DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2010/31

Stratigrafisk ramme for 3D modellering af den miocæne lagserie i Danmark

Erik S. Rasmussen, Karen Dybkjær, Stefan Piasecki, Margrethe Kristensen & Thomas Vangkilde-Pedersen

DE NATIONALE GEOLOGISKE UNDERSØGELSER FOR
DANMARK OG GRØNLAND, KLIMA- OG ENERGIMINISTERIET

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2010/31

Stratigrafisk ramme for 3D modellering af den miocæne lagserie i Danmark

Erik S. Rasmussen, Karen Dybkjær, Stefan Piasecki, Margrethe Kristensen & Thomas Vangkilde-Pedersen

DE NATIONALE GEOLOGISKE UNDERSØGELSER FOR
DANMARK OG GRØNLAND, KLIMA- OG ENERGIMINISTERIET

GEUS

Dansk sammendrag

Overordnet er den miocæne lagserie inddelt i to grupper, Ribe og Måde grupperne. Brejning Formationen henregnes til Oligocæn, så den miocæne lagserie starter med Vejle Fjord Formationen. I det centrale og vestlige Jylland er der kortlagt et større delta-kompleks, som er samtidig med og nogle steder lidt yngre end Vejle Fjord Formationen. Dette benævnes Billund Formationen. Vejle og Billund formationerne inkluderer Skansebakke ledet (Vejle Fjord Formationen) samt Hvidbjerg og Addit ledet. Over disse enheder kommer Klintinghoved Formationen, der hovedsageligt består af lerede, marine sedimenter. Klintinghoved Formationen inkluderer Kolding Fjord Ledet. I store områder af midt- og Sønderjylland findes et stort delta-kompleks tidsækvivalent med den øvre del af Klintinghoved Formationen. Dette deltakompleks benævnes Bastrup Formationen og inkluderer Resen Ledet. Herover kommer den lerede, marine Arnum Formation som i den øverste del interfingerer dels med stormsandsaflejringer, der henføres til Stauning Led og dels med de fluviale og kystslette-sedimenter der henføres til Odderup Formation. Over Odderup og Arnum formationerne træffes marine, lerrige sedimenter henført til Hodde-, Ørnhøj og Gram formationerne. Endelig overlejres Gram Formationen af den sandede Marbæk Formation.

I 3-D modelleringen er den miocæne lagserie inddelt efter en systematik, hvor der navngives efter formationer og aflejringsmiljøer. Der er således ikke anvendt led navne. Vejle Fjord Formationen består af 12 enheder benævnt VFL0 til VFL11. Billund Formation er inddelt i 11 delta enheder benævnt BDS0 til BDS10 samt 4 fluviale enheder. Klintinghoved Formationen er inddelt i 4 enheder der høre til den transgressive fase og 6 enheder der høre til den regressive fase. Bastrup Formation er inddelt i 6 delta enheder og 8 fluviale enheder. Arnum Formationen består af 3 enheder benævnt ARL1 til ARL3. Odderup Formation er inddelt i 3 delta enheder samt 4 fluviale enheder. Enhederne under Mådegruppen er samlet til 1 enhed.

Abstract

This paper provides an updated and revised lithostratigraphic scheme for the uppermost Upper Oligocene – Miocene succession in Denmark. The marine Oligocene Brejning Clay Member is upgraded to formation. The shallow marine and deltaic deposits of mainly Early Miocene age are included in the Ribe Group (new group) while the fully marine Middle and Upper Miocene clay-rich deposits are referred to the Måde Group (new group). The Ribe Group is subdivided into 6 formations. The Vejle Fjord Formation is revised and includes the Skansebakke Member. The Billund Formation (new formation) includes the Addit and Hvidbjerg members (new members). The Klintinghoved Formation is defined formally and includes the Koldingfjord Member (new member). The Bastrup Formation (new formation) is defined formally and includes the Resen Member (new member). Vandel Member is a new member in the Arnum Formation (revised). The Odderup Formation is redefined and includes the Stauning Member (new member) and the coal bearing Fasterholt Member. The Måde Group is subdivided into the Hodde, Ørnhøj (new formation), Gram and Marbæk (new formation) Formations.

The subdivision of the Upper Oligocene – Miocene succession into two groups; the Ribe Group and Måde Group is parallel to the North Sea lithostratigraphic framework where it correlates with the upper part of the Hordaland Group and the Nordland Group, respectively.

