DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2013/47

Geology of the early Eocene Fur Formation, a unique deposit in the North Sea Basin

Excursion guide to geological key localities on Mors and Fur, northern Denmark

Gunver Krarup Pedersen & Stig A. Schack Pedersen

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DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

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Prepared for Winthershall Norge AS

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Introduction to the geological setting of the Eocene diatomite of the Fur Formation

Introduction

An area in the western part of Limfjorden, northern Jylland, is locally called the „moler" area, because it is unified by the occurrence of a spectacular and unique set of geological features exposed in coastal cliffs. „Moler" is the local, Danish name for a marine Eocene diatomite, which is interbedded with grey to black layers of volcanic ash. The ash layers record the dramatic volcanic eruptions during the early break–up of the continents bordering the North Atlantic Ocean about 56 million years ago. The Eocene diatomite (the Fur Formation) is overlain by Quaternary sediments.

The diatomite contains exceptionally well-preserved fossils, including birds, turtles, insects, fish and plants. The diatomite formed in a depositional environment, which preserved the fossils very well, hence the term „Fossil Lagerstätte". These fossils are significant because they represent faunas and floras documenting the responses to the brief greenhouse event termed the Paleocene–Eocene Thermal Maximum (PETM). The PETM occurred only 10 million years after the mass-extinction at the Cretaceous–Tertiary boundary.

The coastal cliffs expose sections through glaciotectonic complexes characterized by folds and thrusts. These structures are enhanced by the black layers of volcanic ash interbedded in the pale yellow diatomite. The glaciotectonic deformation elevated the Eocene strata to their present position above sea level and created the hilly landscape, which is so characteristic of the moler area.

The aim of this report is to present the geology of the moler area, which include the detailed sedimentology of the early Eocene marine clayey diatomite and its lithostratigraphic setting and the correlation of the Fur Formation to the Palaeocene–early Eocene development in the North Sea region. It is prepared for Winthershall Norge AS on the occasion of the field trip arranged June 11-12, 2013. Thus the description of the locality in the second part of this report follows the planned route for the field trip. Due to the request from Winthershall examples of Quaternary sequence stratigraphy and formation of modern dunes are included as well as demonstration of Danian limestone.

The Danish Basin

Overview

The Danish Basin is separated from the Skagerrak-Kattegat Platform by the Sorgenfrei-Tornquist Zone, which includes the Fjerritslev Fault. The Danish Basin contains a thick succession of sediments overlying the pre-upper Permian unconformity, which is easily recognizable in seismic sections at the base of the Zechstein evaporites (Vejbæk & Britze 1994). The Mesozoic and Cainozoic succession is more than 6 km thick in the central parts of the basin on the northern side of the Fjerritslev Fault (Britze & Japsen 1991).

Siliciclastic sediments dominate the Triassic, Jurassic, Lower Cretaceous, and most of the Tertiary, whereas carbonates characterise the Upper Cretaceous and Danian (Lower Paleocene). The Sorgenfrei-Tornquist Zone has a complex history of Mesozoic subsidence terminated by a late Cretaceous – early Paleocene inversion, which is interpreted from compressional structures observed from the Rønne Graben west of Bornholm, through Skåne and Kattegat to the Farsund Basin (Mogensen & Jensen 1994).

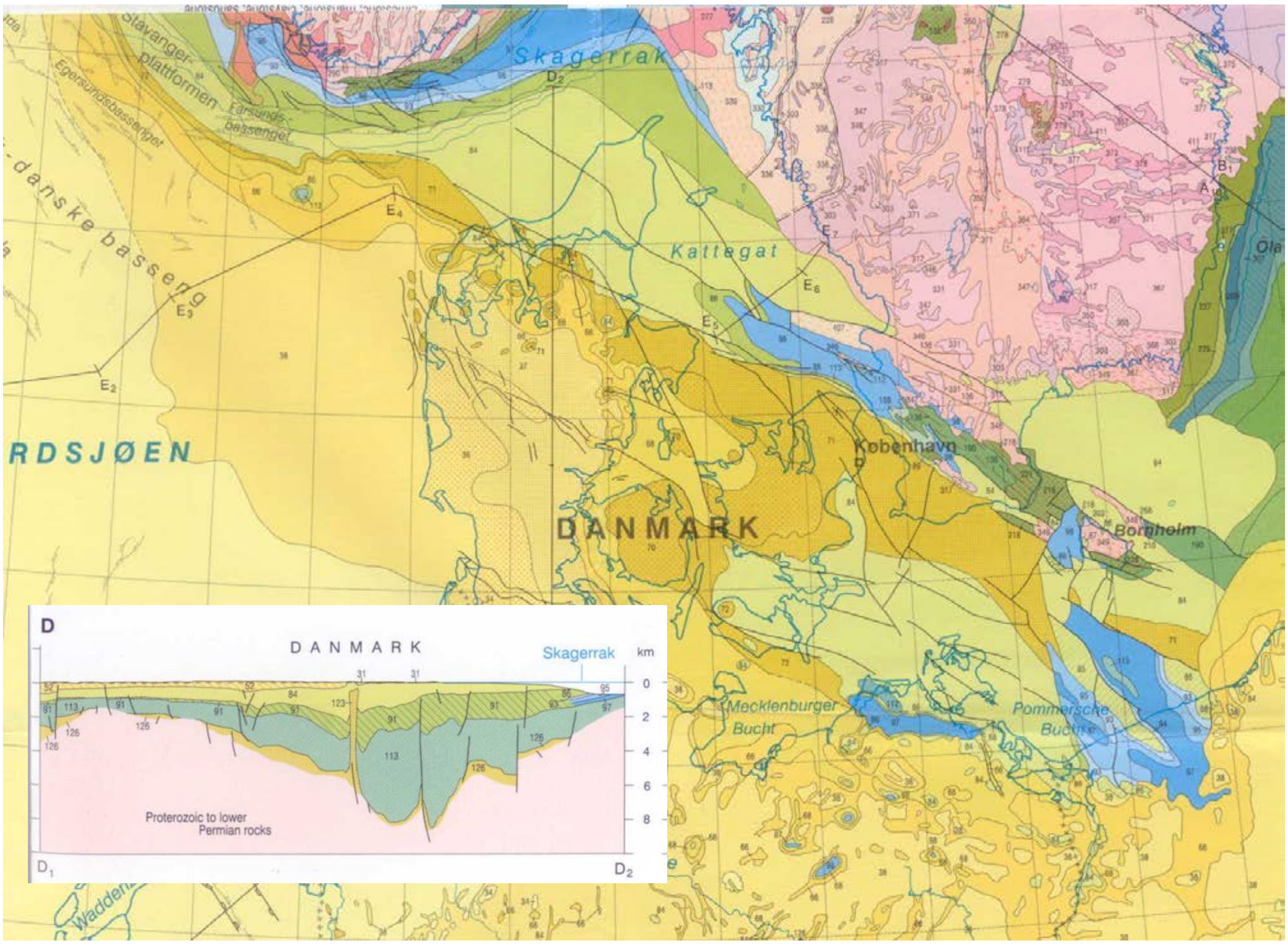

Figure 1. *Geological map of the pre-Quaternary of the Danish Basin with an inset north−south profile. The pre-Permian basement comprises Precambrian crystalline rocks, Lower Palaeozoic sedimentary rocks and local occurrences of Upper Palaeozoic sedimentary rocks. The Upper Permian evaporites are yellow and locally form salt diapirs, the Triassic is bluish green, the Jurassic and Lower Cretaceous is hatched in green, the Upper Cretaceous Chalk Group is green and the Cainozoic is yellow. From Sigmond (2002).*

The Sorgenfrei-Tornquist Zone has a complex history of Mesozoic subsidence terminated by a late Cretaceous – early Paleocene inversion, which resulted in compressional structures which are recognized from the Rønne Graben west of Bornholm, through Skåne and Kattegat to the Farsund Basin (Mogensen & Jensen 1994). The Siri Canyon is an elongated slide scar in the top of the Chalk Group, approximately 15–20 km broad and 120–150 km long, formed by a submarine slide on a deep-marine slope during the early Paleocene. It extends from the palaeoshelf, originally occupying the Stavanger platform to the deep basinal area of the Tail End Graben (Hamberg et al. 2007). The canyon fill consists of Paleocene to early Eocene, deep-marine, hemipelagic mudstones and marlstones interbedded with glaucony-rich sandstones deposited from high-density gravity flows. The sandstones are referred to the Lista Formation and were sourced from uplifted Scandinavian landmasses (Hamberg et al. 2005).

The Chalk Group

The Chalk Group was deposited throughout the Danish Basin and forms the basis for the Tertiary deposits in all areas except northern Jylland (Vendsyssel) and Bornholm. In these areas Paleocene and Neogene erosion has removed all the Tertiary and much of the Upper Cretaceous sediments. A map of the distribution of the pre-Quaternary deposits is seen in Fig. 1. Depth to the top of the Chalk Group in the onshore parts of the Danish Basin ranges from altitudes above sea level to depths of up to 1000 m (Vejbæk et al. 2007).

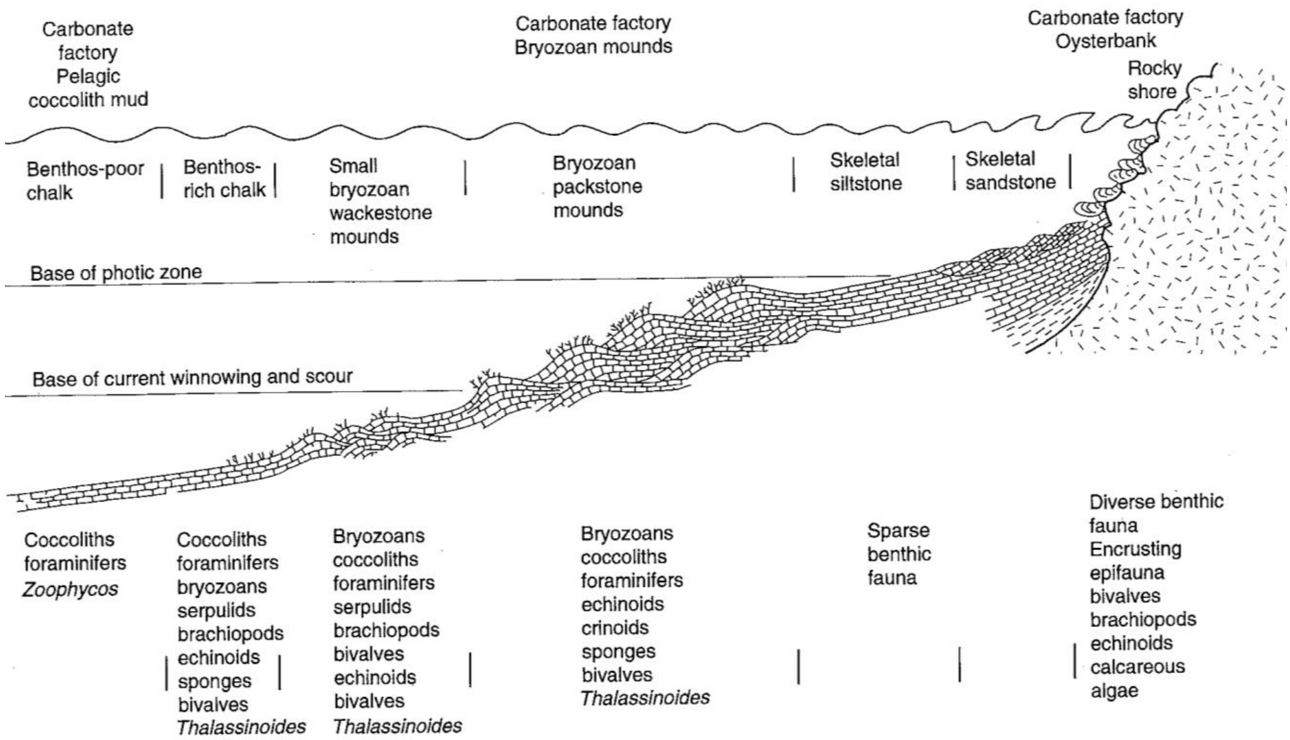

Figure 2. *Depositional model of the Upper Cretaceous and Danian cool-water carbonates of the Danish Basin (Surlyk 1997).*

The Chalk Group in Denmark comprises chalk, a fine-grained coccolithic mudstone, refered to the Tor Formation, of upper Campanian to Maastrichtian age (Surlyk et al. 2006). A depositional model for the cool-water carbonates of the Danish Basin in the Late Cretaceous and Danian was presented by Surlyk (1997) (Fig. 2). Former interpretations of the chalk sea as a low-energy environment with a steady „rain" of coccolith debris are now discarded. Studies of sedimentary facies in outcrops (Anderskouv et al. 2007) and the geometry of reflectors in high-resolution seismic data (Surlyk & Lykke-Andersen 2007) show, that the sea-floor of the chalk sea was characterized by both deposition and erosion from regional current systems.

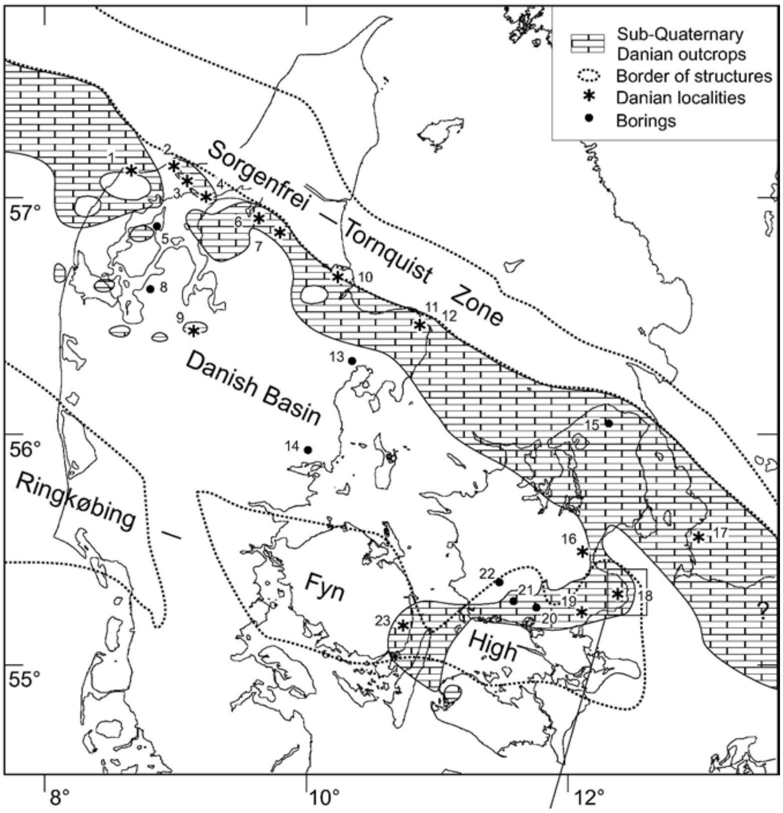

Figure 3. *Main structural elements and distribution of lower Danian bryozoan limestone (Stevns Klint Formation) and chalk outcrops in the Danish Basin. Location of Danian exposures (*) and selected borings : 1 Kællingedal (Hanstholm), 2 Bulbjerg, 3 Klim Bjerg, 5 Mors-1, 6 Vokslev,10 Dania, 11 Karlby, 12 Sangstrup, 16 Karlstrup, 17 Limhamn, 18 Stevns Klint, 19 Faxe, 23 Klintholm. Based on Thomsen (1995). From Bjerager & Surlyk (2007).*

In eastern Denmark the K/T boundary is outlined by a distinct 5−10 cm thick layer of dark grey clay, the Fiskeler Member of the Rødvig Formation. The Fiskeler Member contains the famous iridium anomaly at its base and represents the lowermost Danian (Surlyk et al. 2006). In northern Jylland (Ny Kløv) the K/T boundary is located in chalk facies, and it is less distinct than at Stevns Klint. The Danian comprises a variety of carbonate facies, of which the large mounds of the bryozoan limestone are impressive. They are referred to the Stevns Klint Formation (Surlyk et al. 2006), which is widely known from the subsurface (Thomsen 1995). Outcrops of bryozoan mounds are found parallel to the Sorgenfrei-Tornquist Zone from southeastern Denmark (Stevns Klint, Faxe), southern Sweden (Limhamn), through central Denmark (Klintholm, Sangstrup, Karlby) to northern Jylland (Bulbjerg, Klim Bjerg, Hanstholm) (Fig. 3). Bjerager & Surlyk (2007, 2007b) have studied the bryozoan limestone at Stevns Klint in detail, and have documented a complex interplay between biological and physical processes across the mounds (Fig. 4).

