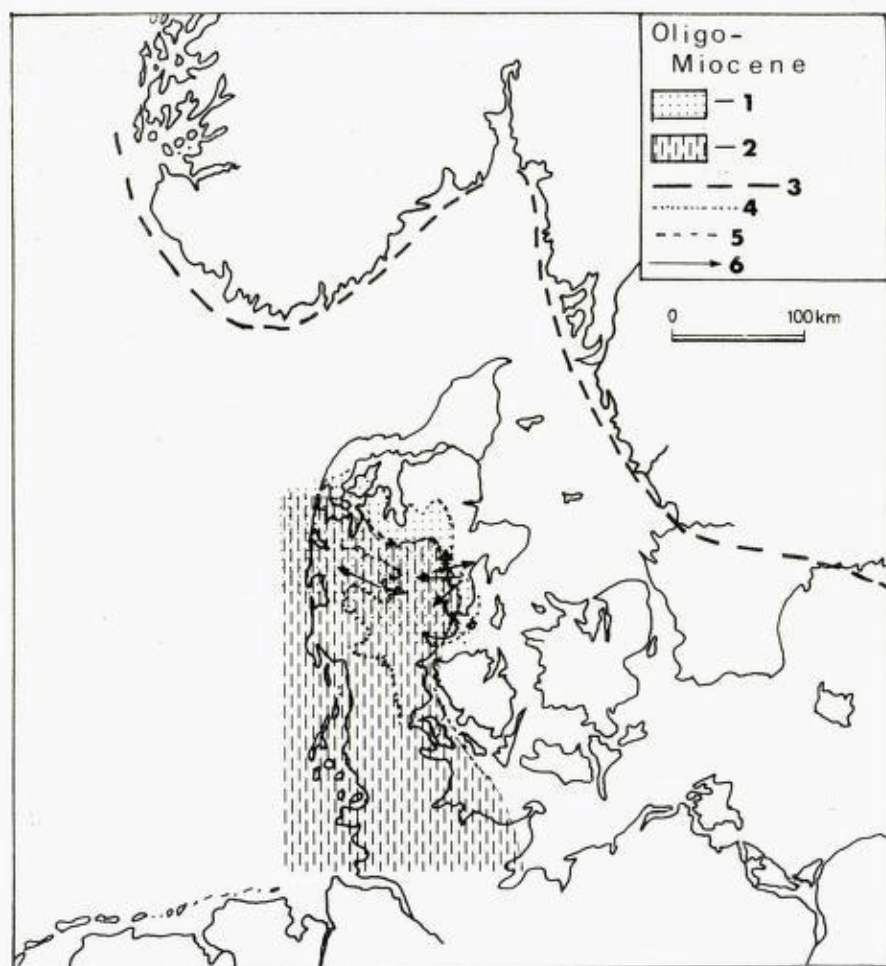


Fig. 5. Palaeogeography of the Oligo-Miocene.

1. Area where Oligocene is represented.
2. Area where Miocene is represented.
3. Generalized coast-line (this moved towards west and south during the Oligo-Miocene).
4. Western limit of the present outcrop of the marine Miocene.
5. Outcrop boundary.
6. Major transport directions (from the observations of Larsen & Friis 1973 and the present author).

rapidly and effectively removed by erosion before consolidation. Similarly, the basins were areas of sedimentation and subsidence. Even if there are hiatuses in the sequence, they are more due to non-deposition than to erosion, except locally on the Fyn-Ringkøbing High and on fault-cliffs formed by small-scale tectonics (small-scale = 200–300 m, compared to the 3000–6000 m along the Høltedahl-line).

Finally, the Pleistocene glaciers have levelled off and eroded both on the Shield and in the basin (especially along the Norwegian Channel), and dis-

turbed the soft sediments. This disturbance is not only due to the direct erosion of the glaciers, but is also associated with isostatic movements resulting from loading and unloading of the ice-sheets. This process resulted in, among other things, reactivation of the salt-domes in the basin, with considerable deformation and even faulting, which could be confused with the tectonic activity of earlier phases (Madirazza 1968a, b).