The new lithostratigraphy creates a genetic and logical system, which removes earlier inconsistencies and brings attention to characteristic units hitherto ignored and stratigraphically out of context. Three major deltaic units (Billund, Bastrup and Odderup Formations) prograded from the north and northeast into the North Sea Basin during the Early – early Middle Miocene. The delta progradation was punctuated by deposition of marine clay and silt associated with minor transgressive events (Vejle Fjord, Klintinghoved and Arnum Formations). During the Middle–Late Miocene, marine depositional conditions dominated (Hodde, Ørnhøj and Gram Formations). A fourth and final progadation (Marbæk Formation) commenced in the latest Late Miocene and the present day Denmark including the North Sea sector became land.

The overall architecture of the Miocene succession is illustrated through 9 log panels which provide a three dimensional framework of the Miocene of Denmark. The study is fundamental for future prospecting for aquifers, the study of interplay between climate and tectonism and the understanding of the Neogene geology of the North Sea Basin.

Introduction

Sediments of Miocene age are outcropping along the east coast of Jylland and in the Limfjorden area. A few inland cliffs in central Jylland also expose Miocene deposits especially in river scars and road cuts. Digging for raw materials for building constructions, i.e. gravel, sand and clay, has resulted in open pits exposing Miocene deposits, mainly in western and central Jylland. During the last decade the increasing need for clean drinking water has initiated intensive drilling programs and acquisition of high-resolution seismic data from the Miocene succession. The renewed interest for the Miocene has gained financial support, so it has been possible to revisit all outcrops and integrate the results with subsurface data as borehole and seismic data. The study has also resulted in the development of a high-resolution biostratigraphy (Dybkjær & Piasecki submitted) that has resulted in a robust stratigraphic framework. Therefore it has been possible to integrate all data from seismic and borehole data with detailled sedimentology of outcrops (Friis et al. 1998; Rasmussen & Dybkjær 2005; Rasmussen et al. 2006) in order to construct a depositional model for the Miocene succession. Associated studies, i.e. of the climatic conditions (Larsson *et al.* 2006; Larsson-Lindgren 2009; Torsten Utescher, personal communication 2009) and provenance studies (Knudsen *et al.* 2005; Olivarius 2009), have further added to the understanding of the depositional system.

The lithostratigraphy of this study includes the upper Upper Oligocene – Miocene succession found onshore Denmark. It is bounded by a major unconformity between Late Eocene – early Late Oligocene clay-rich deposits from more silty and sand-rich deposits of the late Late Oligocene – Miocene time. The top of the successsion is defined by the Quaternary unconformity. During the study of succession it was necessary to establish a number of informal lithostratigraphic units that is now widely used in the mapping for aguifers both in Denmark and Germany (Rasser et al. 2008; Knox et al. in press). In many new publications from the academia the informal names have also found its way. It is therefore time to formally define these units and redefine excisting lithostratigraphic units in order to construct a consisten lithostratigraphic framework, regrading both names and unnecessary locally established units.

The Miocene succession was deposited during a period with world wide tectonism (Potter & Szatmari 2009) and distinct climatic changes (e.g. Zachos *et al.* 2001; Miller *et al.* 2005; Utescher et al. 2009).Two of the most distinct phase in the Alpine orogeny, the Late Oligocene – Early Miocene Savian Phase and the Middle Miocene Betic Phase commenced in the Miocene (Ziegler 1982; Oszczypko 2006; Ribero et al.1990). The opening of the North Atlantic was characterised by the final change in spreading from the Aegir to the Kolbeinsey Ridge and increasing spreading rates in the Early Miocene has been detected (Mosar et al. 2002; Dore *et al.* 2008). In the Middle Miocene a major tectonic reorganisation occurred (Ziegler 1982; Dore *et al.* 2008). The climate was warm temperate in the Early – early Middle Miocene, but changes to a cold temperate climate in the Late Miocene. The Miocene succession studied here was deposited in the eastern part of the North Sea Basin. From north to south it represent an almost complet depositional succession. The Miocene succession thus may act as a natural laboratory for the study of the development of fluvio-deltaic depositional systems, the tectonic impact on basin evolution and the consequences of climatic changes. Therefore it is mandatory to establish a robust lithostratigraphic framework in order to make consistent geological work in the area.

The aim of this paper is to presents an updated and revised lithostratigraphic subdivision of the Miocene succession in Denmark. The systematic subdivision of lithostratigraphic units may be applicable in mapping of aquifers in order to get a consistent mapping procedure by different authorities. The Miocene succession with its variety of different deltaic facies imaged on seismic data, in borehole logs, and in outcrops can add much to the understanding of delta complexes in a ramp setting.