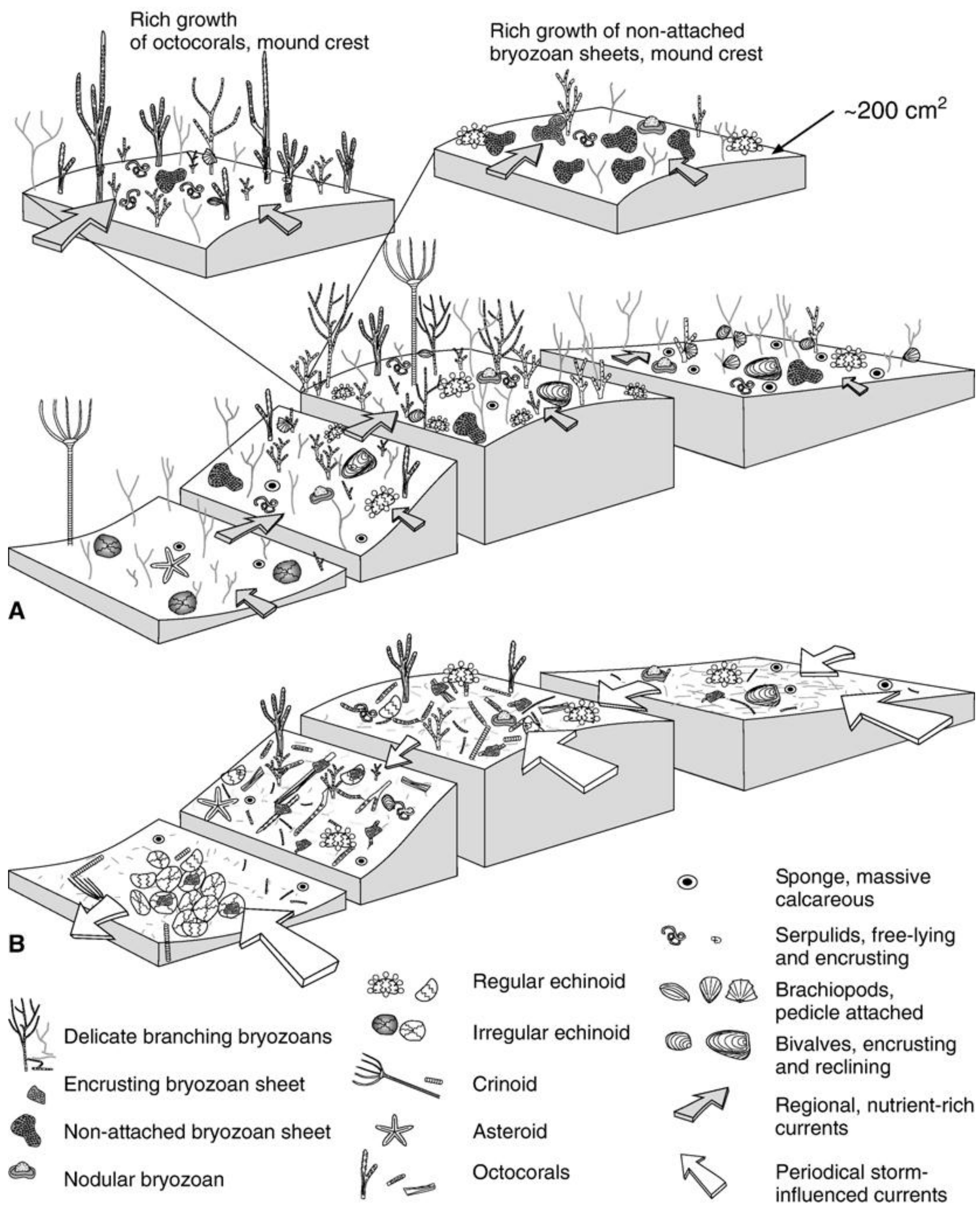

Figure 4. *Simplified 3D reconstructions of bryozoan mound environments : intermounds, steep flank, mound crest, and gentle flank. The sizes of current-arrows indicate relative velocity speed.*

(A) Rich benthic growth especially on the steep flank and crest. Regional nutrient rich bottom currents are indicated. The two mound crests positions at the top indicate periods with rich growth of octocorals, and blooms of bryozoan sheets, respectively.

(B) Storm setting with enhanced current velocity resulting in reworking, skeletal fragmentation and predominantly downflank and strike flank orientations of elongate skeletons. From Bjerager & Surlyk (2007b: Fig. 11).

Geological setting of the early Eocene

The break-up of the North Atlantic – an important geodynamic event

The North Atlantic Ocean is relatively young and the initial formation of ocean crust commenced during the magneto-chron 24, 55–56 million years ago. At that time the North Atlantic igneous province (NAIP) comprised eruption centres in East Greenland, Scotland, Northern Ireland and along the shelf including the Shetland and Faroe Islands. The NAIP includes the basaltic and picritic lavas of Baffin Bay and West Greenland, the ≈7 km thick succession of predominantly tholeiitic lava flows at the Blosseville Kyst of East Greenland, the seaward-dipping reflectors of the Greenland and northwest European volcanic rifted margins; the Faroe Islands and the British Tertiary basaltic lavas, and the aseismic ridges connecting Iceland to either margin of the central Northeast Atlantic. The total area of NAIP is 1.3 x 10^6 km^2, and the total volume is 5–10 x 10^6 km^3 (Fig. 5).

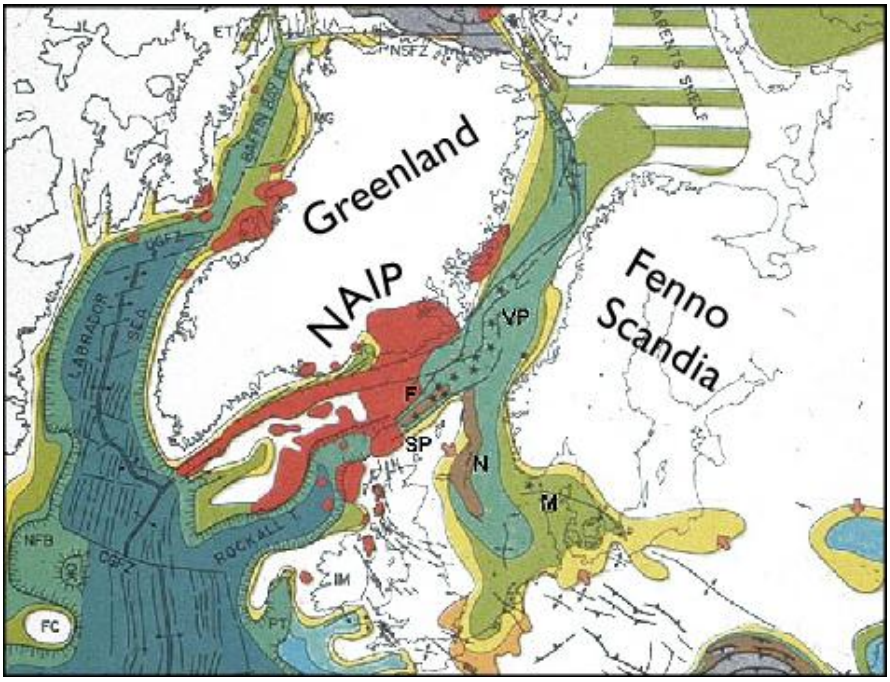

Fig. 5. *Map of the North Atlantic Igneous Province (NAIP) indicated (red) in a pre-drift position.*
F: the Faeroe Islands,
M: Mors and Fur,
N: the North Sea,
SP: the Shetland Platform, and
VP: the Vøring Plateau.
From Ziegler (1988).

Volcanism

The initial activity of the NAIP consisted of continental volcanic eruptions (Larsen *et al*. 1999, 2003, Storey *et al*. 2007) and related rifting of the continental crust. Thick piles of lava flows accumulated in East Greenland and at the Faroe Islands. As the eruption sites moved seawards they were flooded, and the resulting explosive phreatic eruptions generated huge volumes of volcanic ash. The ash from the NAIP spread over large parts of northern Europe, and the ash layers have been recognized in numerous wells in the North Sea, in DSDP hole 550 southwest of Ireland, and at several localities in England, Austria, Germany and Denmark. After a few million years the main eruption centres were again above sea level and generated only small amounts of volcanic ash. Other parts of the Mid– Atlantic Ridge were located at so great water depths that no airborne volcanic ash was produced.

Geochemical analyses of the 187 numbered ash layers in the Fur Formation at Limfjorden and analyses of the known intrusions in the NAIP clearly indicates that the volcanic centers initially were distributed along a broad S-N trending zone, which eventually defined the continental margins. This is exemplified by the igneous complexes in East Greenland and Scotland. However, more "in-land" continental intrusions are known to have existed, such as the granitic intrusion on the island of Lundy in the Bristol Channel off the coast of SW-England. It has a geochemical composition similar to the rhyolitic ash layer –33 in the ash layer succession in the Fur Formation at Limfjorden. A similar correlation exists between ash layers –21 to –17 and the Gardiner igneous complex in East Greenland (Larsen et al. 2003, Storey et al. 2007).

The Paleocene-Eocene Thermal Maximum, PETM

The Paleocene-Eocene Thermal Maximum (PETM) is an extreme, global greenhouse event, which marks the beginning of the Eocene Epoch. It lasted for less than c. 200,000 years (Westerhold *et al.* 2009; McInerney & Wing 2011) and is recognized worldwide as a geochemical anomaly (a C-isotope excursion) in both terrestrial and marine deposits. This anomaly has therefore been selected as the Paleocene/Eocene boundary, (Gradstein *et al*. 2004). The base of PETM (and of the Eocene) has been dated to 55.9 Ma (Westerhold *et al*. 2009). Marine benthic foraminifera have recorded the temperature through δ^{18}O-isotopes and indicate a temperature increase of ocean bottom waters of 5-7°C at high latitudes and 4-5°C at mid-level latitudes. Temperatures remained high during the following million years of the „Early Eocene Climatic Optimum".

In Denmark the base of PETM corresponds to the base of the Stolleklint Clay, a dark grey laminated mudstone, which form the lowest part of the Ølst Formation and correlates to the basal part of the Sele Formation (Fig. 6). The upper, gradational, boundary of PETM is located within the lower part of the Fur Formation.

PETM was probably triggered by greenhouse gases released during the intense igneous activity linked to the opening of the North Atlantic. This event coincides with palaeomagnetic anomaly C24r (Larsen *et al.* 2003). It has been suggested that the gases generated by magma interaction, mainly sill intrusions, with basin-filling carbon-rich sedimentary rocks were the source to the greenhouse effect, although the detailed mechanisms and contributions are still discussed (Svensen *et al*. 2004, Storey *et al*. 2007, McInerney & Wing 2011). The PETM is not accompanied by any significant mass-extinction (McInerney & Wing 2011).

A record of earliest Eocene fossils

Coincident with, and probably related to the PETM, are several turnovers in the global flora and fauna, marine as well as terrestrial, and documented by fossils worldwide (McInerney & Wing 2011). Turnovers represent relative changes in faunal and floral composition and relative abundance of taxa, as well as their evolutionary rates, where new taxonomic groups appear and flourish, while old groups are replaced or diminish in importance. The only major marine extinction event at the PETM resulted in the extinction of 50% of benthic foraminifera species.

Microfossils worldwide record a massive turnover among planktic foraminifera and dinoflagellate species. Significantly, an almost global abundance peak and great expansion of geographic range of the heterotrophic dinoflagellate *Apectodinium* (Fig. 7*)* has been recorded. This biostratigraphic event is termed the "Apectodinium acme" and its duration is used to constrain the PETM event (McInerney & Wing 2011). Terrestrial biodiversity was also afflicted by the rapid global warming. Fossil and geological evidence from around the world indicate the PETM is marked by a brief drying event and increased seasonality recorded by fossil plants, after which wetter conditions reappeared (McInerney & Wing 2011). Some mammal groups went extinct but three groups (artiodactyls, perissodactyls and primates, APP taxa), appeared suddenly and simultaneously in North America and Asia at the initiation of the Eocene Epoch (McInerney & Wing, 2011). The same pattern has been observed in Europe.

Lithostratigraphy of the middle Paleocene – lower Eocene in the North Sea Basin

The *Lista Formation* is characterized by dark grey, non-laminated, non-calcareous mudstones, and becomes tuffaceous towards its top. Glaucony-rich massive sandstones occur in the Lista Formation in the Siri Canyon (Schiøler et al. 2007). The Lista Formation is 20–40 m thick except in the Siri Canyon, where it is locally 100 m thick. The Lista Formations correlates to marine clays of the Æbelø-, Holmehus- and Østerrende Clay Formations onshore Denmark (Fig. 6).

The *Sele Formation* consists of medium to dark grey, brownish or black laminated mudstones. Thin tuff layers occur in the upper part of the formation. Well-laminated intervals are enriched in organic material resulting in a high gamma-ray response, primarily due to increased uranium content. The basal part of the formation contains the most organic-rich, darkest, and most well-laminated sediment. Graded layers of tuff, less than 1 cm thick, are present in the upper part of the formation. The acme occurrence of the dinoflagellate *A. augustum* (Fig. 7) corresponds to the lower part of the Sele Formation (Schiøler et al. 2007). This indicates that the Sele Formation may be correlated to the Stolleklint Clay of the Ølst Formation (Fig. 6). The Stolleklint Clay is interpreted as deposited during PETM (Paleocene Eocene Thermal Maximum) (Schmitz et al. 2004). The lower boundary of the Sele Formation is thus very close to the Paleocene – Eocene boundary.

The Balder Formation is composed of laminated grey fissile shales with interbedded dark and light sandy tuffs. The tuffs are normally graded and less than 5 cm thick (Schiøler et al. 2007). This is surprising, because several ash layers are thicker in the Fur Formation, which is not likely to have been closer to the eruption sites. The Balder Formation is charaterised by the diatom *Fenestrella antiqua*, accompanied by *Coscinodiscus morsianus* in its lower part. Calcareous benthic foraminifers are virtually absent in the Balder Formation, but reappear in the overlying Horda Formation (and the equivalent Røsnæs Clay Formation onshore Denmark) (Schiøler et al. 2007). It is likely that the base of the Balder Formation approximately correlates with ash layer +1 (Schiøler et al. 2007). Ash layer +1 was described from the Fur Formation in 1918 by O.B. Bøggild and marks the boundary between the lower Knudeklint Member and the upper Silstrup Member of the Fur Formation (Pedersen & Surlyk 1983).

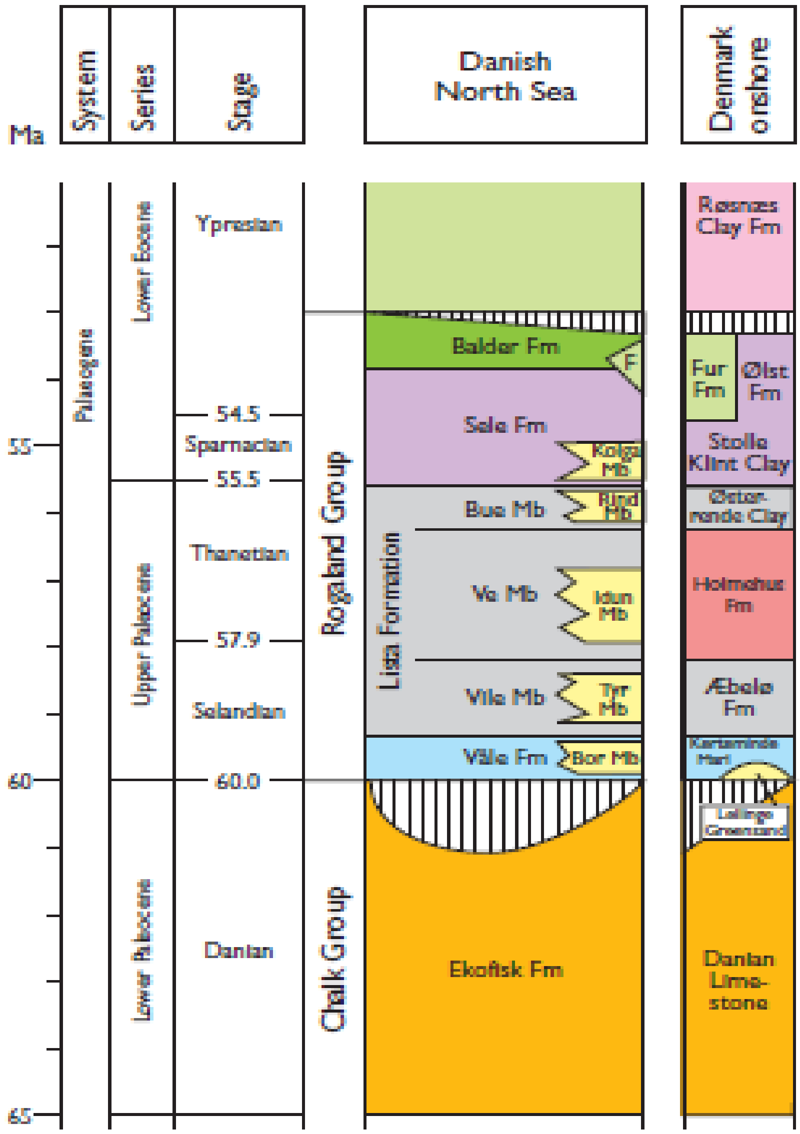

Figure 6. *Lithostratigraphy of the Paleocene – Lowest Eocene in the North Sea Basin and onshore Denmark. From Schiøler et al. (2007).*

Lithostratigraphy of the middle and upper Paleocene in the Danish Basin

During the middle and late Paleocene the Danish Basin was characterized by deposition of marine mudstones, which reflect an overall deepening and expansion of the „North sea" during the middle Paleocene, followed by a sea-level fall in the latest Paleocene. In large parts of Denmark the lowermost Eocene deposits rests on an erosional unconformity (Heilmann-Clausen 2006). Four formations are distinguished.

Lellinge Grønsand is a fossiliferous sandy marl with a high content of glaucony, which was deposited in the eastern part of the Danish Basin at moderate depths adjacent to the coastline. In deeper waters the Lellinge Grønland is replaced by the *Kerteminde Mergel,* which also overlies the greensand.

Kerteminde Mergel is a thick unit of pale grey, siliceous marl. The carbonate derives partly from Paleocene foraminifers but mostly from reworked Cretaceous coccoliths from the chalk. This shows that the chalk was subject to erosion probably due to uplift in the Sorgenfrei-Tornquist Zone. The marl contains few macrofossils but has a rich trace fossil fauna and is interpreted as deposited at water depths of 100–150m (Heilmann-Clausen 2006). The Kerteminde Mergel is correlated to the Våle Formation of the North Sea (Fig. 6).