In the Baltic the palaeogeography is more complex than in the Kattegat and the Skagerrak, and Scania forms a transitional zone between the Shield and the basin over which the transgressions are partly preserved. The Campanian transgression is — as could be expected — the one which reaches farthest in the Shield, but remains of Danian and Eocene transgressions are also found. It is important to note that the Tertiary sediments on the Kattegat side — just as the Cretaceous ones — retain their open oceanic character up to the contact with the Shield, with very little by way of real littoral sediments. They are found in the Cretaceous only where the beds are in virtual contact with the Precambrian rocks. The only exception to this rule, the Upper Cretaceous or Danian Åhus sandstone in E. Scania, is well into the Baltic. This indicates that there were sediment filters (mangrove swamps or the like) in the estuaries, which in connection with low relief on the Shield and run-off evenly distributed over the year, reduced the influx of terrigenous material into the basins to a minimum.

In the Baltic there are indications of Tertiary littoral sediments. Most of them are found as erratic boulders along the north coast of Germany. A review of their age, lithology and distribution is given by Hucke (1967, pp. 106–108). Our present knowledge is insufficient to locate the original source of these rocks, and thereby the Tertiary coast-line in the region, but it is likely that it was situated largely between a N–S line through Bornholm and a NW–SE line through the southern part of Öland, until the Oligo–Miocene regression transferred it towards the west and south.

No littoral sediments of Tertiary age are known from the Kattegat region. The only observation is by Gottsche (1883), who referred the so-called *Cyrena*-boulders, which are found as erratic boulders in part of E. Denmark, to the Oligocene. This observation has been widely repeated in the literature.

Studies in progress by F. Strauch (Cologne), O. Bruun Christensen (Copenhagen) and the author indicate that these boulders are of Wealden age, and in a facies which is well known from the brackish-water Wealden in N. Germany. They probably come from submarine exposures in the Kattegat, close to the Swedish coast.

Miocene

The Danish Miocene is well known through the classical monographs of Sorgenfrei (1940, 1958, 1960) and L. B. Rasmussen (1961, 1966, 1968). Lithologically the Miocene consists of an alternation of micaceous clays and sands. The micaceous clays carry a marine fauna dominated by molluscs (cf.

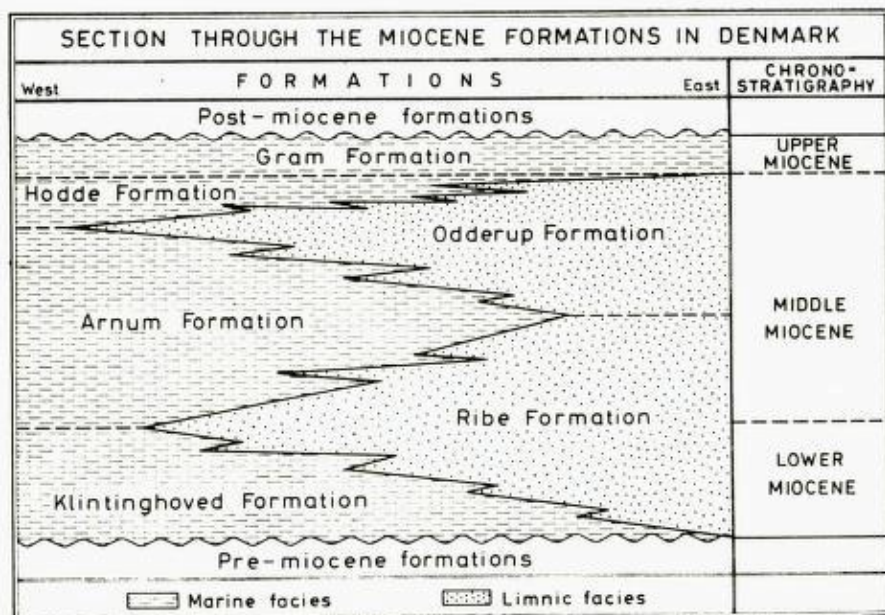


Fig. 6. Diagrammatic E-W section through Jutland, showing the Miocene formations and their inter-relationship (from Rasmussen 1966).