Geological setting

The evolution of the North Sea Basin was strongly controlled by the collision between Africa and Europe, vulcanism in Central Europe and the opening of the North Atlantic (Ziegler 1982; 1991; Ziegler *et al.* 1995; Martinsen *et al.* 1999; Faleide *et al.* 2002; Rasmussen *et al.* 2005; 2008; Rasmussen 2009a; Gabrielsen *et al.* in press). The result of this activity and changing eustatic sea level resulted in a final closure of the southern connection towards the Tethys during Early – Middle Miocene (Harzhauser & Piller 2007) and the only connection to the Atlantic was through a strait between Norway and Shetland (Fig. 1).

The depositional basin of the eastern North Sea area which covered the present-day Denmark, was bounded towards the northeast by the Fennoscandian Shield (Bertelsen 1978; Vejbæk 1997; Fig. 2). The transition to the basin was the southeast – northwest trending Sorgenfrei–Tornquist Zone. The basin was subdivided into two subbasins; the Norwegian-Danish Basin and the North German Basin, with the east-southeast – west-northwest striking Ringkøbing–Fyn High separating the subbasins. The Ringkøbing-Fyn High is further segmented into a number of north–south trending elements e.g. the Rødding Graben and the Brande Trough (Fig. 2). These structural elements were formed during Permian rift tectonics and later reactivated in the Jurassic and during Late Cretaceous and Early Paleocene inversion tectonics (Ziegler 1991; Liboriusen *et al.* 1987; Mogensen & Jensen 1994). Reactivation of some of the older structures occurred in the Oligocene as well as in the Miocene (Rasmussen 2004a; 2009a; Japsen *et al.* 2007). During the Middle Miocene the North Sea Basin experienced increased regional subsidence (Ziegler 1982; 1991; Vejbæk 1992; Koch 1989; Michelsen *et al.* 1998; Clausen *et al.* 1999; Rasmussen 2005). In the late Pliocene – early Pleistocene the North Sea Basin was tilted towards the southwest (Japsen 1993; Japsen *et al.* 2002; Rasmussen *et al.* 2005).

The North Sea Basin was located in the northern westerly wind belt. The climate was warm temperate to tropically in the early part of the Paleogene (Buchardt 1978; Heilmann-Clausen 1995a; Zachos *et al.* 2001). A dramatic change occurred at the Eocene–Oligocene transition where a distinct climatic deterioration took place. The early Oligocene icehouse climate resulted in a marked eustatic sea-level drop mainly due to fixation of water in icecaps primarily at Antartica (Buchardt 1978; Prentice & Matthew 1988; Miller *et al.* 1996; 1998; 2005; Zachos *et al.* 2001). At the end of the Oligocene a subtropical climate prevailed in the North Sea Basin area (Larsson-Lindgren 2009; personal communication Torsten Utescher 2009). At the boundary of the Palaeogene & Neogene a marked, but transient, climatic deteoriation occurred with buildup of widespread icecaps at Antartica. This climatic event resulted in a major, global sea-level fall (Miller *et al.* 1998; Zachos *et al.* 2001. The Early Miocene climate in the North Sea Basin area was characterised by oscillation between cool temperate and warm temperate climates (Mai 1967; Larsson *et al.* 2006). An overall increase in temperature culminated at the Early to Middle Miocene transition, the socalled "Mid-Miocene climatic optimum" (Buchardt 1978; Zachos *et al.* 2001). In the North Sea Basin area warm temperate to subtropical climate prevailed (Mai 1967; Friis 1975; Utescher *et al.* 2000; 2009). At the termination of the Middle Miocene a marked drop in global temperature commenced and during most of the Late Miocene the North Sea Basin area was characterised by a cool temperate climate (Buchardt 1978; Utescher *et al.* 2000; 2009; Zachos *et al.* 2001; Larsson-Lindgren 2009).

Fine-grained sediments of mainly deep marine origin were deposited in the North Sea Basin during the Palaeogene (Heilmann-Clausen *et al.* 1985). A general sea-level lowstand and tectonic re-organisation during the Oligocene resulted in erosion or non-deposition in the area, especially in the central and southern part of the study area. In the northern part of the North Sea Basin prodeltaic, clay-dominated wedges were laid down. In the latest part of the Oligocene resumed transgression resulted in the deposition of glaucony-rich clay. This was followed by deposition of deltaic and coastal-plain sand and clay in the Early Miocene. Three major progradations of the coastal plain occurred during the Early Miocene. The third and final progradation was characterised by extensive coal deposition. Upon the deposition of the dominantly fluvio-deltaic deposits of the Lower to lower Middle Miocene, fully marine, clayey sediments dominated the remaining part of the Middle and Upper Miocene.

Late Pliocene – early Pleistocene tilting of the whole eastern North Sea area (Japsen & Bidstrup 2000), combined with periodical growth of icecaps in the northern hemisphere, resulted in strong erosion of the substratum and therefore Middle and Upper Miocene deposits are missing in the eastern and northern parts of Denmark (Fig. 3).