Æbelø Formationen consists of grey, often silicified marine mudstones, devoid of calcareous microfossils. It is correlated to the lower part of the Lista Formation.

The overlying *Holmehus Formation* is a 5–15 m thick unit of very fine-grained marine clay with bluish, greenish and reddish colours. The sedimentation rate was probably as low as 6–7 mm/ 1000 years. The fine-grained clay contains dinoflagellate cysts and trace fossils, notably *Zoophycos.* The clay is interpreted as deposited in deep water, probably at more than 300 m depth (Heilmann-Clausen 2006). The formation is widely distributed in the Danish subsurface, but is rarely exposed. It is correlated to the Lista Formation (Fig. 6). The Holmehus Formation is locally overlain by a grey mudstone, the *Østerrende Clay*.

Lithostratigraphy of the lowest Eocene in the Danish Basin

The *Ølst Formation* consists of fine-grained marine clay and is known from various outcrops in Denmark (Heilmann-Clausen *et al*. 1985). It has its name from the type locality in eastern Jutland, and is correlated to the Sele Formation and the lower part of the Balder Formation in the North Sea (Schiøler *et al*. 2007). The succession of volcanic ash layers known from the Fur Formation are also found in the Ølst Formation. Here the volcanic glass is strongly altered, but they still constitute important isochronous marker beds and allow detailed correlation between occurrences of the earliest Eocene deposits in Denmark. Interbedding between diatomite and clay is seen in the Harre Borehole in Jutland (Nielsen 1994), and is also known from exploration wells in the North Sea (Danielsen & Thomsen 1997). The Ølst Formation is divided into a lower Haslund and an upper Værum Member (Fig. 6). The lowest part of the Haslund Member constitutes the Stolleklint Ler, an informal unit which was deposited during the PETM. The uppermost part of the Stolleklint Ler is exposed in Knudeklint, and more extensive exposures may be found at Stolleklint, one of the cliffs on the north coast of Fur.

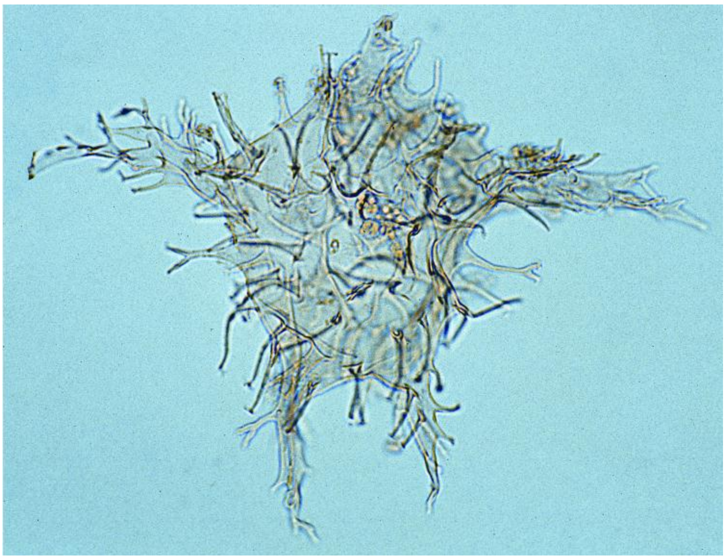

Figure 7. *Dinoflagellate cyst of the species* Apectodinium augustum*, which is characteristic of the PETM interval, and has an acme occurrence. The length is c. 100 µm.*

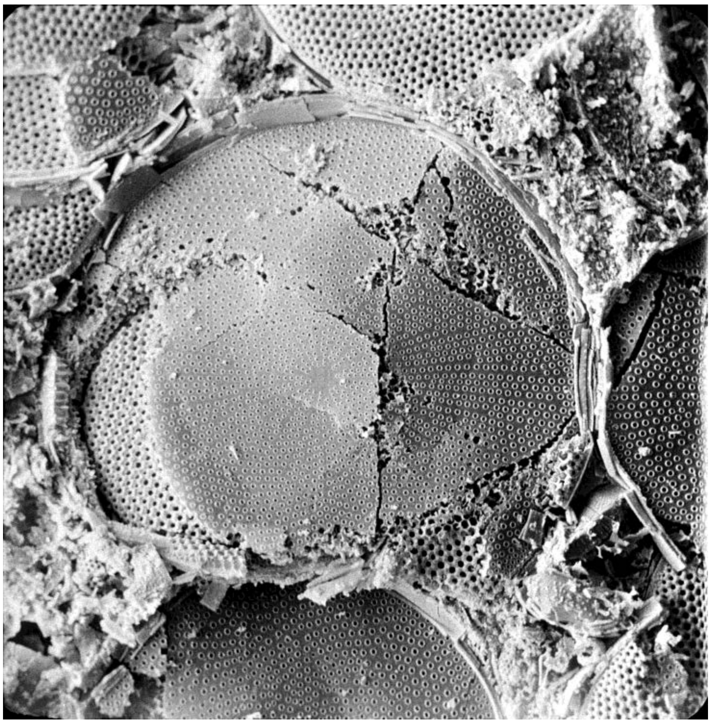

Figure 8. *Very large centric diatom,* Coscinodiscus *sp., which is common in the Fur Formation. The diameter is c. 200 µm.*

The *Fur Formation* is a c. 60 m thick marine clayey diatomite interbedded with 187 layers of air-borne volcanic ash (Fig. 9). Calcareous concretions characterize certain levels of the formation, which contains a wealth of terrestrial and marine fossils (Pedersen & Surlyk 1983). Each ash layer was deposited from one ash cloud (one eruption) and deposition was almost instantaneous. Consequently the ash layers constitute isochronous marker horizons, numbered –39 to +140 by Bøggild (1918), which divide the formation into a high number of time-slices and allow an unusually detailed correlation within the Fur Formation and between the Fur and Ølst Formations. The Fur Formation was deposited in the eastern part of the North Sea during the Early Eocene. Its original extent is not known, due to later uplift and erosion. The thickest and most complete stratigraphical sections are found on Mors and Fur in the western part of Limfjorden. The diatomite, the ash layers, and the fossils are described in more detail below.

The *Røsnæs Clay Formation* comprises dark grey and green clay grading up into red-brown clay. The thickness of the Røsnæs Clay at Knudeklint is only 5 m. The boundary between the Fur Formation and the Røsnæs Clay Formation is an erosive unconformity. The boundary is intersected by burrows and the trace fossils are filled with glaucony-rich fine-grained sand and clay, which also occur in the lowermost 0.5 m of the Røsnæs Clay Formation. The Røsnæs Clay Formation contains calcareous microfossils. It is correlated to the lower part of the Horda Formation in the North Sea and the London Clay in Se England.

Sedimentology of the Fur Formation

The diatomite

The diatomite is a whitish, fine-grained sediment with a high porosity (c. 70%) and a density of 0.8 g/cm^3, when dry. Locally it is called „moler". The origin of this term is uncertain, but old papers suggest that it designated a pale, fine-grained sediment. The diatomite consists of marine diatoms (algae with frustules (tests) of opal), which are 20–200 µm in diameter and are referred to 138 species (Fig. 8). The diatom frustules constitute 60–70 % of the sediment, and the remaining 30–40 % are clay minerals, dominantly smectite, and volcanic dust (Pedersen et al. 2004).

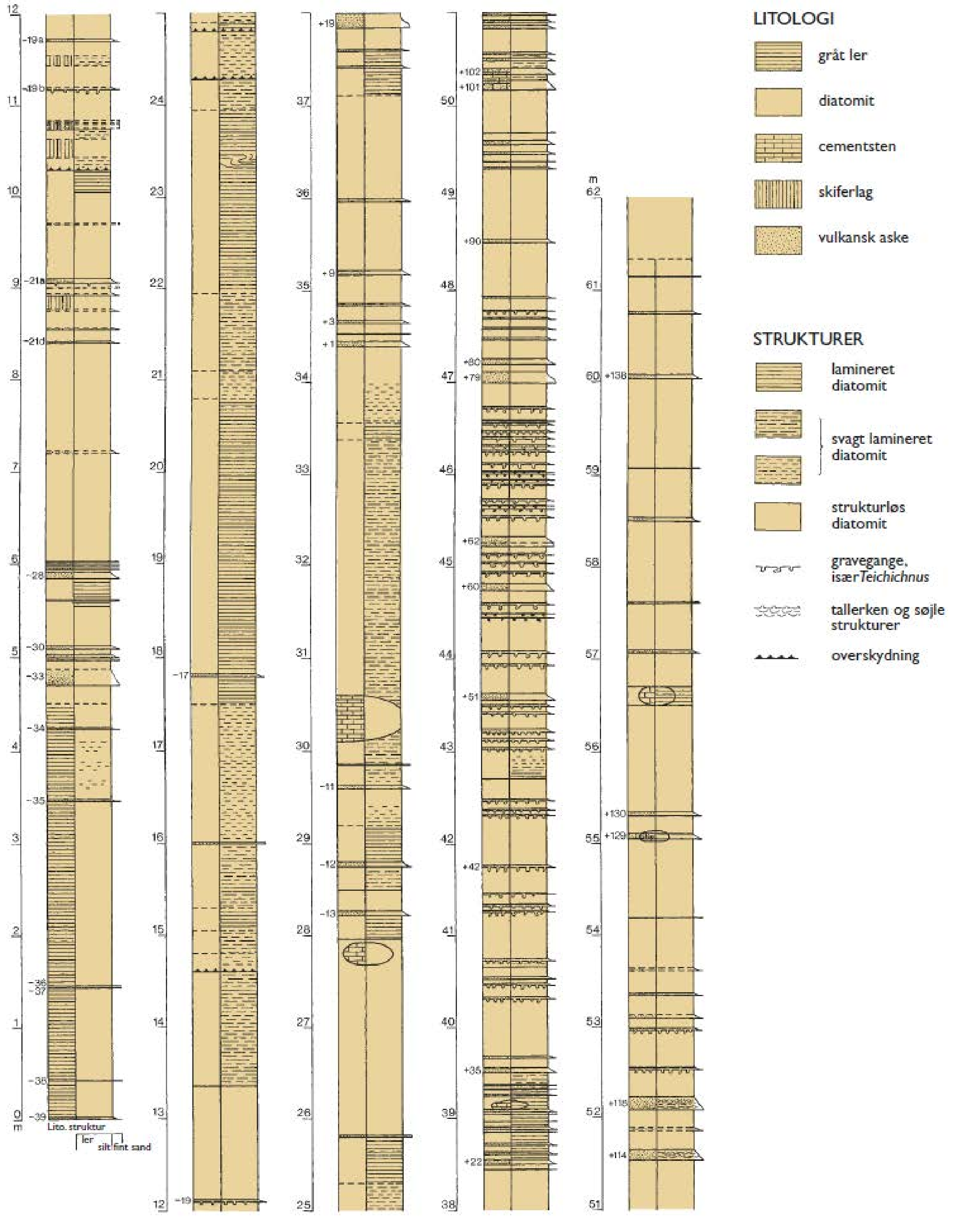

Figure 9. *Sedimentological log of the Fur Formation. The numbers of the prominent ash layers are indicated. Note that there is a negative and a positive numbering of the ash layers after Bøggild (1918). The thickness in meters is relative to ash layer -39, according to Pedersen & Surlyk (1983). Ash layers –39 to –34 are now placed in the Stolleklint Ler of the Ølst Formation. Ash layers –33 to –1 occur in the Knudeklint Member, ash layers +1 to +144 are included in the Silstrup Member.*

Many diatoms are planktonic and thrive in waters with nutrient-rich water, for instance in zones of coastal upwelling. Eventually the frustules sink towards the sea-floor. Up to 90% of the diatom frustules are dissolved in the water column and additionally 7 % are dissolved on the sea-floor. The c. 50 m of diatomite thus equals 3% of the diatom production in the surface waters of the earliest Eocene „North Sea".

The white or yellowish colour of the diatomite is the result of weathering and oxidation. Originally the sediment was dark grey to black, pyritic and probably with a smell of H_2S, produced during the bacterial decomposition of the organic tissue in the diatoms. The decomposition of organic matter consumed most or all the oxygen dissolved in the bottom water, and the depositional environment was thus characterized by anoxic or nearly anoxic conditions. The diatomite may be divided into three sedimentary facies: laminated diatomite, weakly laminated diatomite and structureless diatomite (Figs 10a, b).

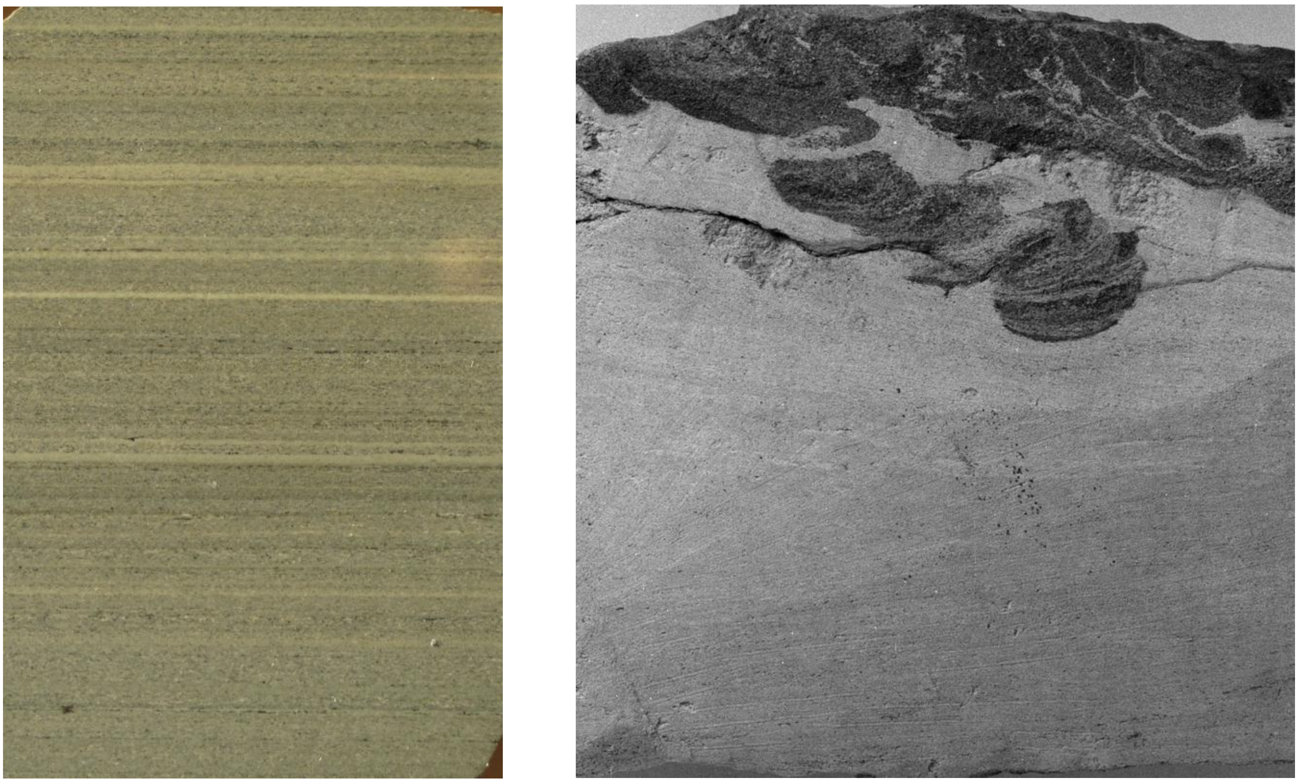

Figure 10. *A. Laminated diatomite, note that the laminae are continuous and of constant thickness (0.1−3 mm). B. Structureless diatomite overlain by a layer of volcanic ash. Ash-filled trace fossils* (Teichichnus *isp.) were produced by burrowing animals, deposit feeders. The height of the photos is c. 10 cm.*

The laminated diatomite consists of 0.3−5 mm thick laminae of varying colours, and different proportions of diatom frustules and clay minerals. The lamination reflects variations in the production of diatoms in the surface water and in the supply of clay from rivers or in air-borne volcanic dust. The preservation of the lamination shows that no animals lived at the sea floor and disturbed the sediment. The absence of life is interpreted as caused by lack of oxygen, and the possibly the presence of poisonous H_2S. The structureless diatomite is a homogeneous sediment, and burrows are observed at the boundary between diatomite and ash layers (enhanced by the contrast in lithology). This facies is interpreted as completely bioturbated, and it is inferred that the content of oxygen in the bottom water was sufficient to allow a fauna of benthic animals to living at the sea-floor. The weakly laminated diatomite is interpreted to have formed at conditions intermediate between the laminated and the structureless diatomite (Pedersen 1981). The strong contrast between the laminated and the structureless diatomite may reflect changes in oxygen content from less than 0.1 ml O_2/l (no fauna) to 0.2–0.3 ml O_2/l (sufficient for a sparse, specialized fauna). In comparison fully oxygenated water contains 8 ml O_2/l. The floor of the „moler sea" was thus at all times an anoxic or nearly anoxic environment. This environment was perfect for preservation of fossils (no scavengers to disturb or destroy the fossils), and explains why the laminated sediments of the Fur Formation and the underlying Stolleklint Clay are famous for a large number of unusually well-preserved fossils (see below).

Calcareous concretions occur at certain horizons within the diatomite. The concretions are ellipsoidal and sometimes form more-or-less continuous layers (Pedersen & Surlyk 1983). The concretions are described below in the chapter on diagenesis.