Sorgenfrei 1958; L. B. Rasmussen 1968) and foraminifera (Kristoffersen 1972, 1973 – in L. B. Rasmussen 1973b). Bryozoans, ostracods, fish otoliths and hystricospherids are common, and whales are often met with. Because of the well-studied faunas and the proximity in time to modern faunas, it is easy to evaluate the depth, temperature and other ecological parameters. The environment of the upper part of the Miocene (the Gram Formation) was one of an open shelf with marine water of normal salinity, climatic conditions similar to the west coast of North Africa or the SW Iberian Peninsula, and depths of around 100 m. The organic production was high, as was the sedimentation rate. The pore water of the sediments, but not the bottom water itself, was anaerobic, and pyrite is common in unweathered sediments. When the clay is exposed to weathering, the resulting acidity leads to leaching of the carbonates. Many localities, therefore, do not carry any carbonate-shelled fossils, only corroded ones. The content of fresh mica (dominantly muscovite) in flakes from more than 1 mm in diameter down almost into the clay fraction, indicates rapid transport and sedimentation, and unusually immature weathering considering the climatic situation where the source rock normally would be exposed to much more mature weathering. This indicates that the relief of the Shield had been considerably sharpened, and that this process continued throughout the Miocene, supplying fresh terrigenous material.

The detailed stratigraphy is seen in Fig. 6 (from L. B. Rasmussen 1966).

The lower, typical marine beds are lithologically the same type as the Gram Formation, but restricted faunas indicate reduced salinity or other adverse

conditions. The occurrence of high percentages of planctonic forms in some of these restricted foraminiferal faunas indicates that the salinity was not the only restricting factor, and that the hydrographic situation was probably complicated and rapidly changing. Kristoffersen (1972) has described the faunal changes, and discussed this problem, in connection with the definition of the Oligo-Miocene boundary in Denmark.

The Hodde Formation has a characteristic lithology — a black, stiff clay with glauconite where the calcareous fossils are mostly missing, presumably due to leaching. The transitional zone to the Gram Formation is a strongly glauconitiferous clay horizon. This Hodde/Gram sequence is easily identified even without fossils, and forms an excellent marker horizon.

The top of the Miocene is always a surface of glacial erosion (except in the extreme south-west corner of Denmark, cf. L. B. Rasmussen 1958, 1966), and the local distribution and structure of the Miocene is much affected by glacial activity (cf. L. B. Rasmussen 1966). The beds below the base of the Gram Formation increase rapidly in thickness towards the west; at the Danish west coast they reach over 300 m, and in the North Sea they exceed 800 m (L. B. Rasmussen 1973a, 1974). This isopach pattern, and the fact that the sediments apparently do not become finer westwards, indicate that the basin pattern also changed radically in the Oligo-Miocene, and that at least the greater part of the terrigenous sediments in the central North Sea came from the north (Norway) or north-west (Scotland), rather than through the drainage system across Denmark.

The sand sequence in the Miocene (cf. Fig. 6) is partly fluvatile-lacustrine-estuarine, and partly marine-littoral. The sedimentary environment with micaceous clays requires large bodies of sand from which the clay was winnowed, between the area where the clays was deposited and the land. Part of this, low-lying, sand area was probably at least partly above sea level, but was dominated by marine influences. The transport directions found by Larsen & Friis (1973) show that directions from between W and NW and from between NE and SE dominate. Even if the observational material is not really sufficient, the author would like to interpret the NE/SE set as indicating the original direction of fluvatile transport (i.e., towards SW to NW), whereas the W-NW trends are more likely due to tongues of marine transgressions coming in from the W and NW. This is also supported by observations in the lignite pits, where the sand between the lignites shows transport from the east, whereas the coarsely cross-bedded sand above the lignites shows current directions from W and NW. The real picture was certainly a rather complicated one, with rapidly changing environments and transport directions and many separate sand tongues. Fjeldsø Christensen (in Koch et al. 1973) has shown that there are plant-bearing clays between the presumably marine sand and the marine Hodde Clay in one locality. More observations are therefore needed in order to unravel the detailed depositional picture of the lignite basin.

The lignites, and their flora and depositional environment, have been studied

by Koch & Friedrich (1970) and Koch et al. (1973). Their preliminary results on partly excellently preserved plant remains show a strong ecological resemblance to the North German lignites, and further studies are likely to give precise datings of the lignite beds.

Pliocene

In Denmark, Pliocene rocks are found only in the extreme south-west corner (L. B. Rasmussen 1958, 1973a). They represent a continuation of the Upper Miocene, and like the Miocene they appear to thicken and become more complete towards the west, beneath the North Sea (L. B. Rasmussen 1974).