Previous studies

Forchhammer (1794–1865) wrote the first Danish Geology (Forchhammer, 1835; see also Gabroe, 1961b) and described the Diluvial "Rullestensdannelse" (Boulder Fm.) which he considered very important as it occurred all over Denmark. He included part of it in the Tertiary. The lower part was named the Amber-Browncoal Formation and included fossiliferous strata of "the western system", which was recognised in west and central Jylland as well as further down in Germany and on the island Sylt. This certainly includes the marine Miocene of today. Beyrich (1853) in Berlin studied molluscs collected by Forchammer from the island Sylt and in 1854, he informed Forchhammer that he had identified these as a Miocene fauna (Gabroe, 1961a). Molluscs from southwestern Jylland (e.g. at Esbjerg) and northern Germany (e.g. at Gram) were also identified as Miocene and the results were presented by Mørch at the Scandinavian Research Meeting in Copenhagen in 1873.

It was the palaeontologist Ravn (1866–1951) who established the first Miocene (and Oligocene) stratigraphy in Denmark based on his comprehensive study of the fossil fauna in respectively dark brown and grey, mica-rich clay which occurred widely in Jylland. His work was completed in 1906 when he published the resulting stratigraphic scheme of Lower, Middle and Upper Miocene deposits and listed associated exposures (Ravn, 1906) one year before his monography on the Oligocene and Miocene mollusc fauna (Ravn, 1907). Ravn realised that Lower Miocene marine fauna was missing in his study, and therefore suggested that the widespread deposits with brown coal represented the Lower Miocene. He also included part of the mica-rich clay and sand succession from southeast Jylland, the Lillebælt region, in the Lower Miocene based on mixed Oligocene–Miocene faunas.
The botanist Hartz (1867–1937) studied the succession with brown coal. At his time, relatively few exposures of brown coals were actually available but he concluded that the coals and the associated mica-rich sediments are all freshwater deposits (Hartz, 1909) and he found no contradictions to the Early Miocene age suggested by Ravn (1906).

DGU performed two drilling campaigns in 1917 and 1921 under the leadership of V. Milthers and more brown coals were localised. Later, on the initiative of K. Milthers, DGU drilled almost 9.000 localities during the years from 1941–1949 (Rasmussen, 1988). The last campaign from 1958–1963 drilled more than 2.000 holes i.e. approximately 11.000 holes all together (Rasmussen, 1988).
Some geological results did arise from these extensive programs besides engineer data as volume, numbers and extension of brown coal seams. The succession of the Middle–Upper Miocene strata was not understood prior to the Second World War but the second drilling campaign sorted out the correct stratification and approximately thickness of these strata (Heller, 1960; Milthers, 1949). A lower brown coal formation was claimed (e.i. two major units with coal seams, ?Ribe and Odderup Formations) below approx. 100 meters of marine Middle Miocene (Arnum Formation?).

The previous lithostratigraphy

Vejle Fjord Formation

The mixed Oligocene–Miocene fauna reported by Ravn (1907) in the Lillebælt region impelled Eriksen (1937) to study the same succession in this region for fossils and he found a sparse mollusc fauna in the Brejning exposure at the south coast of Vejle Fjord and in the neighbouring cliffs. The fauna in the lower, glauconitic strata was Oligocene but the poor fauna in the following black, micaceous clay could indicate Lower Miocene. The highest part of the succession with micaceous, grey sand was barren of fossils. Larsen & Dinesen (1959) studied the same strata in two exposures and lithostratigraphically, formalised the Vejle Fjord Formation which comprise the glauconitic "Brejning Ler" and the following, black to grey, micaceous clay and sand respectively of the "Vejle Fjord Ler" and "Vejle Fjord Sand". Analyses of the foraminifer fauna in the "Brejning Ler" clearly show an Upper Oligocene affinity whereas higher, diverging foraminifer fauna in the basal "Vejle Fjord Ler" may indicate Lower Miocene strata. So this supports the results based on the mollusc fauna and indicates that the major part of the formation, i.e. "Vejle Fjord Ler" and "-Sand", is most probably Lower Miocene. The Oligocene–Miocene transition is thus excellently located near the shift from glauconitic "Brejning Ler" to black pyritic clay of the "Vejle Fjord Ler".

The following years, the "Vejle Fjord Ler" and "-Sand" were systematically excluded from most Miocene stratigraphic schemes. It was not until much later that Danish stratigraphers incorporated the Vejle Fjord Formation and the foraminifer stratigraphy in a Miocene stratigraphic scheme but still without actually combining the Vejle Fjord and Klintinghoved Formations in the same figure (see Buchart-Larsen & Heilmann-Clausen in Vinken, 1988).