The thick diatomite is only known from a fairly small area in the vicinity of Mors and Fur. Towards the east and south the diatomite is replaced by the clays of the Ølst Formation. In the Harre borehole (northern Jutland) and in wells in the North Sea diatomite have been encountered, but only as much thinner units. This suggests that conditions, favourable for a huge production of diatoms, existed within a restricted area. It is not yet established whether the favourable conditions were due to marine current patterns (increased local upwelling) or to increased supply of nutrients, or to a combination of several factors.

In summary the diatomite is interpreted as deposited in a region of extraordinary large production of diatoms. The diatomite was deposited at water depths below storm wave base, in anoxic or weakly oxic bottom waters.

Anoxic events

Sedimentological logs through the diatomite demonstrate that laminated-, weakly laminated-, and structureless diatomite occur repeatedly through the formation, and that laminated diatomite is found between the same ash layers at almost all localities (Fig. 11). The ash layers are isochronous and therefore show that the water in the „moler sea" was subject to basin-wide changes between anoxic and weakly oxic conditions. The laminated diatomite form units that are 1–3 m thick. The sedimentation rate (after compaction) was probably less than 0.1 mm/year (Pedersen et al. 2012), and the laminated units thus represent time intervals on the order of 10–30,000 years. The anoxic events, however, are not distributed uniformly through the Fur Formation. Much of the older Knudeklint Member is characterized by laminated or weakly laminated diatomite, whereas the younger Silstrup Member is characterized by structureless diatomite. This distribution of facies indicates increasing oxygen supply to the bottom water (increasing circulation) or decreasing oxygen consumption (decreasing diatomite production). These changes may be related to changes in the overall palaeogeography during the earliest Eocene.

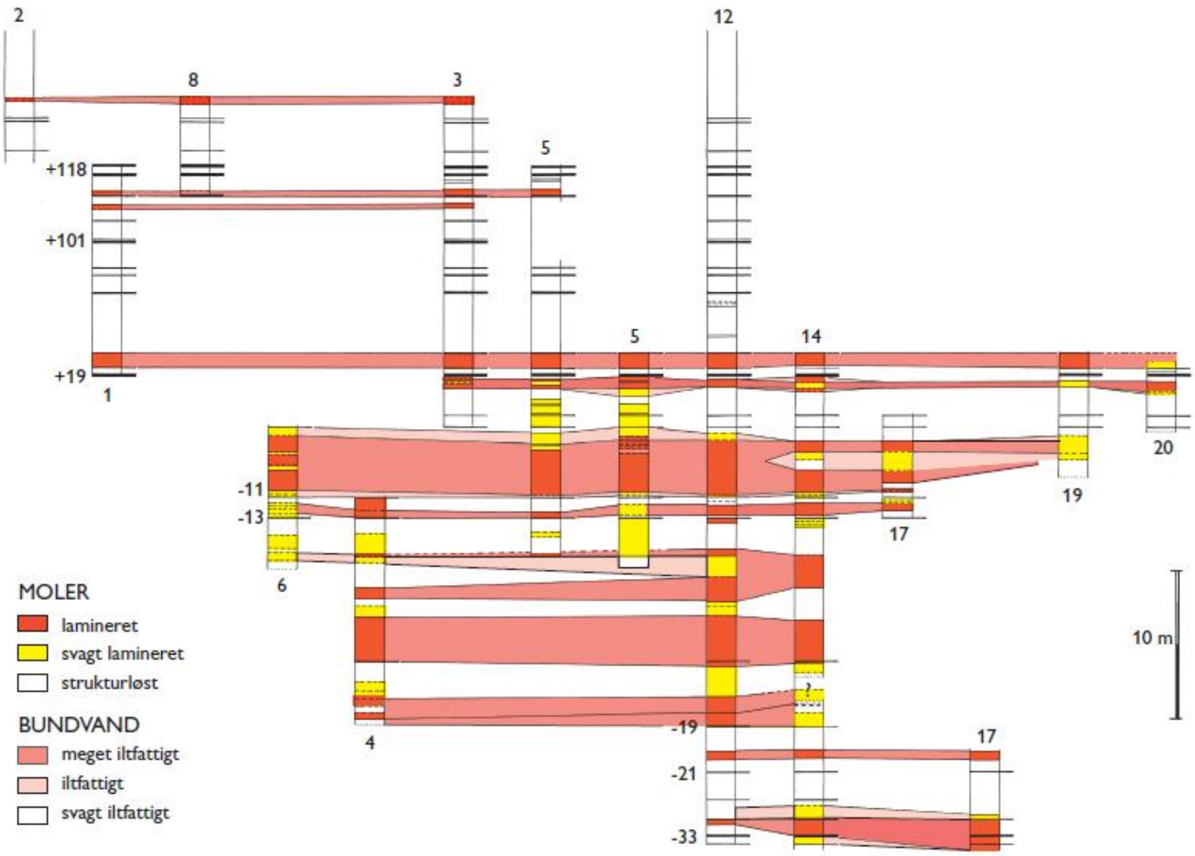

***Figure 9**. Alternation between laminated diatomite (anoxic events, red), weakly laminated diatomite (nearly anoxic, yellow), and structureless diatomite (oxygen poor bottom water (white). Note that the shift between facies are almost co-eval through the basin. The most important ash layers are indicated (−33 to +118). The numbers at the logs refer to localities: 1 Siltrup, 2 Silstrup Sydklint, 3 Feggeklit, 4 Skarrehage, 5 Ejerslev and Harhøj, 6 Skærbæk, 8, Hanklit, 12 Fur Knudeklint, 14 Stolleklint, 17 Pits Central Fur, 19, Junget, 20, Ertebølle .*

Volcanic ash

The 187 numbered layers of volcanic ash are 0.2−19 cm thick, but good outcrops may show some extra ash layers, which are very thin and discontinuous. The ash layers consist of volcanic glass and microcrystalline, almost opaque particles as well as a small amount of crystals, mainly feldspar (Larsen et al. 2003). The size of the ash particles range from silt to fine-grained sand, and the colour vary with the petrological composition. Basaltic glass is black and shiny, whereas rhyolitic glass is white or pale grey. In the Stolleklint Clay, and especially in the rest of the Ølst Formation, the volcanic glass is partly or completely devitrified (altered to clay). The ash layers have graded bedding (coarsest particles at the base of each layer) (Fig. 12). This shows that one ash layer is deposited from one ash cloud and that the ash particles were sorted while they settled through the water column. Deposition of an ash layer took 1−3 days. A few of the ash layers are so-called „double layers", which show that two large volcanic eruptions were almost simultaneously (maybe within one year).

Three of the thick ash layers (+101, +114 and +118) show water escape structures (dish- and pillar structures), which formed when the porous diatomite became instantly compacted by the weight of c. 10 cm of volcanic ash (Pedersen & Surlyk 1977).

Figure 12. *Black, basaltic, volcanic ash layer, 2 cm thick, in a calcareous concretion. Note the graded bedding (decreasing grain-size upwards) due to quicker settling of the larger ash particles. The ash layer did not disturb the lamination in the diatomite below. Each ash layer was deposited from one ash cloud (one eruption by the volcano).*

Diagenesis in the Fur Formation

The diatomite is remarkable for its very low degree of diagenetic alterations despite the presence of easily altered constituents such as biogenic opal and volcanic glass. It is no coincidence that both volcanic ash layers and numerous, well preserved fossils occur in the same diatomite succession.

The diatomite consists of silt- and sand-sized diatom frustules made of biogenic opal, opal-A. Studies outside the Fur Formation show that opal-A is transformed to opal-CT and eventually to microcrystalline quartz during burial diagenesis. However, in the Fur Formation the transition to opal-CT is only observed in a few samples in the lower part of the formation. This indicates that the burial depth was never large.

The silicified layers ('Skiferlagene')

The lower part of the Fur Formation (below ash layer −19) comprises a few thick, dark brown beds, locally known as „skiferlagene‟. Within these beds the diatomite is cemented by clinoptilolit (a zeolite mineral) and opal-CT. The cemented diatomite is dark grey, but weathers to a dark brown, splintery, chert-like lithology. Soft diatomite consisting of opal-A is found below the silicified layers, which indicates that the precipitation of opal-CT is not due to burial diagenesis, but must be attributed to local factors. It may be speculated that diatoms with very thin frustules became abundant and that their frustules were dissolved at shallow depth in the sediment and re-precipitated as opal-CT.

Preservation of volcanic glass and organic tissue of macrofossils

It is easily observed that volcanic glass is well-preserved (almost fresh) in the diatomite, while the identical ash layers are devitrified in the clays of the Ølst Formation. A likely explanation is that the abundance of fairly soluble opal-A (from the diatoms) maintained a pore-water chemistry, which protected the volcanic glass from devitrification. The best preservation is found in the calcareous concretions, where diatomite and volcanic glass have been sealed from pore-water reactions (Larsen et al. 2003).

The decomposition of organic matter from the diatoms consumed almost all oxygen from the bottom water. This ensured that organic tissue in the macrofossils (fish bones, insects, birds‟ feathers, delicate winged insects, and pigments) was not decomposed, and the absence or a sea-floor fauna of scavengers have preserved many fossils articulated.

Glendonite, calcite pseudomorphs after ikaite

Crystals of glendonite often occur as rosettes with crystal lengths of 20-40 cm (Fig. 13). The crystals displaced the sediment during growth, and the glendonites are best preserved where they are included in the calcareous concretions described below. X-ray diffractograms demonstrate that the crystals now consist of calcite, while measurement of angles between the crystal faces, demonstrate that the original mineral was ikaite (Huggett et al. 2005). The huge crystals of ikaite were replaced by calcite during early diagenesis. The conditions under which the ikaite crystals grew are still being investigated. At normal conditions the mineral ikaite, $CaCO_3 \cdot 6H_2O$, is only stable at temperatures below 6°C. At higher temperatures ikaite decomposes to calcite and water. Since the discovery of ikaite in the Ikka Fiord in Greenland, similar crystals, with well-preserved crystal faces, have been found at Antarctica and in the Okhotsk Sea. The formation of ikaite requires low temperatures and alkaline pore water with a content of phosphates, which prevent precipitation of other carbonate minerals. Such conditions are found in organic-rich marine sediments with methanogenesis. In modern sediments ikaite forms in the upper part of the sediments and the growth of the crystal may displace the original sediment. The formation of ikaite on a sea-floor in a subtropical climate (PETM) is not yet fully explained.

Figure 13. *Calcareous concretion with large glendonite crystals, calcite pseudomorphs after ikaite. Note that the growth of the crystals has disturbed the underlying thin layers of volcanic ash. The thickness of the concretion is c. 30 cm.*

Calcareous concretions

Calcareous concretions, locally called „cementsten" have formed by precipitation of calcite in the pore space in diatomite or its interbedded layers of volcanic ash. The concretions are ellipsoidal, and rarely more than 50 cm thick. The cementation may also form continuous layers. In the Silstrup Member, with many closely spaced ash layers it is easy to demonstrate that the concretions occur at specific stratigraphic levels at all localities. This is probably also the case in the Knudeklint Member though more difficult to prove, because the ash layers here are fewer and more widely spaced.

In the centre of the concretions the calcite content is 75−90 % (by weight), which shows that calcite precipitated before compaction of the diatomite. This is supported by the beautiful preservation of fossils, some of which have escaped compaction. The precipitation of cement took place at a shallow depth in the sediment. Analyses of the stable isotopes indicate that c. 25 % of the calcite derived from marine calcareous organisms, and that the remaining calcite is of bacterial origin (Pedersen & Buchardt 1996).

Ash layer stratigraphy

O.B. Bøggild (1918) numbered the ash layers –39 to +140 (Fig. 14). Later field work has discovered a few additional ash layers: –18b, –19a, –19b, –21a, –21b –21c, –21d and –29a (Gry 1940, Larsen *et al*. 2003). The volcanic ash layers record dramatic eruptions during the early break–up of the Laurentian-Eurasian continental margins bordering the North Atlantic Ocean c. 56 million years ago. The volcanic glass, which is the main constituent of the ash layers, is very well preserved in the diatomite, which allows detailed investigations of the petrology of the ash layers. The individual ash layers are recognized on basis of their thickness, their colour (white, grey, black), their distance to overlying ash layers, and their position relative to a few horizons of calcareous concretions. Most ash layers are 1−5 cm thick, but a few layers are more than 10 cm thick, and these are easily recognized.

The volcanic ash layers exposed in the Moler Cliffs are known from outcrops in Denmark, England and from numerous oil exploration wells in the North Sea. In most of the region the volcanic ash is interbedded with clays and consequently is heavily altered. Major-element analyses of bulk ash samples often show hydration and leaching to such an extent that the original chemical composition of the ash is unrecognizable. In contrast the volcanic glass is fresh where it is interbedded in the diatomite (Bøggild 1918, Larsen *et al.* 2003), and it is possible to determine major-element data from microprobe analyses and to determine glass inclusions in feldspar crystals. In the altered ash layers it is still possible to obtain useful data on immobile elements such as Ti, P, Zr, Nb, and Y from analysis of bulk ashes (Larsen *et al*. 2003).

Radiometric datings of the ash layers has been focused on ash layers –17 and +19, which have been dated by several workers. Recently –17 was dated to 55.12 ± 0.12 Ma by Storey *et al*. (2007). Please note that $^{40}Ar/^{39}Ar$ ages are given relative to a standard (the Fish Canyon Tuff). New determinations of the age of the standard affects the calibrated ages of ash layer –17, which now is given as 55.39 ± 0.12 Ma (Pedersen et al. 2012).

Ash layer –17 is an important marker bed for correlations within the NAIP, due to its distinct mineralogical and geochemical composition (Larsen *et al*. 2003). Knox (1985) recognized ash layer –17 in several wells in the North Sea as well as on the Atlantic shelf (Goban Spur) and demonstrated its value for correlation and its wide geographical distribution. Ash layer –17 was subsequently recognized as interbedded with subaerial lava flows in the Skrænterne Formation in East Greenland (Storey *et al*. 2007). Radiometric datings confirm the correlation of the Skrænterne Formation Tuff with ash layer –17 in Northwest Europe. In East Greenland the volcanic succession shows that the Skrænterne Formation Tuff was erupted after the onset of massive flood basalt volcanism but within the error of estimated continental break-up time (Storey *et al*. 2007). Most of the ash layers with negative numbers represent the continental break-up. During the active rifting large volumes of ash were emanated, which are represented by the positive ash layers, most of which are of a tholeiitic basaltic composition. A notable exception is ash layer +19, which is 20 cm thick and andesitic (Fig. 15).

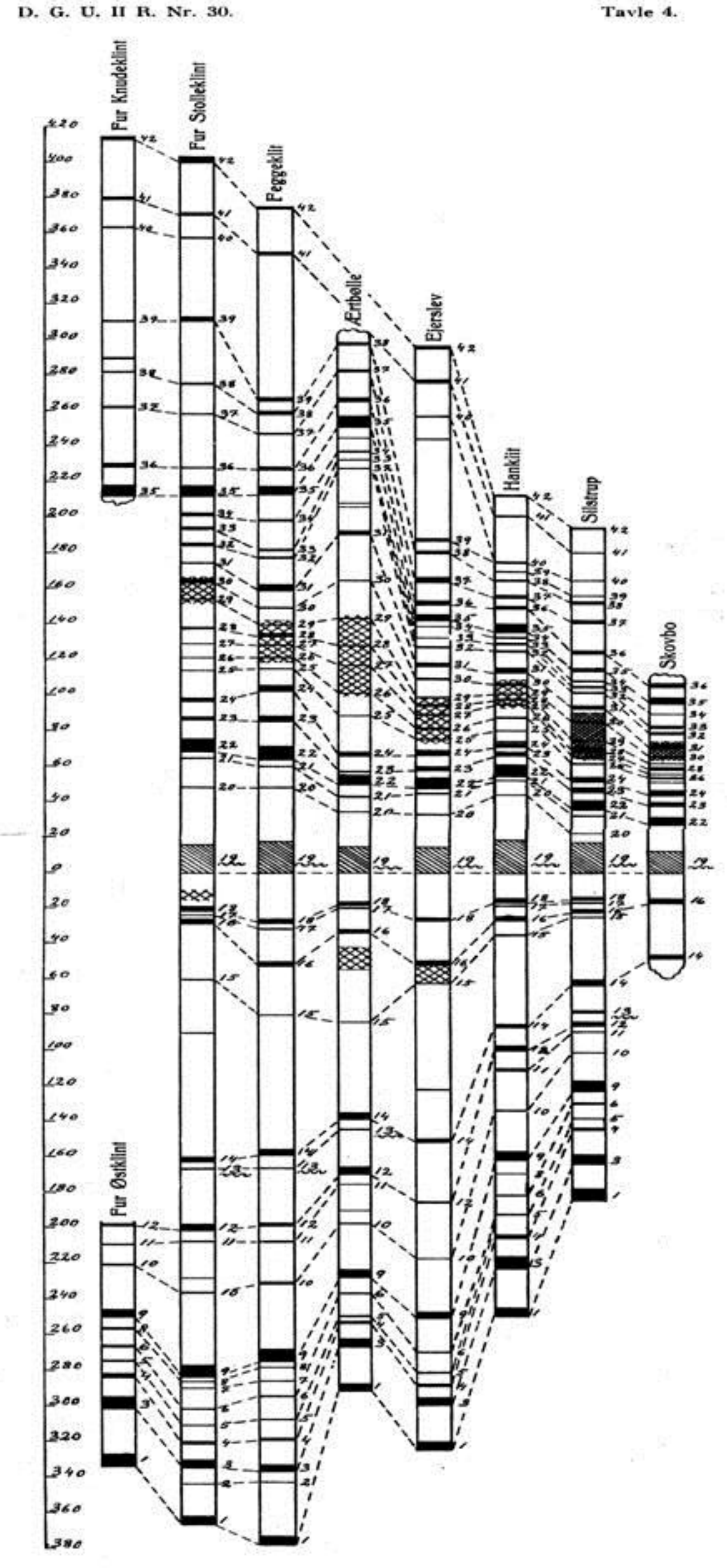

Figure 14. *Volcanic ash layers measured by Bøggild (1918). Please note that the thicknesses of the ash layers changes very little over distances of tens of kilometres. At Skovbro the ash layers are interbedded in marine clay (Ølst Formation) and this section is clearly condensed relative to the sections in the Fur Formation.*

Figure 15. *Volcanic ash layers interbedded in diatomite. Ash layer +19 is thick and pale grey (andesitic composition). The overlying black ash layers are basaltic. The beds in the calcareous concretion are less compacted than the surrounding diatomite, which indicate that the concretions formed at shallow depth below the sea floor.*

Larsen *et al*. (2003) analysed the chemical composition (main elements and trace elements) in a total of 104 samples from *c*. 77 different Danish ash layers and two samples from Germany. The ash layers were sampled in the Fur Formation, and if possible in the calcareous concretions formed during early diagenesis. Comparison demonstrated that the carbonate-cemented ash layers contain much less clay than the non-cemented samples, and the grain size distribution is different with many more small particles because these have not been turned into clay (Larsen *et al*. 2003). This shows that although the volcanic glass is well preserved in the diatomite, it is even better preserved in the calcareous concretions where seafloor weathering and other alterations were reduced to a minimum (Larsen *et al*. 2003).