LATE TERTIARY MOVEMENTS

There are two types of derived siliceous material which are relevant to the interpretation of the youngest Tertiary in Denmark. The first is the chert conglomerate described by Ødum (1968). This is a siliceous rock, composed of angular or slightly rounded fragments of chert, mostly or wholly of Danian age, cemented with a silica matrix. The type of chert fragments indicates weathering on land in a fluvial environment, and is entirely different from the well-rounded, often flat, ellipsoidal chert stones found in the beaches below cliffs of Maastrichtian or Danian chert-bearing carbonates. The distribution of the boulders of chert conglomerate indicate (Ødum 1968) a source between north of the present outcrop of the Danian (Fig. 2) and the Oslo Fjord. This indicates that in this area Danian carbonates, without an appreciable cover of younger rocks, were subject to subaerial weathering in Tertiary time. The original bedrock for the chert conglomerate has either been completely removed by glacial erosion (second last glaciation), or is still preserved on the bottom of the Skagerrak.

The only fossil found in the chert conglomerate — a pine-cone of Neogene affinities — also supports the interpretation of the rock being a product of subaerial weathering, and lag deposition.

In the sands intercalated with the lignites there are also silicified fossils ('silicificates'); these have been described by the author (Spjeldnæs, in Koch & Friedrich 1970, pp. 180–181). The fossils are of Early Palaeozoic age, and come from a restricted region in the Baltic where silicified fossils are common in rocks of this age, and where they have also been reported weathered free from submarine exposures (Veltheim 1962). Such silicificates have been known for a long time, but it must be mentioned that the term is used here in a restricted sense, including only the determinable fossils of well-known age (Middle Ordovician to Lower Silurian) and provenance (the area shaded in Fig. 7). As shown by Voigt (1970), silicified fossils also of Danian (and unknown) age can be found in similar situations, and uncritical use of the silicificates has led to erroneous stratigraphic conclusions (cf. Friis 1972). The author interprets the occurrence of the silicificates in the sands at Fæstervik (the main locality in the North Jutland lignite basin), as being derived from

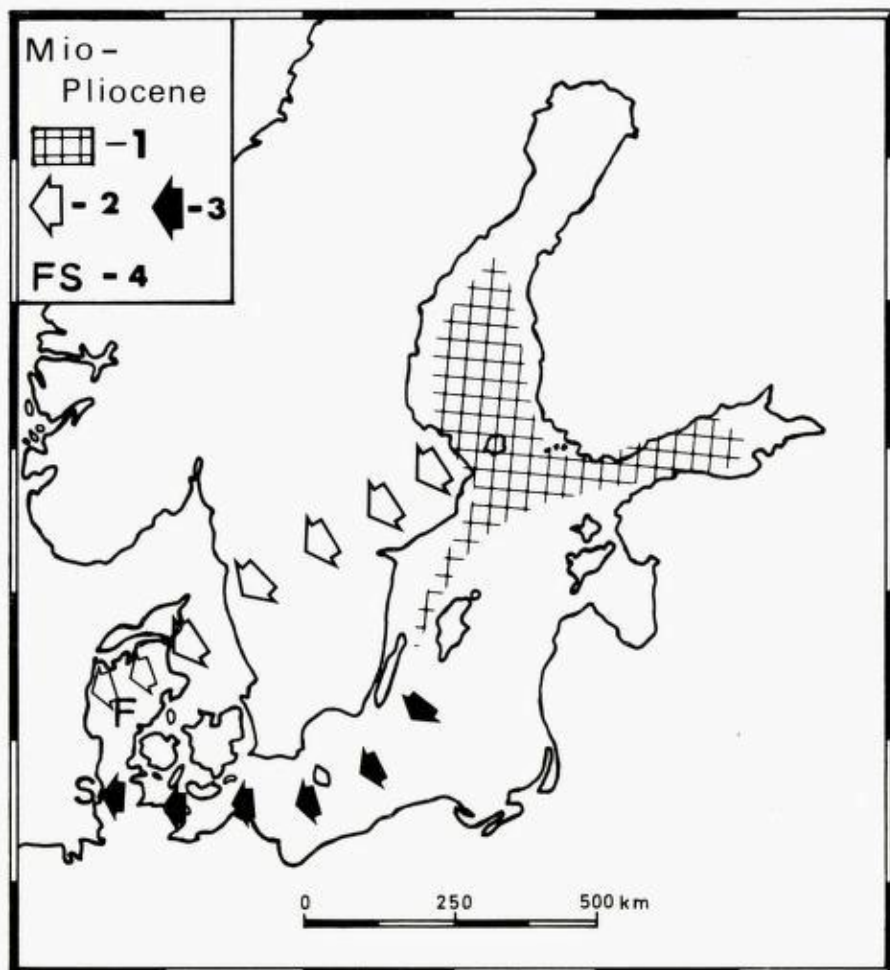


Fig. 7. Transport pattern of silicified lower Palaeozoic fossils in the Miocene and Pliocene.