Much further north in Jylland, Christensen & Ulleberg (1973) defined the Viborg and Sofienlund Formations. The latter was subdivided into four members; the Ulstrup Clay, the Sofienlund Clay, the Sofienlund Silt and the Sofienlund Sand. The foraminifer content of the Sofienlund Formation suggests a Chattian age for the two lower members and a post-Chattian age for the two upper members. The lithology and the biostratigraphy clearly indicate that these sediments should have been referred to the earlier Vejle Fjord Formation which also was stated by Larsen & Kronborg (1994) in the book "Det mellemste Jylland; the lower two members are "Brejning Ler" and the two upper members are "Vejle Fjord Ler" and "-Sand".

Klintinghoved, Ribe and Arnum Formations

The fossil mollusc fauna of the Lower and Middle Miocene exemplified by fauna from the coastal cliff at Klintinghoved and seven deep wells in southern Jylland was studied by Sorgenfrei (1940, 1958). The Klintinghoved Formation was never defined formally, but arose from the work on the outcrop of a glacial, dislocated and folded sedimentary plate of sediments considered of Early Miocene age (Sorgenfrei, 1940).

Two new formations were defined on the basis of the deep wells, the Ribe and Arnum Formations, and the marine clay of the Arnum Formation was considered Middle Miocene on the basis of the fauna (Sorgenfrei, 1958). The barren Ribe Formation of quartsitic sand occurred below the Arnum Formation in one well near the town of Ribe. In the Danish American Prospecting Company (DAPCO) well at Arnum, Sorgenfrei

(1958) characterised quarts gravel and sand below mud and sand of the Arnum Formation as Ribe Formation and underlying clays as Klintinghoved clay? based on the sedimentary succession only (no molluscs).

Arnum, Hodde and Gram Formations

In the comprehensive stratigraphic work by Rasmussen (1966; 1968) he focussed on the upper Arnum Formation, and especially the Hodde- and Gram Formations which he defined already in 1961. He continued and extended Sorgenfrei´s work and he zoned biostratigraphically the uppermost Arnum-, as well as the Hodde and Gram Formations. Rasmussen concludes that the Gram Formation (including the basal strata of the Sæd well) is Upper Miocene and the Hodde Formation is Middle Miocene, which also includes Arnum, Odderup and parts of Ribe Formations. Lower Miocene includes the lower Ribe and Klintinghoved Formations (Fig. 4). Besides minor details, his ages for the Hodde and Gram Formations are precise but the ages of the Arnum Formation and the terrestrial Odderup and Ribe Formations are questionable.
There are two critical points in this great work. Rasmussen (1966) continues to use his stratigraphic scheme from earlier work and he follows earlier traditions of correlating his faunas to the North German, Miocene "stufen" despite that international Miocene chronostratigraphy is available at this time. These German "stufen" are defined by a mixture of sedimentology, depositional facies and faunal assemblages, and are not properly defined as stratigraphic units.

Odderup Formation, terrestrial Miocene

The Odderup Formation is defined with very few words by Rasmussen (1961) as the brown coal and quarts sand between the marine clays of the Arnum Formation and the overlying Hodde Formation. Brown coal or coal fragments and quarts sand below the marine Arnum Formation in certain wells disturb the clear stratigraphic picture for Rasmussen but he insists on two major prograding deltas (Ribe and Odderup Formations) subdividing the marine Miocene into three major units.
The geology of the Søby-Fasterholt area was published by Koch in 1989. Here the Odderup Formation is framed by the overlying, marine succession of Hodde and Gram Formations and the underlying marine strata of the Arnum Formation. The brown coal bearing part of the succession was defined as the Fasterholt Member of the Odderup Formation.

Sequence- and onshore-offshore Neogene stratigraphy

Michelsen (1994) divided the late Palaeogene–Neogene succession of the Danish North Sea into 3 allostratigraphic units; Units 5 to 7. The succession was further subdivided into 11 depositional sequences. The unconformities recognised in the offshore geophysical data, is not directly tracked to the onshore succession. However, the sequences are correlated to the onshore lithostratigraphic units with significant uncertainty because of very limited biostratigraphic support of the onshore deposits. Later, two more sequences (7.5–7.6) were added in the Quaternary succession (Michelsen *et al.* 1998) and the biostratigraphy behind the correlation to the onshore succession was presented. The obvious problems with correlation to onshore Neogene stratigraphy were probably caused by limited understanding of the onshore stratigrahy. However, the Danish offshore stratigraphy was integrated with the UK and Norwegian stratigraphy. The Danish