Magma types and igneous development

The four stages of volcanic activity in the Danish ashes are related to the following source areas by Larsen *et al*. (2003):

• Stage 1. Basalts and peraluminous rhyolite, layers (−39?) −35 to −22: sources on the NW European shelf such as the Lundy (peraluminous rhyolite), Darwin, Erlend, or non-analysed complexes.

• Stage 2. Trachytes, rhyolites, alkali basalts, nephelinites, and phonolite, layers −21b to −15: sources on the NW European shelf and in East Greenland. The suite of strongly alkaline layers could all have originated from a nephelinitic volcanic complex such as the Gardiner igneous centre in East Greenland.

• Stage 3. Alkali basalts, layers −13, −12, −11, may be the products of a failed or propagating part of the opening rift.

• Stage 4. Tholeiitic ferrobasalts and rhyolites, layers +1 to +140, represent a cataclysmic stage sourced from a gigantic volcanic system representing the nascent Proto-Iceland within the opening ocean.

The eruption of thick succession of subaerial lavas in East Greenland occurred during stage 1–2 and probably stage 3. The cataclysmic character of stage 4 can be understood if the areas of extremely high magma production at this time moved away from the continent and into the sea-covered opening rift, thus switching the bulk of volcanism from effusive to explosive. When Proto-Iceland finally emerged, the explosive activity abated again (Larsen *et a*l. 2003).

Knox & Morton (1988) and Knox (1997) distinguished three phases of ash deposition in the North Sea. Phase 1 is early, and synchronous with the main volcanism in the British Isles from where the ashes were probably derived. Coeval ash layers in Denmark should be situated in the Holmehus Clay Formation and the Kerteminde Marl (Heilmann-Clausen *et al*. 1985). Such layers have not yet been reported, probably because they are inconspicuous and may easily be overlooked in the few, relatively poor outcrops. Phase 2 comprises several sub-phases.

• Phase 2a (or 2.1 and 2.2a) comprises the ash layers with negative numbers in the Ølst and Fur Formations in Denmark and in the Sele Formation in the North Sea.

• Phase 2b (or 2.2b) comprises the ash layers with positive numbers in Denmark and in the Balder Formation in the North Sea. Phase 2b is the phase of paroxysmal activity.

• Phase 2c (or 2.2c) and phase 2d (or 3) comprise sporadic ash layers in the younger sediments and are also represented in Denmark in the Røsnæs Clay Formation (Heilmann-Clausen *et al*. 1985, Knox 1997).

Thus, the ash layers at Fur and Mors represent eruption sites, which were active *c*. 56–54 Ma ago. This is the time of formation of the major part of the flood basalt succession in East Greenland and the middle and upper lava formations in the Faroes. There was also volcanism on the Vøring Plateau (Larsen *et al*. 2003). There is thus circumstantial evidence pointing to sources for the Danish ashes in the Faroe–Greenland area. This implies transport over distances of at least 1100 km to Fur, 1200–1600 km to the deposits in SE England and northern Germany, and about 2000 km to deposits in Austria. In recent times, ash from the 1875 eruption of Askja in central Iceland fell in a 0.5-cm thick layer in Stockholm, 1700 km away (Thoroddsen, 1925, pp. 208–209).

Fossils

The fossil assemblage of the Fur Formation is extremely diverse; containing both micro- and macrofossils originating from both marine and terrestrial environments. The chief fossil microflora elements are marine diatoms, which make up upwards of 60% of the sediment (Pedersen *et al.* 2004). Additionally dinoflagellates, terrestrial spores and pollen have been reported, along with silicoflagellates and radiolarians (Heilmann-Clausen 1995, Willumsen 2004). The macrofossil assemblage is dominated by marine bony fish and terrestrial insects, but includes terrestrial plants, terrestrial birds, marine and terrestrial turtles as well as a few invertebrate bivalves, snails and crustaceans (Bonde et al. 2008, and a long list of publications included in Pedersen et al. 2012).

The Fur Formation is well-known internationally from three-dimensionally preserved, articulated vertebrate fossils and insects. Furthermore, its taphonomy indicates it is a *Konservat-lagerstätte*, an area of exceptional fossil preservation (Dyke & Lindow 2009). Fossil preservation of feathers (as melanosome grains) and other soft tissue, which is extremely rare on a global scale, has been described from birds and bony fish. Finally, certain levels of the diatomite contain abundant trace fossils (Pedersen 1981, Pedersen and Surlyk 1983).

Fishes

The fish fauna of the Fur Formation is oceanic, pelagic and rich, with c. 60 species of ray-finned fish (teleosts), most known from complete specimens. These are unusually well preserved, some with skulls preserved in three dimensions, and a few with colour spots on fins. Seven or eight species of pelagic sharks are also known. The fish fauna of the Stolleklint Clay and Fur Formation is the first rich fauna following the end-Cretaceous mass-extinction. The most common fish (more than 95% of the finds) is a very primitive argentinoid, distant relative of all others in the group. It must be the last survivor of an old lineage from the Early Cretaceous. The second most common fish a very primitive osmeroid (smelt-like fish), which is also a survivor from the Early Cretaceous.

Several unusual and exceptional features make the fish faunas in the Stolleklint Clay and Fur Formations important worldwide: The faunas include four osteoglossomorphs („bony tongues‟), which today are confined to freshwater environments on southern continents. The faunas also demonstrate the earliest diversification of anguilliforms, gadiforms, lampridiforms, and of the perciforms, which dominate the marine waters today. A small proportion of the fishes from the Stolleklint Clay and Fur Formation can be referred directly to 15 living families. The remaining fishes are referred to 30 families, which are now extinct. On the generic level, only 2-3 of the genera from the Fur Formation still exist in the present.

Figure 16. *One of the most common fish fossils in the Fur Formation is the barbudo, Polymixiid. The fossil is 12 cm long and was preserved without matrix between the fish bones in a calcareous concretion near ash layer +15.*

Birds

Anatomically modern-looking birds (Neornithes) probably evolved at the end of the Cretaceous. They include the ancestors of living ostriches, ducks, landfowl, owls etc. These anatomically modern forms were the only birds to survive the great mass extinction at the end of the Cretaceous period 65 million years ago. It is now certain that the entire, broad diversity of living birds, as well as a number of now extinct bird groups, sprang solely from the survivors among the „modern birds" or Neornithes.

More than 170 fossil bird specimens are known from the Fur Formation, of which 40% are isolated feathers. The fossil preservation is exceptional, also on an international scale, as several specimens are preserved as nearly complete, articulated and three-dimensionally preserved skeletons within carbonate concretions. The 3D- preservation has allowed detailed anatomical studies and the fossil birds have already contributed important information to the international research into the early evolution of modern birds. So far the Fur

Formation has provided the earliest known fossil representatives of the following living bird groups: trogons, swifts, parrots and ibises, as well as the first representatives of a number of now extinct lineages.

Figure 17. *The Fur Formation is especially well known for the fossils of birds. This very well preserved skeleton of a bird (*Morsavis sedilis*) is the oldest known species representing the sea gulls and waders. However, the construction of its feet indicates that it in contrast to its present relatives was more adjusted to live in the woods. The width of the photo is c. 15 cm.*

Reptiles: Sea turtles, freshwater turtles, snakes

Several fossil sea turtles, with fairly complete skeletons are known from the Fur Formation. Turtles are among the most successful animal groups in the history of the Earth. Since they first emerged some 220 million years ago, the armoured animals have adapted to life on both land and in the sea. Their recent habitat and distribution are often closely correlated to temperature and environment, and their fossil relatives can therefore often contribute significantly to our information about prehistoric environments, climate and biogeography.

The earliest known fossils of marine turtles indicate that they took to the sea some 110 million years ago. Only two groups of marine reptiles (one of these are the turtles) survived the mass extinction at the end of the Cretaceous period. The Fur Formation har preserved an almost complete specimen of a large leatherback turtle, *Eosphargis breineri.* Recently, a number of exceptionally well-preserved turtle specimens have been recovered, two of which have been recognized to be a completely new species of the genus *Tasbacka*. One specimen is a complete, 11 centimetres long juvenile sea turtle, which has preserved traces of soft tissue, including skin around flippers and scutes at the edge of the shield.

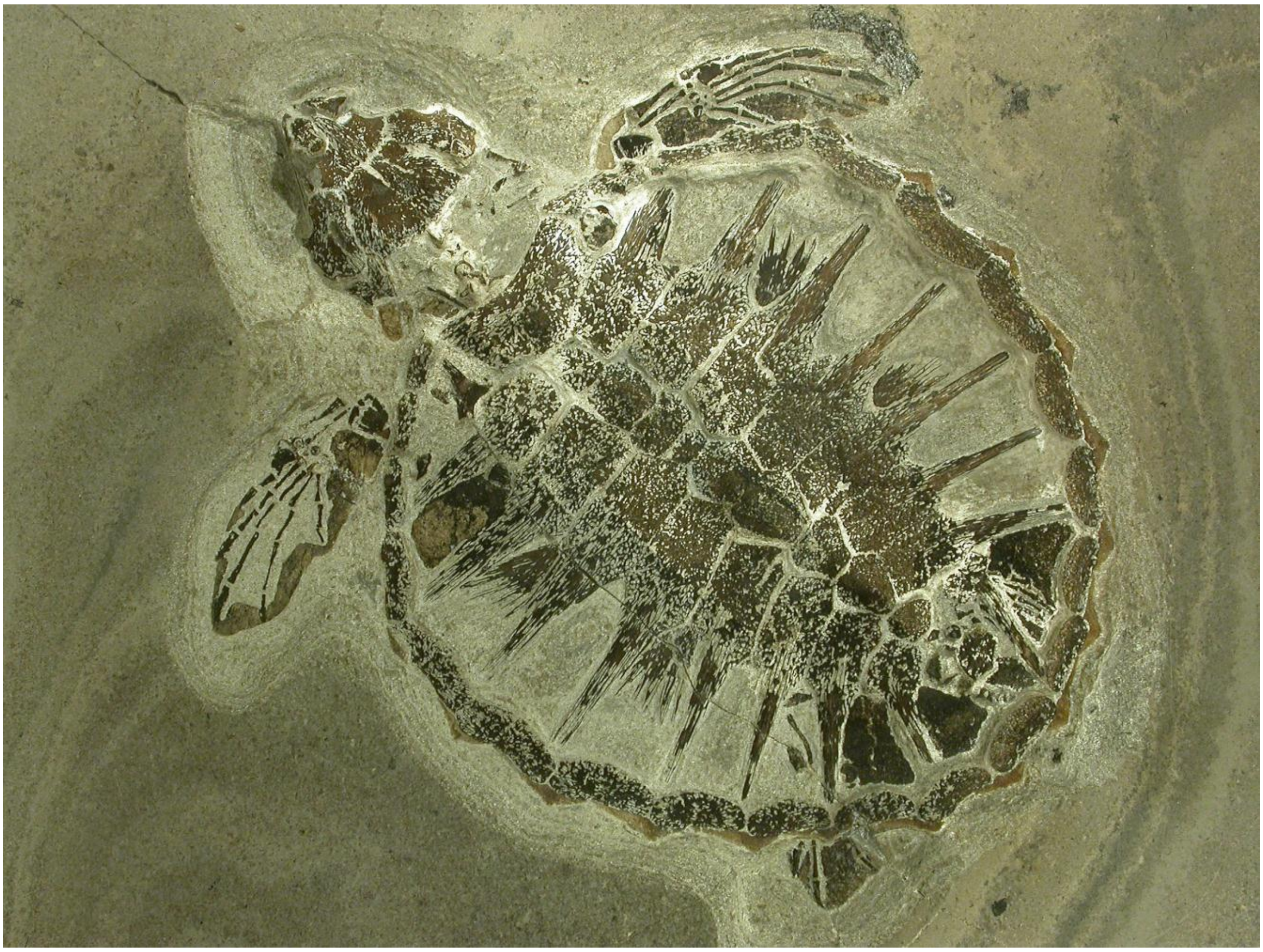

***Figure 18**. Young sea turtle, Tabacka sp., 10 cm in size. The turtle is very well preserved and even the web of the flipper can be recognized. It was found in the Fur Formation on northern Mors.*

Insects

The most common macrofossils of the Fur Formation are insects and at least 25,000 fossil insect specimens housed in various collections. They are characterised by a brilliant preservation of even the finest details and c. 200 species has been identified so far. The most common insects belong to the Diptera (true flies), Heteroptera and Auchenorrhyncha (cicadas). These are particularly diverse, and include a large number of planthoppers (Fulgoromorpha). The Lepidoptera (moths and butterflies) are represented by more than 1700 specimens representing 6 species. Saltatoria (grasshoppers, locusts, crickets), Neuroptera (lacewings) and Hymenoptera (wasps, bees, ants) are also represented by several species. It has been possible to reconstruct the original singing and hearing apparatus in the most abundant grasshopper. Other insect taxa: Odonata (dragonflies, damselflies, Mantodea (mantises), Blattoidea (cockroaches), Dermaptera (earwigs, Coleoptera (beetles), Mecoptera (scorpionflies) and Trichoptera (caddisflies) are likewise represented by outstanding fossils.

The insects of the Fur Formation allow deep insight into a terrestrial ecosystem during the global greenhouse climate about 55-54 Million years ago. They are of eminent importance for the analysis of the early development of modern insect diversity.

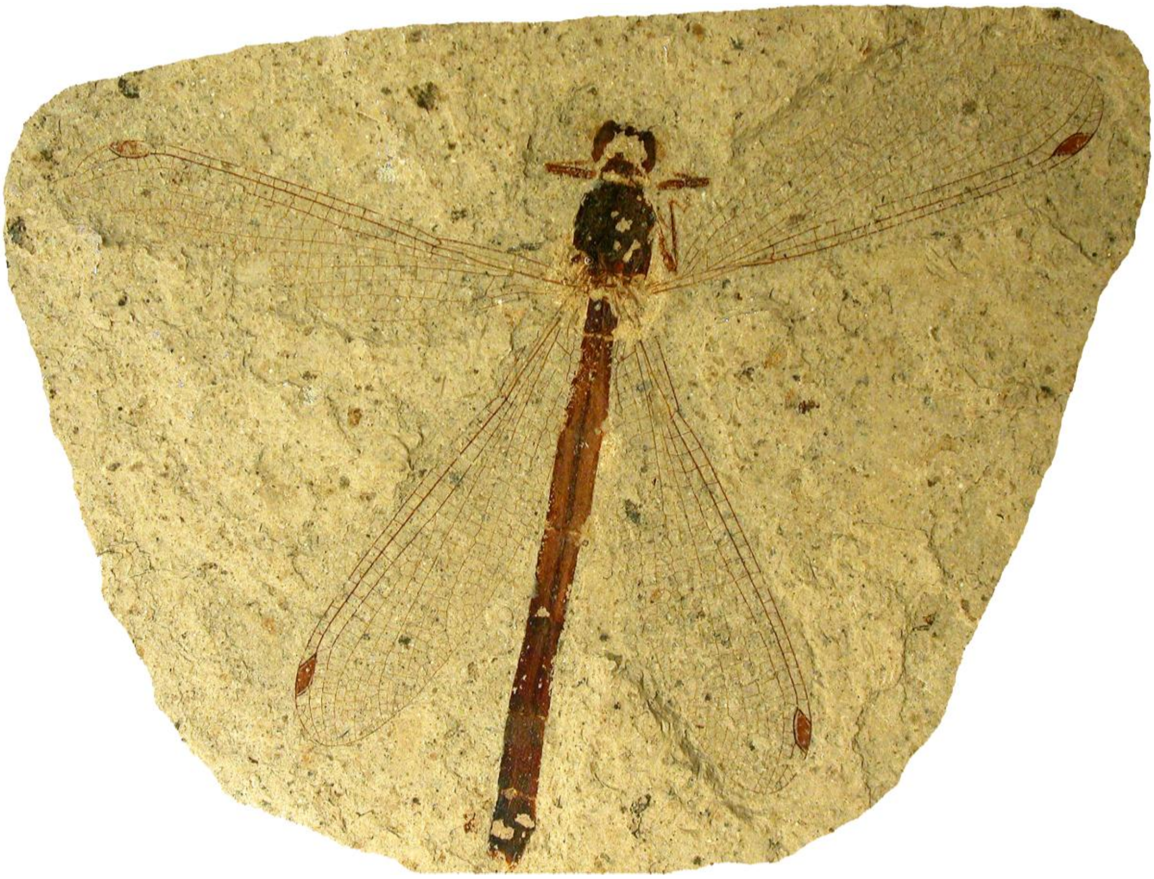

Figure 19. *A well preserved damselfly from the Fur Fomation. The size of the insect is 40 mm.*

The insects were transported from southern and south-western Scandinavia to the former North Sea by active flight, passive wind drift or attached to plant remains. Flightless forms have not been found. In addition, the faunal composition shows that insects always flew during summers with high temperatures and prevailing northerly winds. The climate of the North Sea area was possibly subtropical The high diversity of plant-sucking insects gives evidence of lush and highly diverse vegetation on the Scandinavian mainland. A broad spectrum of freshwater insects suggests the existence of large and diverse lakes, ponds, swamps, and rivers. Other insects indicate the existence of forests and open areas with shrub vegetation.