1. Source area for the silicified Middle Ordovician to Lower Silurian fossils.
2. Suggested transport direction for the silicificates found in the Miocene sands in the North Jutland Basin.
3. Pliocene transport direction for the derived Ordovician and Silurian fossils in the Pliocene of Sylt.
4. Localities (F - Fasterholt, S - Sylt).

the central part of the Baltic Area (shaded area in Fig. 7) being transported by rivers flowing towards the south-west over central Sweden, deposited in the Miocene North Sea or one of its estuaries, and reworked into a transgressive sand with transport directions from the W and NW.

Material of the same age, but in coarser blocks, partly locally decalcified, have been found in the Pliocene of Sylt, in N. Germany, just south of the Danish border (Gripp 1967, 1968). This indicates an increased relief, or a different transport mechanism, and that the route of transportation was deflected towards the south. This may be related to a final phase in the oblique uplift of the western edge of the Fenno-Scandian Shield.

This oblique uplift was first described by Høltedahl (1934, 1960) and is a major tectonic feature in the North Sea area, and to the north along the Norwegian coast. As mentioned above, the tectonic mechanism is not yet unravelled, but it seems to be connected with the opening of the North Atlantic and rifting in the foreland. The chronology of the uplift is not well known, but the available evidence indicates that the major part of it was late, starting in the Oligocene and reaching its maximum after the Upper Miocene, even if movement had been going on along the Høltedahl-line since the Jurassic or even before. This will explain the marked and continuous sharpening of the relief, and the large quantities of fresh terrigenous material transported into the basin in the Miocene, Pliocene and early Pleistocene.

It has been suggested (cf. Gripp 1967) that the boulders found in the Pliocene fluviatile kaolinite sands in N. Germany (Sylt) were related to an early-Pliocene phase in the glaciation of Scandinavia. Such large blocks in a fluviatile environment can be more reasonably explained by transport by winter ice. The climatic conditions necessary for this are not more severe than those of the present day in the area, and it is suggested that rather than indicating a Pliocene glaciation, the climate cooled from that of the Upper Miocene *lusitanian* to conditions similar to those now prevailing in the North Sea area.

The oblique uplift of the Fenno-Scandian Shield may have triggered off the Pleistocene glaciations, by creating high mountains close to the ocean in the most favourable latitudes, but this can hardly be considered as the primary cause of the glaciations.

Summary

The palaeogeographic picture outlined here starts with an area where special conditions on the Baltic Shield (low relief, run-off evenly distributed during the year in connection with sediment filters in the estuaries) provided an unusually low supply of terrigenous clastics into the Danish part of the North Sea area. These conditions changed in the Oligocene, and there was a great influx of freshly weathered material in the Upper Oligocene and Miocene.

The coastline was probably parallel and close to the present coastline of S. Norway and W. Sweden from the end of the Middle Cretaceous into the Oligocene. In the later Oligocene and Miocene it fluctuated above Denmark, and the area became land in the Pliocene.

Three distinct phases of movements can be identified. The strongest was between the Danian and Selandian, where faulting caused severe disruption of the normal sedimentation pattern, and included the formation of fault-cliffs (probably dominantly submarine, but to a minor degree also on land). The available data give no clear picture of the fault-pattern, but it seems to be connected with the NW-SE trend of the Fyn-Ringkøbing High.

The second phase is expressed as a hiatus between the Eocene and the Oligocene. The younger Eocene and the Middle Oligocene are missing on the

High, and the Lower Oligocene appears to be missing all over Denmark. Because of the plastic sediments deposited in this time interval, it is difficult to define the types of movement, since vertical movements in these rocks are likely to have been taken up plastically and softened out. It is therefore not known if part of the faulting observed in the more brittle carbonate rocks took place in this interval.

The third phase of movements seems to represent the major period of oblique uplift of the western edge of the Fenno-Scandian Shield. The tectonic style and type of movements of this phase are not known, and pose some perplexing problems. In Denmark, these movements are indicated by the strongly changing sedimentary environment (more coarse, freshly weathered terrigenous material) and the drift of the coast-line towards the south-west.

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