Cen-4 and -5 units were correlated with the Hordaland Group, (Lark Formation of Schiøler *et al.* 2007) and the Nordland Group.
Sequence stratigraphy was applied to the onshore Miocene succession in southernmost Jylland in 1996 based on analyses of petrophysic logs from 6 wells combined with seismic data (Rasmussen, 1996). The succession was divided into 6 depositional sequences from the latest Oligocene to uppermost Miocene. Precise dating of these sequences was limited due to absence of biostratigraphy, but correlation to the existing lithostratigraphy was performed. Rasmussen (2004b) introduced a new sequence stratigraphic subdivision this time based on 16 new boreholes, outcrops and multichannel seismic data distributed in central and southern Jylland. This resulted in a subdivision of the upper Oligocene–Miocene succession into 6 depositional sequences similarly to the subdivision of Rasmussen (1996). However, the age of the sequences were strongly revised, because of the introduction of dating by using dinoflagellate cysts (dinocysts) (Piasecki 1980; 2006; Dybkjær & Rasmussen 2000; 2007; Dybkjær 2004a,b; Dybkjær & Piasecki submitted).

Data and methodology

25 outcrops, one cored borehole at Sdr. Vium (DGU no. 102.948) and c. 50 boreholes, drilled using the airlift drilling technique, has been available for the study (Fig. 5). Most of the boreholes were drilled in order to solve stratigraphic problems others were drilled in order to test seismic facies interpretations. All boreholes are identified by their DGU borehole numbers, whereas outcrops are named by nearest locality name.

All 25 outcrops and the cored borehole were measured sedimentologically and samples were taken for biostratigraphy. The airlift borehole samples representing one meter were described for grain size and mineralogy and c. 50 samples were taken for biostratigraphic (dinocyst) analysis. The description and the sedimentary logs from the Fasterholt Member are based on Koch (1989).

In boreholes drilled using the airlift drilling technique there are some problems in getting fine-grained sand to the surface and thus the recovery is very low or even zero in fine-grained sand intervals. In all 50 boreholes a gamma-ray log was standard. The gamma-ray log is normally good at distinguishing sand and clay. There is, however, some noise from heavy minerals and from intervals with high mica content. In the correlation panels presented in this study the lithology in all boreholes are described by the main author, except from: Fjand (DGU no. 76.635), Fjelstervang (DGU no. 84.2649), Lindved (DGU no. 116.1569), Løgumkloster (DGU no. 159.739), Ribe (DGU no. 140.42), Rømø (DGU no. 148.52), Tinglev (DGU no. 168.1378), Uldum (DGU no. 1444), Ulfborg (DGU no. 73.971),Vester Sottrup (DGU no. 169.799) and Vollerup (DGU no. 160.799). Lithological descriptions of the latter boreholes are from the "Jupiter database" at GEUS. All sample depths from boreholes are adjusted by the gamma-ray log in order to get true depths of the samples. Thus there may be a discrepancy between depths indicated in the Jupiter database (measured depth; md) and the depths assigned to the lithostratigraphic units in this study. The measured depth (md) of a cuttings sample is, however, indicated in the text.

Approximately 1000 km 2D high-resolution seismic data have been used to correlate between boreholes and to indicate the overall architecture of the Miocene succession. The correlations are further based on dinocyst studies of most of the boreholes included here. These studies have resulted in a detailed dinocyst zonation (Dybkjær & Piasecki 2008; submitted). The geological age of each lithostratigraphic unit is based on the dinocyst stratigraphy combined with Sr-datings on mollusc shells (Dybkjær & Piasecki submitted, Tor Eidvin personal communication 2009).

Revised lithostratigraphy

In this study the Oligocene Brejning Clay Member of the Vejle Fjord Formation is upgraded to Formation: the Brejning Formation and includes the Øksenrade Member. The Miocene succession is subdivided into two groups: The Ribe Group and the Måde Group. The Ribe Group consists of the Vejle Fjord, Billund, Klintinghoved, Bastrup, Arnum, and Odderup Formations. The Vejle Fjord Formation includes the Skansebakke Member, the Billund Formation includes the Hvidbjerg and Addit Members, the Klintinghoved Formation includes the Kolding Fjord Member, the Bastrup Formation includes the Resen Member, the Arnum Formation includes the Vandel Member and the Odderup Formation includes the Stauning and Fasterholt Members. The Måde Group comprises the Hodde, Ørnhøj, Gram, and Marbæk Formations (Fig. 6).

Brejning Formation

New formation

History. The Brejning Formation corresponds to the Brejning Clay Member of the Vejle Fjord Formation of Larsen & Dinesen (1959).

Name. The Brejning Formation is named after the town Brejning at Vejle Fjord.