Together with the Baltic amber the diatomite of the Fur Formation is the most important *Lagerstätte* of Tertiary insects in Northern Europe. The preservation of the fossil insects is outstanding. In some cases the preservation of specimens is three-dimensional and even soft tissues are sometimes found. Many groups of insects have been recorded for the first time in the Fur Formation and these finds are therefore crucial for the reconstructions in insect phylogeny.

Plant macrofossils

Fossil wood, from stems to twigs, are relatively frequently found in the Fur Formation, and may originate from *Sequoia/Metasequoia*, Juglandacea (walnut family), *Araucaria* and other trees. Leaves include *Macclintockia kanei, Cercidophyllum* (Katsura tree) and other representatives of the "Arcto-Tertiary-Flora". The leaves of *Macclintockia* are so well preserved that the cellular tissue may be extracted for studies of the climate adaption of the plants.

The plant fossils were transported by rivers from the land. Soil with Upper Cretaceous flint is preserved among roots in tree stumps indicate that the terrestrial domain included areas of weathered chalk. An 8 m long stem has been identified as redwood (*Sequoia*), a species well known as giant trees in California. Twigs and pollen of *Sequoia* have also been found (Fig. 20). Fossil wood has recently been identified as related to *Juglandicarya*, interpreted as an ancient type of walnut. Other fossils are identified as pine and monkey puzzle/Norfolk Island pine *(Araucaria)* represented by branches and spruce needles, some with attached amber. Futhermore, spruce cones have been found. Leaves are rather sparsely represented, probably due to easy disintegration during transport. Oak leaves have been found with traces of insect attack, and among other deciduous trees maple, plane, ash and *Ginkgo* have been identified. Long, bamboo-like leaves are frequent, and the leaves, seeds and small fruits from water ferns (*Salvinia*) occur as well. Characteristic small fruits from palm trees are common.

The land areas surrounding the "moler sea" were covered by coniferous forest, but more open areas with deciduous trees and grass-steppe existed here and there. Ferns and horsetails have been recognized. The insects indicate that a number of flowers were grew in the various environments, but very few have been found as fossils.

Figure 20. *Twig of Sequoia (redwood).*

Spores and pollen

The spore and pollen assemblages are excellently preserved and highly diverse and comprise a minimum of 45 spore and 95 pollen species. The assemblages reflect changes from a subtropical to a temperate maritime vegetation in the North Sea region during a period of less than 1 million years. Furthermore, significant changes in the assemblages of marine dinoflagellate cysts resulted in a high-resolution palynological zonation for the Danish part of the North Sea.

This unique record provides the basis for retrieving detailed information about environmental shifts in the vegetation during the PETM greenhouse event (Heilmann-Clausen 1995, Willumsen 2004, further references may be found in Pedersen et al. 2012).

D A N M A R K S O G G R Ø N L A N D S G E O L O G I S K E U N D E R S Ø G E L S E R A P P O R T
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Geology of the early Eocene Fur Formation, a unique deposit in the North Sea Basin

Excursion guide to geological key localities on Mors and Fur, northern Denmark

Gunver Krarup Pedersen & Stig A. Schack Pedersen

Description of the localities visited during the Winthershall fieldtrip 11–12 June 201

Localities

Day 1

Figure 21. *Map of localities to be visited during the morning June 11-2013.*

Localities 1-3: Quaternary geology of Vendsyssel.

The geology of Vendsyssel is markedly influenced by glacio-isostasy. From Hirtshals we are mainly driving on the elevated sea beds from the Yoldia Sea, which are named after landscape in northern Jylland: the Vendsyssel Formation. The formation was deposited shortly after the ice melted back from Vendsyssel about 18 500 years BP. The arctic marine waters transgressed the area from the Atlantic through the North Sea to Vendsyssel and northern part of Kattegat. The marine conditions terminated temporarily about 15 000 years BP and the terrestrial conditions were established in Vendsyssel, where the flat lying plain was lifted out of the sea due to the isostatic rebound. During the elevation the plain became intersected by incised valleys,

Figure 22. *Dune front of the Rubjerg Klit. The lee side is c. 15 m high, and the dune is migrating from west towards the east. Note the prograding and aggrading stratification of the lee side.*

Loc. 1 – Rubjerg Knude recent dune formation

The dunes along the west coast of Vendsyssel, as well as further down the west coast of Jylland, started to form in the Little Ice age about 300 years ago. There are plenty of records of dune migration and villages that were covered by aeolian sand. We‟ll pass the old Rubjerg church, which was abandoned in 1904 due to sand cover. One of the highest dunes in Denmark is the Rubjerg Klit (klit=dune), which accumulates above the cliff head of Rubjerg Knude. A lighthouse was built here in 1900 in a safe distance from the steep cliff. However, with an erosion rate of 1.25 m/year the cliff face has steadily approached the lighthouse. Meanwhile, accumulation of dunes on top of the cliff head blocked the light, and in 1959 the lantern was removed and the lighthouse given up. 25 years ago it was predicted that the lighthouse would face a dramatic end: first it would be covered by sand dunes, and secondly it should reappear on the stoss side, before it finally should be destroyed in a landslide and eroded away by the breakers in the year 2012 (Pedersen 1986). However, the prediction was incorrect. The dunes have bypassed the lighthouse, and today it is standing on the stoss side of the dunes. It never became covered, because the wind‟s turbulence around the tower kept it free from sand. The lower buildings surrounding the lighthouse are still covered by sand. As you can see the predicted collapse of the lighthouse has not yet happened, but it may happen, while we walk to the dunes for a detailed study of aeolian sand dynamics. We will not go up to the lighthouse but walk to the edge of the dune complex by a path through the wood. The distance is 500 m , so please move quickly. There used to be nicely eroded cross sections in the dunes to the right of the path through the wood.

Loc. 2 – Børglum Kloster

A focal point in the landscape is the hill crowned by an impressive white building, the Børglum Kloster. We will pass the hill, stop and walk up to the windmill on the other side of the main road, if time permits. Børglum Kloster and the windmill are located on top of an old island formerly located in the Yoldia Sea, now constituting a fossil island. The Yoldia Sea was named after the bivalve Yoldia, now known as *Portlandia arctica*. The marine deposits are now defined as the Vendsyssel Formation, which you can see as the planar horizontal surface beyond the windmill hill (Fig. 23).

***Figure 23**. The Børglum Kloster (old monastery) and the windmill on the top of the former island in the Yoldia Sea. The island constitute glacial deposits, whereas the flat road runs on the Vendsyssel Formation*

The melting of the Weichselian ice caps stopped c. 5 000 years ago in the Holocene. The warmer climate in the Holocene caused the remaining ice caps in Scancinavia and North America to melt and the Atlantic transgression drowned the deeper incised valleys. This is the case at Løkken, where we will pass one of these fossil fjords. The reason why the fjord at Løkken is called fossil is that it is elevated 10 m above present sea level due to the continued isostatic uplift. The beds in the fjord are now exposed at the Løkkens Blånæse, which, however, are not included in this trip.

Loc. 3 – Store Vildmose

From Løkken we will drive southwards to Saltum, where there is a good view over a lowland plain, the Store Vildmose, a raised bog with *Spagnum* peat. The peat growth began when the Postglacial sea floor was elevated (isostatic uplift) and developed into a sandy plain without drainage.. The *Spagnum* moss started to occupy the plain about 2 000 years ago in the Iron Age. At that time the plain was elevated about 3–4 m above present day sea level. The elevation today is 5–6 m a.s.l. We will drive down to the Vildmose plain immediately after passing the village Saltum (Fig. 24, 25).

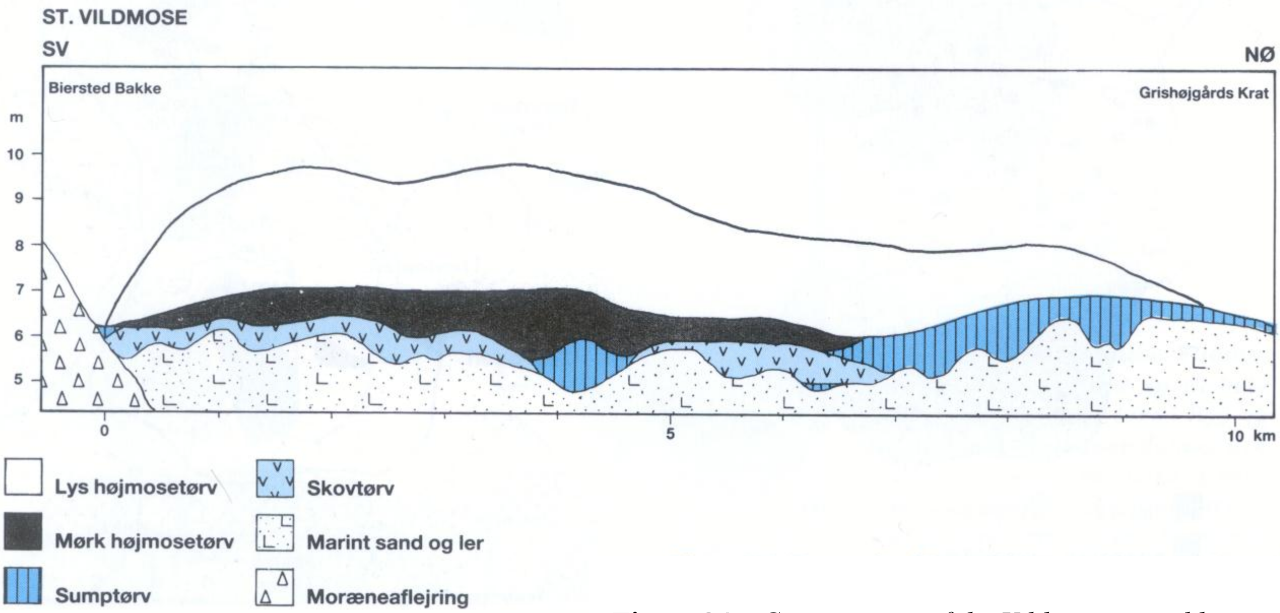


Figure 24. *Cross section of the Vildmose raised bog.*

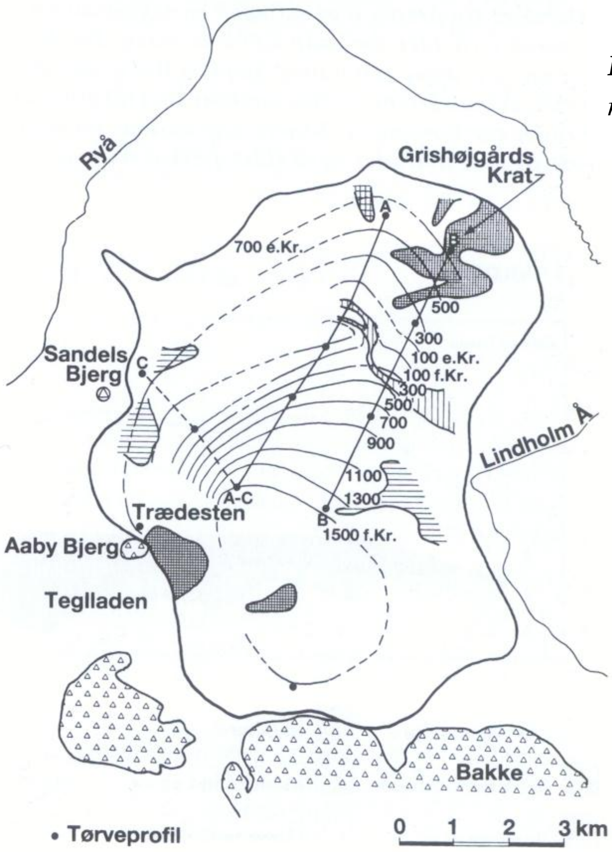


Figure 25. *Map of the timing of the migration of the raised bog.*

Loc. 4 – The Bulbjerg limestone cliff.

Before we reach the Bulbjerg locality we have to drive a relatively long distance (1½ hour). On the way to the cliff we will pass the small town Fjerritslev, which gave name to the Fjerritslev Fault, the southern boundary fault of the Sorgenfrei-Tornquist Zone (Fig 1). Near the fault an outcrop of chalk may be seen at the road side. When we arrive at the locality we will first walk a few hundred meters along the beach to the limestone cliff. (Fig. 26). The limestone comprises bryozoan mounds instructively outlined by the flint bands. The bryozoan limestone is lowermost Danian, which is characterized by the *Tylocidaris Abildgaardi* sea urchins (echinoids). The spines of the "sea mouse" can easily be recognized in the limestone, which is a bio-clastic sediment with mounds build up by various species of bryozoan (Fig. 27).

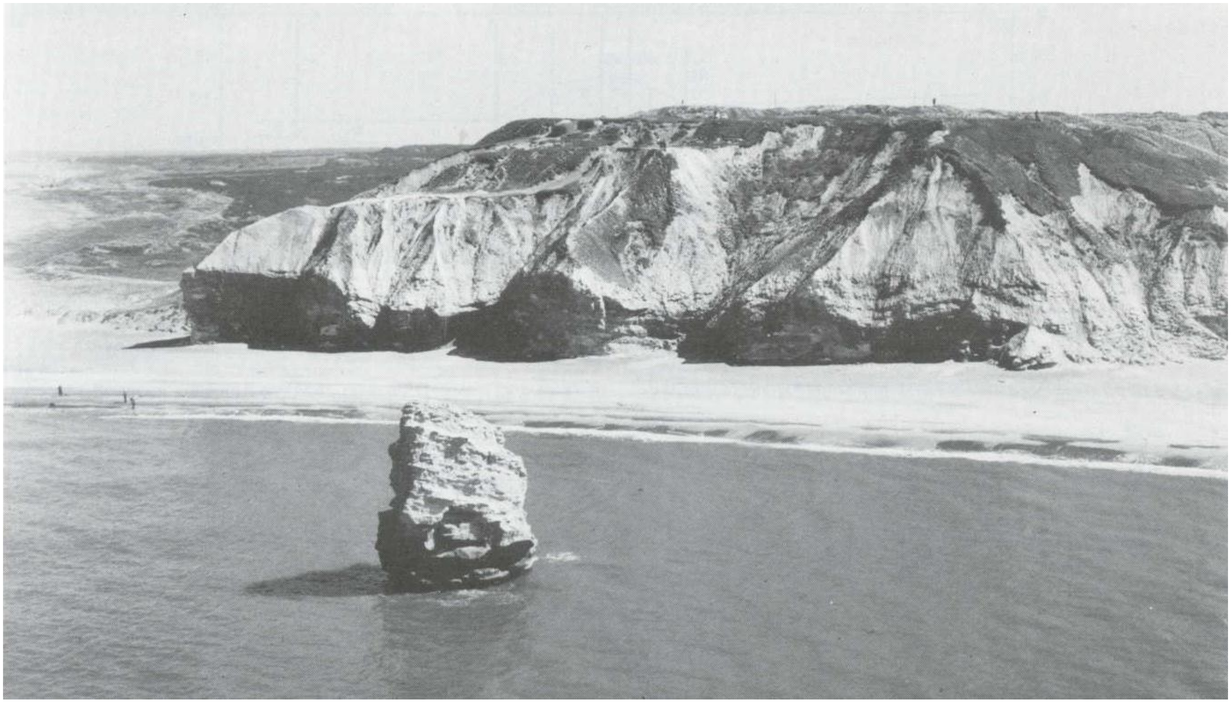
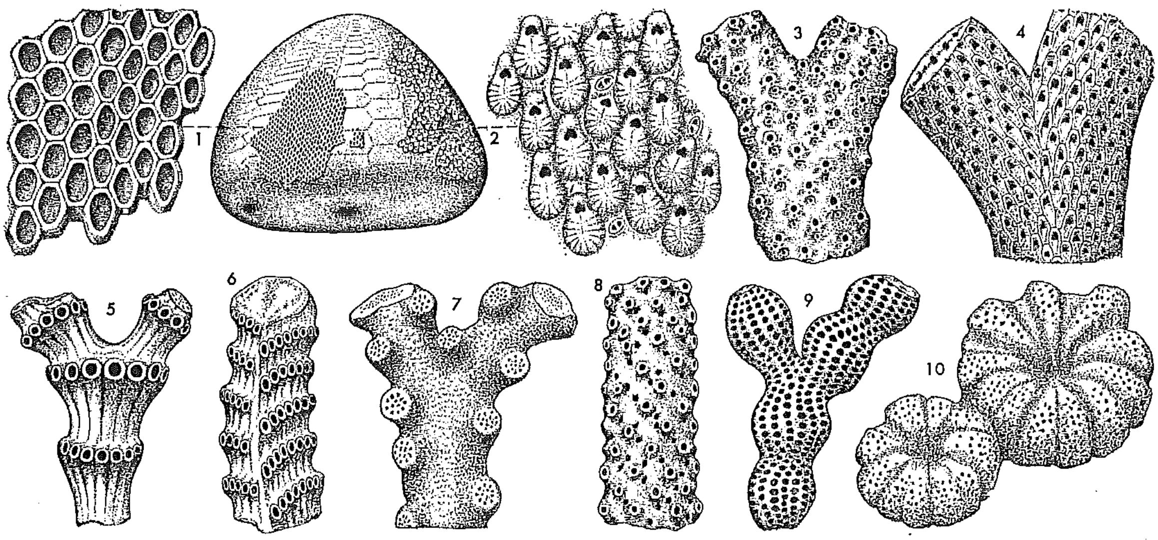


Figure 26. *The cliff at Bulbjerg. The needle (Skarreklit) toppled down during a storm on 19th September 1978.*

When we have studied the cliff we will return to the bus and drive to the top of the cliff (restrooms are found in the old German fortress). From the top of the cliff we will have a viewover the landscape towards Hanstholm. From Bulbjerg to Hanstholm the limestone comprises a synform depression. The limestone is coming up again in the anticlinal dome, of which the northern limb is forms a hill crest trending E-W terminating at the harbour at Hanstholm (Fig. 29).



Bryozoer fra skrivekridt. x 6. (De samme slægter findes i dan). 1, Membranipora. 2, Membraniporella. 3, Porina. 4, Coscinopleura. 5, Spiropora. 6, Idmonella. 7, Desmepora. 8, Heteropora. 9, Ceriopora. 10, Actinopora.

***Figure 27**. Bryozoans are unicellular, colonial organisms, which may build mounds. They occur in high abundances in Danian (lower Paleocene) limestones in Denmark. The bryozoans shown here are from the Upper Cretaceous and Danian in Denmark (drawing by C. Rasmussen).*

Loc. 5 – Nye Kløv chalk bluff with the C/T boundary.

In the hill bluff at Nye Kløv the chalk exposure contains the K/T boundary. From Bulbjerg we'lldrive to Østerild and cross the Hjardemål cliff crest. The Danian limestone (Stevns Klint Formation) overlie the Maastrichtian chalk (Tor Formation) surrounding the Thisted dome in a horse shoe pattern (Pedersen & Petersen 2001). We pass Hunslev church and drive along the hill side, a former coastal cliff, to pass the Nye Kløv locality. The chalk is visible from the bus. We shall be heading for the ferry to Mors.

The Feggesund ferry will bring us acrossthe strait to the northernmost peninsula on Mors, the Feggeklit, and here the Feggesund Færgekro is located. This will be the lunch stop of the day.

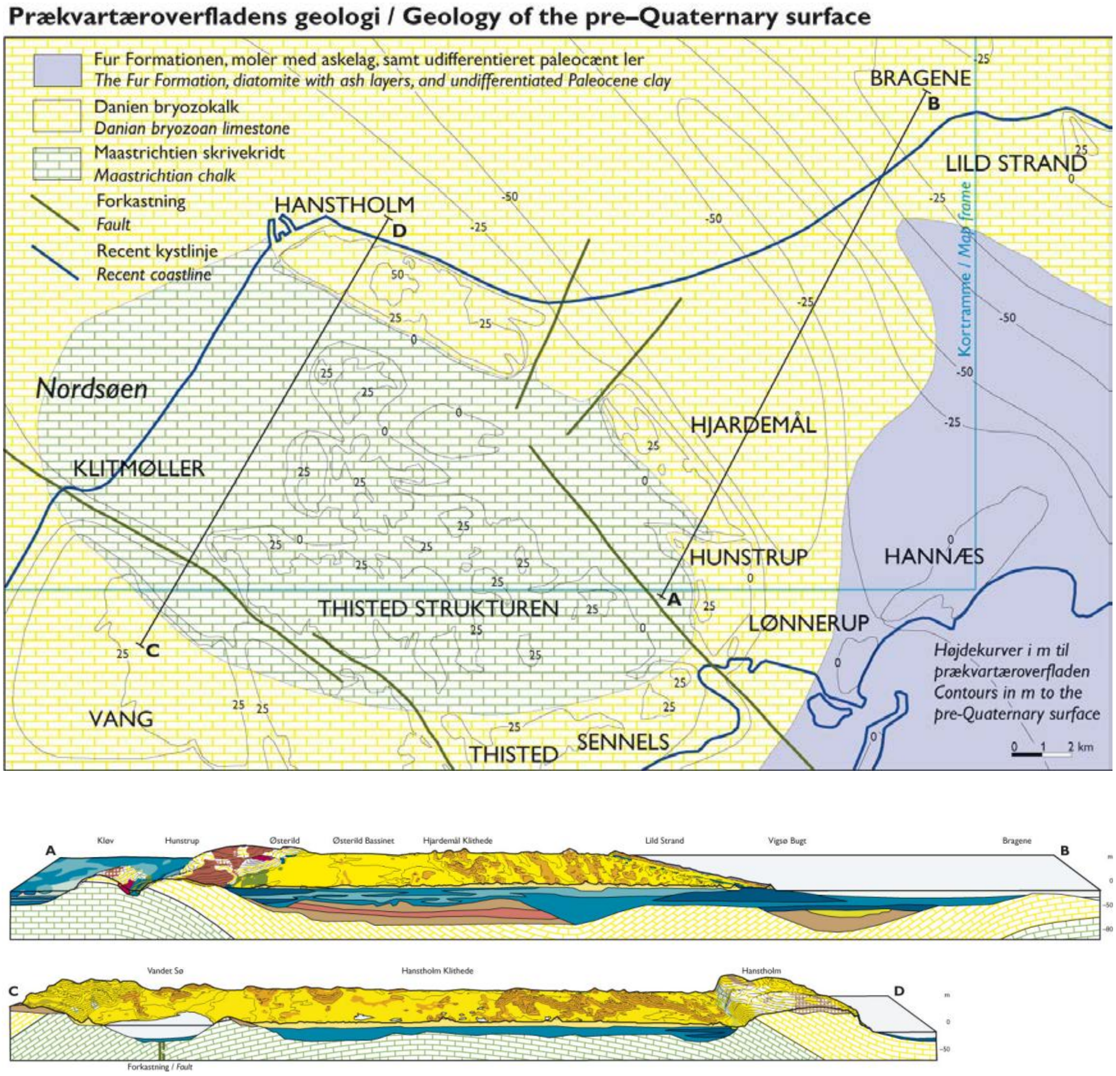


Figure 28. *Geological map of the bedrock above the Hanstholm salt dome (Thisted Structure) and two cross-sections illustrating the geological framework on the northern flank (A–B) and the doming in the central part of the structure (C-D), respectively. Note the WNW-trending fault zone at Klitmøller. Recently a groundwater well has here been so popular that people in Klitmøller bottle and distribute mineral water from this locality. The yellow unit of top of the cross-sections indicates aeolian sand with the highest dunes outlined in orange. The blue colour below the dune areas represent marine deposits from the postglacial Atlantic time. (From Pedersen & Petersen 2002).*

Figure 29. *Map of the localities to be visited in the afternoon June 11th. The needle (Skarreklit) toppled down during a storm on 19th September 1978.*

Loc. 6 –7 Feggeklit.

After lunch we will drive a short distance down to the southern end of Feggeklit. If the conditions permit we will walk along the cliff section, where the Fur Formation is very nicely folded in a series of parallel-folded anticlines and synclines. At the beginning of the cliff the uppermost part of the Silstrup Member crops out. The two thick characteristic ash layers +118 and +114 are easily identified. Note the dish-&-pillar structures in the normal graded, fine-grained sandy ash layers. Further along the cliff to the north we pass a broad syncline with various glacial deposits: two tills are overlain by a kink-folded glaciolacustrine unit, discordantly truncated by a glacitectonite and a till. Where the glacial succession terminates at the northern limb of the syncline we pass vertical beds around ash layer +101, which are thrust over by a thrust sheet containing the lowermost part of Silstrup Member and the top part of the Knudeklint Member (Fig. 30). The details of glaciotectonic structures and calculation of the depth to the decollement surface for the thrusting is described in Pedersen (1996). We will however, return to the bus at this point.

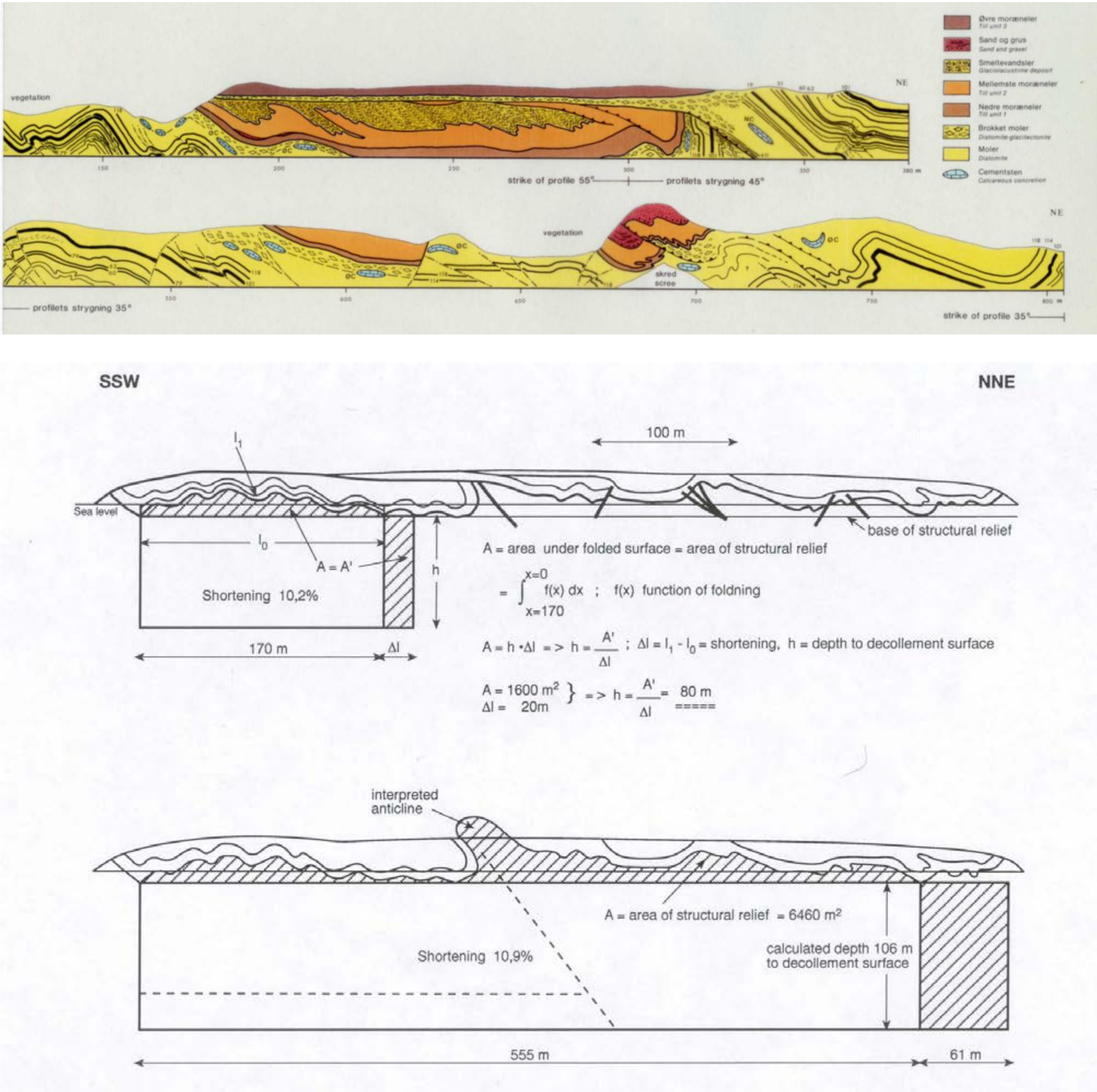


***Figure 30**. The Feggeklit cliff section and the demonstration of the calculation of the depth to the décollement surface by the application of the balanced cross section method.*

Loc. 8 – Skarrehage.

The Skarrehage moler pit and the Moler Museum are located on western side of northern Mors just above the moler factory, which is famous for its production of cat litter. One of the interesting things about the diatomite as a glacial deformed unit is the occurrence of superimposed deformation. In the base of the now abandoned Skarrehage moler pit a very instructive example of an arrow head structure is present, which clearly was folded by two different glacial events (Pedersen 2000). In general we refer to the two last ice advances as the Norwegian Ice and the Swedish Ice. The ice advances affected Mors about 28 000 years BP from Norway (Hadanger Vidda) and 24 000 years BP from Sweden (Dalarne) (Pedersen 2005). Details of this will only be briefly mentioned, but you should appreciate the view of a nicely folded syncline with all the positive ash layers down to the distinct thick grey ash layer +19. At the Skarrehage moler pit a group of people took initiative to establish a moler museum, where local collectors of fossils donated their private collections to the exhibition. If time permits or weather conditions demands for it, we will visit the Moler Museum on Mors.

***Figure 31**. The horizontal cut off at the base of the moler pit in Skarrehage displayed the peculiar framework of an arrowhead structure. The analysis of the structure gave an easy explanation as due to simple superimposed deformation.*

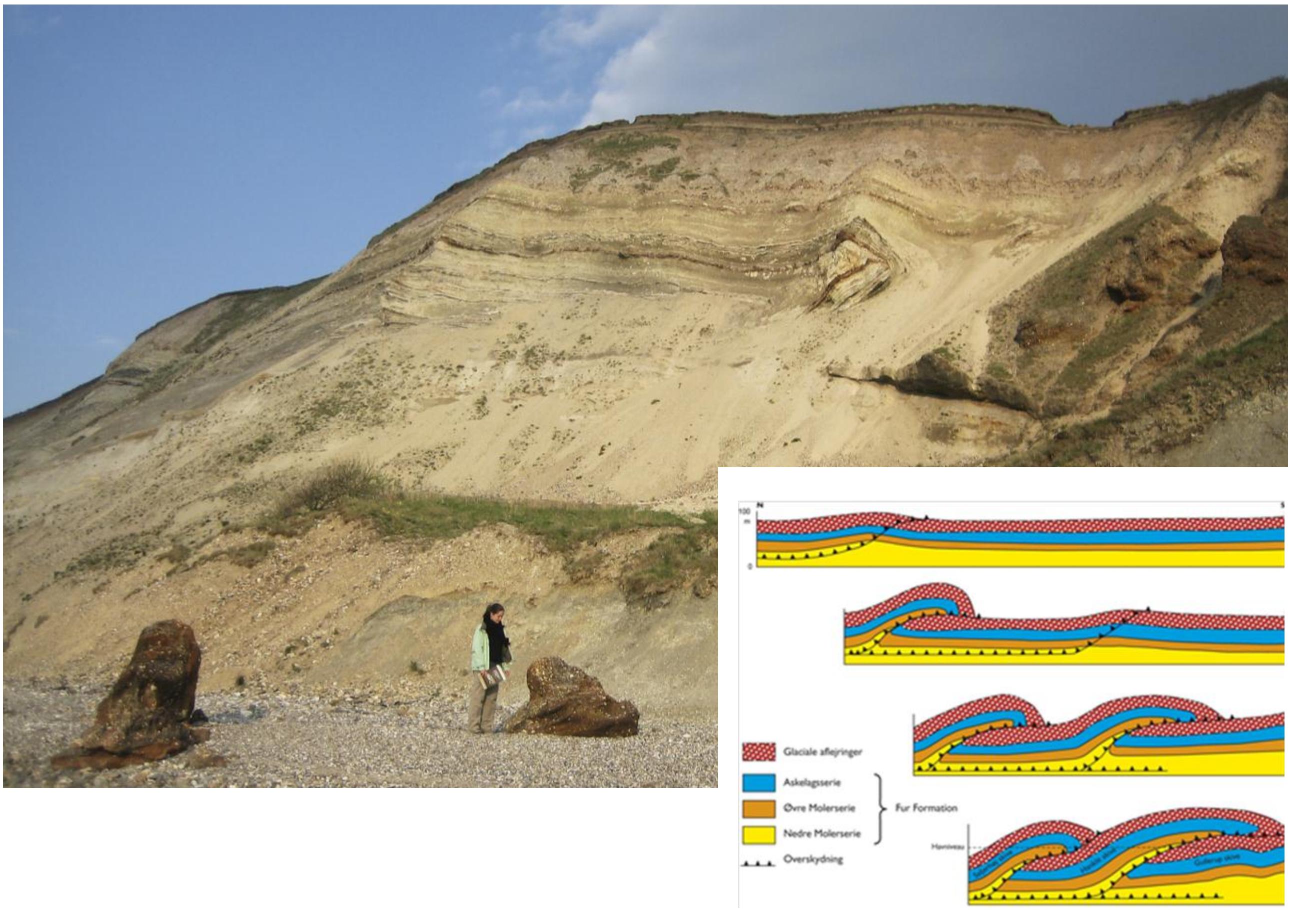


***Figure 32**. The Hanklit coastal profile. The corss sections to the right show four stages in the progressive dynamic cevelopment of the thin-skinned thrust faulting, that created the impressive hanging-wall anticline at the tip of the Hnaklit thrust fault.*

Loc. 9 – Hanklit.