Type and reference section. The exposure at Dykær forms the type section for the Brejning Formation (Fig. 7). The Brejning Formation is at low sea-level exposed in the basal, eastern part of the Skansebakke profile at Brejning. The succession penetrated by a boring at Brejning was described by Larsen & Dinesen (1959). The borehole encountered a c. 4 m thick (-0,4–-4,65 m) succession of Brejning Formation. Other exposures of the formation are found at Sanatoriet, Fakkegrav and Juelsminde in the Vejle Fjord area, and at Jensgård at the mouth of Horsens Fjord. In central Jylland the formation is outcropping at Sofienlund clay pit and in the Limfjorden area the formation is exposed at Lyby and Mogenstrup. Periodically the formation crops out at Søvind, Sønder Vissing, and in the Ølst clay pit. The reference section is the interval from 96,50–100,90 m (measured depth (md.) 97–101 m) in the Andkær borehole (DGU no. 125.2017) (Fig. 7).

Thickness. The Brejning Formation is normally 2–4 m thick, but a 50 m thick succession of Brejning Formation has been encountered in the Borg-1 borehole (DGU no. 158.760).

Lithology. The Brejning Formation consists of greenish to brown, glaucony-rich clay with scattered pebbles (Fig. 8). In the upper part there is an increased content of organic matter, silt and sand. Siderite concretions are common in the upper part of the formation.The clay mineralogy is dominated by illite, but smectite, kaolinite and gibbsite are also present (Rasmussen 1995). Mica is common in the upper part of the formation.

Log characteristics. High gamma-ray readings characterises the Brejning Formation (Fig. 7), especially the lower part may show extremely high gamma-ray response due to the high content of glaucony.

Fossils. The marine clay of the Brejning Formation contains a rich mollusc fauna (Ravn 1907; Eriksen 1937; Schnetler & Beyer 1987, 1990). Also marine microfossils such as foraminifers (Larsen & Dinesen 1959; Laursen & Christoffersen 1999) and dinocysts (Dybkjær 2004a,b; Rasmussen & Dybkjær 2005) are abundant and diverse. In the upper part of the formation a gradual change/detoriation in the mollusc fauna was interpreted as reflecting a shallowing upward trend. Similary, the abundance and diversity of foraminifer (Larsen & Dinesen 1959) and dinocysts (Dybkjær 2004a,b; Rasmussen & Dybkjær 2005, in the Dykær and Jensgårde exposures) decreases in the upper part of the formation. Echinoids, crinoids, asteroids, anthozoans, otoliths, shark teeth, brachiopods, crustacean and bryzoans have also been found.

Depositional environment. The Brejning Formation was deposited in a fully marine, sediment starved environment (Larsen & Dinesen 1959; Rasmussen 1995; Rasmussen & Dybkjær 2005; Schnetler & Beyer 2008). The water depth was in the order of 200 m in the Norwegian–Danish Basin (Schnetler & Beyer 1990; Caterina Morigi, personal communication 2009). On the Ringkøbing–Fyn High substantially shallower water predominated. The upward increase of silt and sand indicates progradation of the shoreline in the latest Oligocene associated with a sea level fall (Rasmussen & Dybkjær 2005).

Boundaries. In southern and western Jylland the Brejning Formation rests with a sharp and erosional boundary on the Eocene Søvind Marl Formation (Heilman-Clausen et al. 1985)(Fig. 8). The boundary may, however, locally be intensively bioturbated. In central and northern Jylland the boundary is seen as a transition from darkbrown clay of the Branden Formation to greenish glaucony-rich clay of the Brejning Formation. Upper boundary; see definition of the Vejle Fjord Formation, below.

Distribution. The Brejning Formation is present in most parts of Jylland but is absent on most of the Ringkøbing–Fyn High (Fig. 9A). The youngest part of the Brejning Formation is only present in southern and western Jylland. The northern and eastern extent of distribution follows closely that of the Miocene deposits (Fig. 3).

Biostratigraphy. The *Deflandrea phosphoritica* Dinocyst Zone of Dybkjær & Piasecki (submitted) is recorded in the Brejning Formation. In addition the *Chiropteridium galea* Zone is recorded in the upper part of the formation in the southern parts of Jylland.

Geological age. The age of the Brejning Formation is late Chattian to early Aquitanian, latest Late Oligocene to earliest Early Miocene. The absolute age of the oldest known part of the Brejning Formation (in the Harre-1 borehole, at 67.5 m; Friis 1994) is approximately 24.4 My**.** The dinocyst stratigraphy indicates that the upper boundary of the Brejning Formation is diachroneous. In the northern and central parts of Jylland the boundary possibly correlates with the Oligocene–Miocene boundary (Rasmussen 2004b; Rasmussen & Dybkjær 2005; Dybkjær & Rasmussen 2007), the age of which is 23.03 My according to Gradstein *et al*. (2004). In the southern part of Jylland the deposition of glaucony rich clay apparently continued into the early Aquitanian, earliest Early Miocene. The duration of the deposition is then between 1.4 and 2.0 My.