From Skarrehage we will drive along the western coastline of Mors to Flade, which is a hilly area pressed up by the Norwegian Ice. The highest point on Mors, Salgjerhøj 89 m a.s.l., is situated above the village Flade. A cross section of the internal structure of the hill is the target of the next locality. The bus will drive down to the parking lot at the beach, and we will walk along the cliff and enjoy the view of Hanklit. The central cliff section at Hanklit is 60 m high, and its most impressive structure is the thrust sheet with a hanging-wall anticline displaced 300 m along a gentle dipping thrust fault. This thrust sheet is the middle one in the complex comprising three large sheets displaced piggy-back on each other. The stratigraphy of the thrust sheets constitutes about 40 m of the Fur Formation (Eocene diatomite with volcanic ash layers) overlain by 15-20 m glacial deposits of Weichselian age (Gry 1940, Klint & Pedersen 1995) (Fig. Hanklit). A detailed structural analysis including a profile and a balanced cross-section was provided by Klint & Pedersen (1995) (Fig. 32). The Hanklit profile represents a cross-section through the proximal part of a 3 x 10 km^2 wide arc-formed composite ridge system known as the Bjergby Arc pushed up by the Norwegian Ice Advance about 28.000 years ago.

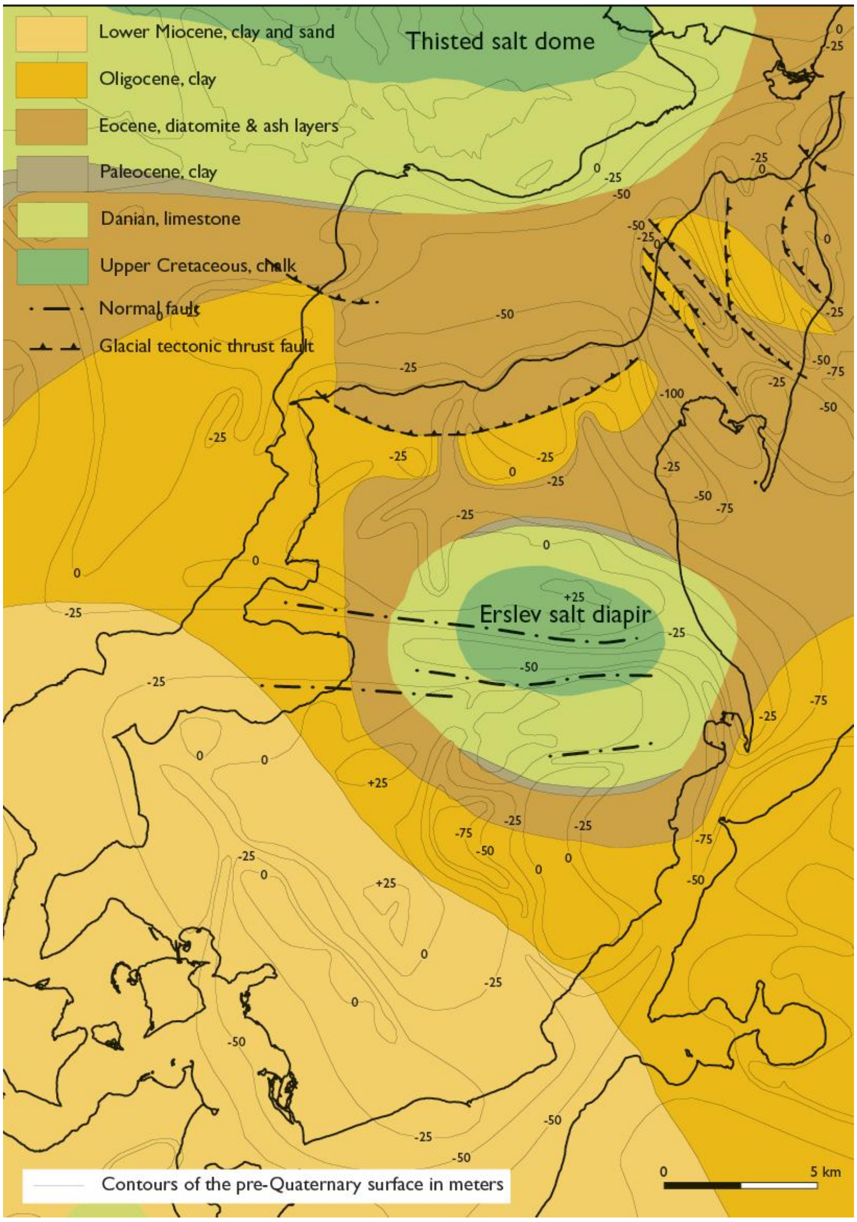


Figure 33. *The geological map of the bedrock of Mors.*

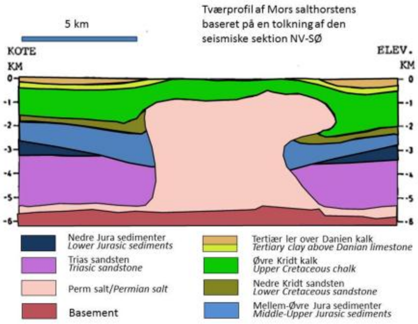


Figure 34. *The cross section shows the 5 km raising salt diapir below the village Erslev on Mors.*

We will pass Bjergby on the way southwards across Mors while we are heading for the hotel at Sallingsund. Before we reach the main road, small roads will take us past the old chalk kiln at Erslev. Formerly chalk was excavated from the northern flank of the Mors salt diapir structure located centrally on Mors (Fig. pre-Quaternary map of Mors). The salt diapir became famous 30 years ago, when it was suggested to be suitable for storage of nuclear waste in the salt 1.5 km below the surface. Geologists argued against this solution due to the complex internal structure and shear movements in the diapir, and the arguments stopped the establishment of nuclear power plants in DenmarkThe depth to the base of the Permian salt is 6 km. The cap rock is located ca. 600 m below the surface (Fig. tværsnit). Accommodation is at hotel Pinen on the SE-side of Sallingsund. The bridge was built in 1978 and replaced a ferry crossing.There was a lot of traffic, so people always had to wait for the ferries, which were named “Pinen and Plagen” (the pain and the plague). The hotel on the Salling side now keeps the name of one of the ferries.

Day 2

***Figure 35**. Map of the main important points to pass during the 12th June 2013.*

The landscape on northern part of Salling is the third example of salt diapirism in the subsurface. On the way to the ferry to Fur we will pass the still operating chalk pit at Batum, before we head to the ferry crossing.

Loc. 8 – The Batum chalk pit.

The chalk pit can be seen from the bus, and we'll only make a brief stop at the road side. The chalk pit is situated at the top of the diapir, and the chalk at the base of the pit is uppermost Campanian – lowermost Maastrichtian . The salt diapir is one of the western diapirs in a ring-formed complex with the Mors structure in the middle.

Loc. 9. – The Hill Crest of Fur.

When we arrive at Fur the bus will drive us up to the hill crest parallel to the north coast of Fur. Here we will pass the highest point on Fur, Bette Jens Høj. From the hill top we have a view to the central moler pit where the clayey diatomite is excavated to be used in the brick factory beyond the hill, the one with the high chimney.

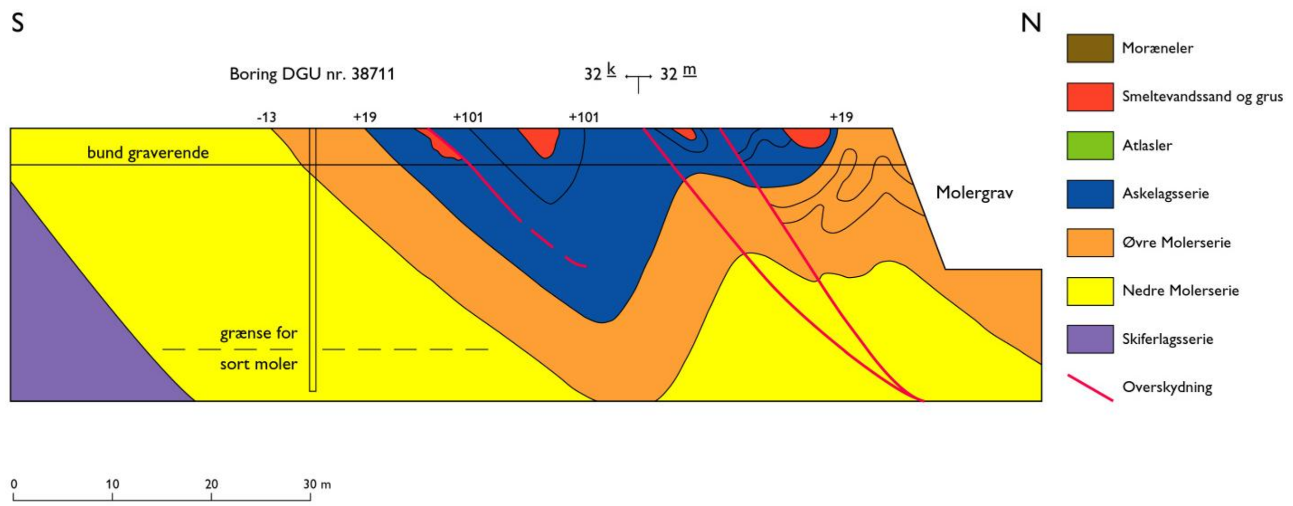


***Figure 36**. The hill crest of Fur is still the target for exploitation. In the pit instructive cross sections of the up thrust diatomite with ash layers can be seen.*

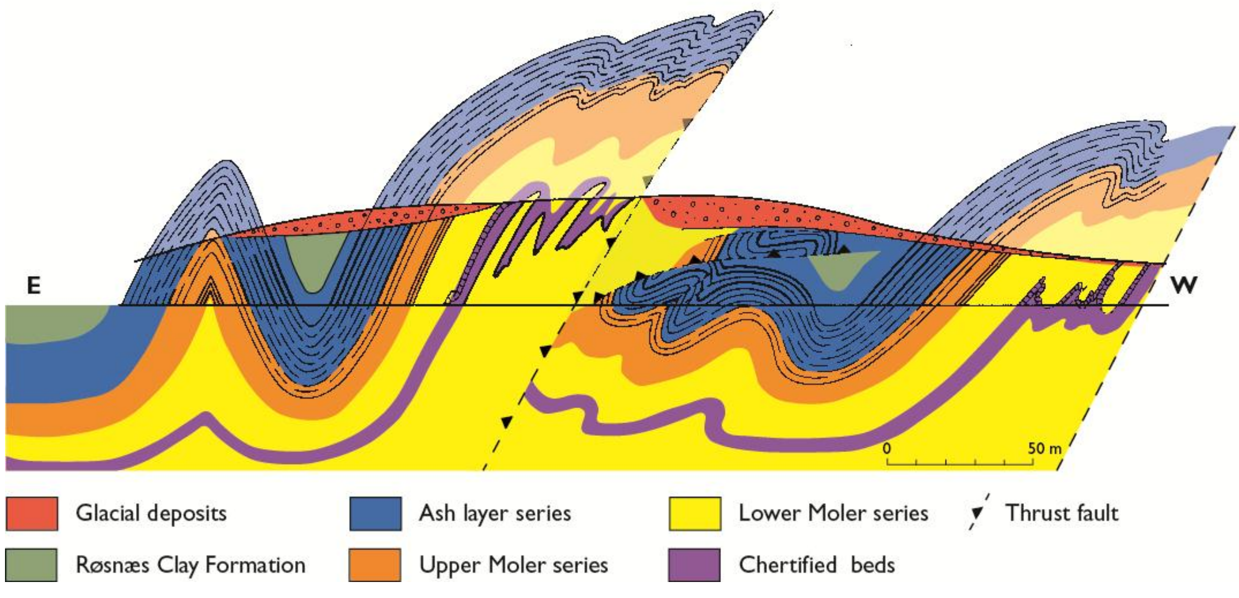


***Figure 37**. The cross section of Fur Knudeklint is exposed at the NW corner of Fur.*

Loc. 10 – Knudeklint northwestern corner of Fur

Knudeklint is a 35 m high coastal cliff on the NW-corner of the island of Fur (Fig. 37). The profile is about 1 km long and contains seven larger thrust sheets with the early Eocene Fur Formation as the dominant lithological unit (Gry 1940, 1965). The most impressive structure is the large-scale folded thrust-sheet at the transition from the proximal to the distal part of the complex. This structure comprises two anticlines separated with an upright, tight syncline. In the core of the syncline the beds of the Røsnæs Clay Formation overlies the upper boundary of the Fur Formation, whereas the lower boundary of the Fur Formation crops out along the hanging-wall ramp limiting the distal anticline (Pedersen 2000, 2011).

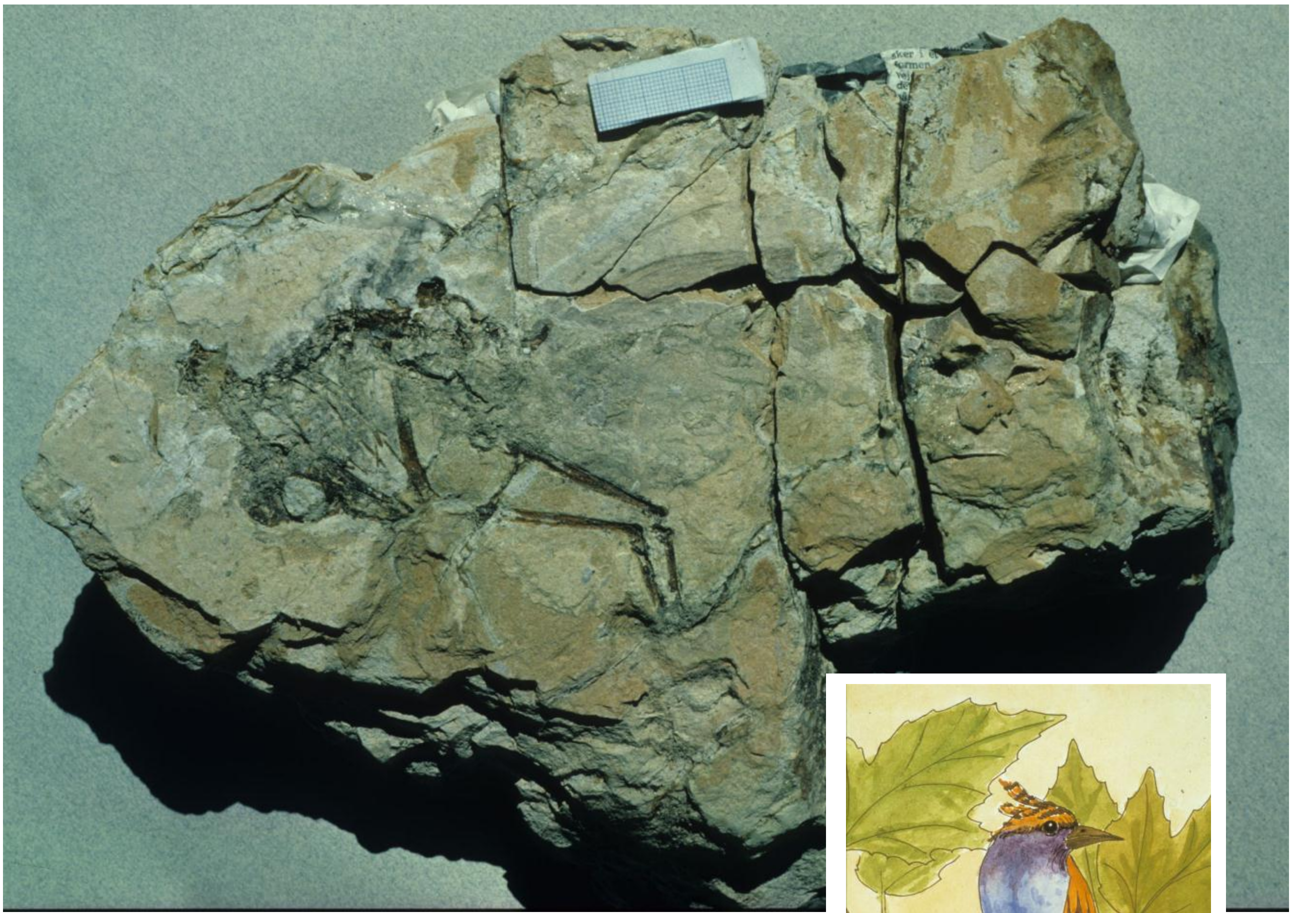
Due to the complete stratigraphic succession the Knudeklint is the type locality of the Fur Formation. The deformation of the glaciotectonic complex on Fur took place during the Norwegian Ice Advance about 28.000 years ago (Pedersen 2011). A succession of 8-10 m glaciofluvial sand and gravel was carried piggy-back on the thrust sheets. This sand unit represents a proglacial outwash deposit, which in the foreland of the glaciotectonic complex fill out a former tunnel-valley more than 60 m deep. The advancing ice pushed the thrust sheets up in a composite ridge system creating the hilly northern part of the Fur island.

Figure 38. *An air photo look of the Fur Knudeklint. Follow the line of threes to the right for finding the way to the Fur brewery.*

Loc. 11 – Fur Museum

Fur Museum was founded in 1954, and was based on Mr. M. Breiner Jensen‟s large, private collection of fossils from the Fur Formation. He worked initially as unpaid head of the Museum, which eventually (1962) received economical support from the municipality. At that time the museum housed historical artifacts as well as fossils. In 1970 the M. Breiner Jensen was offered the position as head of Fur Museum. He supervised two expansions of the museum in 1960 and 1977. The third wing was built in 1984. M. Breiner Jensen was succeeded by a palaeobotanist, and the later heads of the museum have been geologists.

Fur Museum has formal responsibility for the care of exceptional fossils, the so-called „danekræ". Those who find fossils or minerals of scientific importance are required to hand in the finds to a museum, but are awarded a sum of money. Fur Museum has an impressive, and steadily growing collection of fossils and other samples from the Stolleklint Clay and the Fur Formation. The visitor is almost sure to find new exhibits at each visit to the Museum.



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