Subdivision. The Brejning Formation includes the new Øksenrade Member.

Øksenrade Member

New member

History. The Øksenrade Member is mentioned by Rasmussen (1975) as the "Middelfart malm".

Name. The member is named after a coastal cliff on the southern side of the Øksenrade Skov south of Middelfart.

Type and reference section. The type section is the coastal cliff facing the Fænø Sund at the coast south of Øksenrade Skov, at Middelfart (Fig. 10). The reference section is the interval from 210–212 m (md. 212–214 m) in the borehole at Gadbjerg (DGU no. 115.1474) (Fig. 10).

Thickness. The member is up to 2 m thick.

Lithology. The Øksenrade Member is composed of reddish ooids and gray, fine-grained quartz sand (Figs 11,12). At Jensgård some subtle cross-bedding can be seen. The ooids is build up of concentric layers of goethite with a core of shells or quartz grains. The cement consists of siderite and some calcite. The iron content is up to 30 % (Rasmussen 1987). Impressions of shells occur commonly.

Log characteristics. Generally low gamma-ray readings characterise the Øksenrade Member (Fig. 10) but distinct spikes may occur due to horizons with glaucony.

Fossils. The Øksenrade Member is characterised by dense impressions of mollusc shells (Rasmussen 1975).

Depositional environment. The Øksenrade Member was deposited above storm wave base as indicated by cross-bedding (Rasmussen & Dybkjær 2005). Impression of shells (Rasmussen 1975) also indicates a shallow water depositional environment. The transgressive lag that is locally found on the Ringkøbing–Fyn High indicates fluvial sedimentation in the final phase of deposition (Rasmussen & Dybkjær 2005). A subaerial depositional environment at the transition from the Oligocene to the Miocene is also evident in the presence of fresh water algae in the upper part of the Brejning Formation (Rasmussen & Dybkjær 2005).

Boundaries. The Øksenrade Member rests with a sharp and often erosional boundary on the underlying part of the Brejning Formation (Fig. 12). The lower boundary is also marked by a change from darkbrown, clayey silt, with scattered sand lenses to fine-grained, reddish sand.

Distribution. The Øksenrade Member is present in east Jylland and the extreme western part of Fyn from Horsens in the north to Middelfart in the south (Fig. 9). The western most distribution has been found at Gadbjerg near Give where it is located on a footwall crest at the boundary fault of the Brande Trough.

Biostratigraphy. No samples from this member has been analysed for palynology.

Geological age. The deposition of the Øksenrade Member took place between 24.4 Ma and 23.03 Ma, but the duration of the deposition is probably much shorter.

Ribe Group

New group

History. Non-fossiliferous sand and gravel below 125.6 m in a borehole at Ribe (DGU no. 140.42) were defined as the Ribe Formation by Sorgenfrei (1958). The borehole terminated at a depth of 127 m and thus the base of the formation was never defined. Rasmussen (1961) suggested that the succession consisting of quartz gravel and sand with some lignite penetrated at 144.5 to 255.7 m in Arnum-1 borehole should be correlated with the Ribe Formation. He further indicated that the fluvio-deltaic and brown coal bearing succession around Silkeborg and Skanderborg may be correlative with the Ribe Formation. This study, however, shows that the fluvio-deltaic deposits at Silkeborg correlate with the Vejle Fjord and Billund Formations.
The Ribe Formation was included in the stratigraphic chart of Rasmussen (1961) and here suggested to represent the fluvio-deltaic deposits below the Odderup Formation. The age of the formation was indicated as Early to early Middle Miocene (Fig. 4). During the last decade detailed biostratigraphic and sequence stratigraphic studies of the Lower Miocene succession have been carried out (Rasmussen 2004; Dybkjær 2004; Rasmussen & Dybkjær 2005; Rasmussen et al. 2006; Dybkjær & Piasecki submitted). These studies have revealed that the stratigraphy of the Lower Miocene deposits is more complicated than formerly believed. Therefore, as the definition by Sorgenfrei (1958) does not follow the international formally definition sensu Salvador (1994) with a clear description of both the upper and lower boundaries, and as the lower part of the Odderup Formation actually is interpreted also to be of Early Miocene in age, the fluvio-deltaic sediments that are so characteristic for the Lower Miocene – lower Middle Miocene succession are here defined as the Ribe Group. The introduction of the Bastrup Formation, which replaces the Ribe Formation in southern Jylland, is also consistent

with the new lithostratigrafi of northern Germany, Schleiswig-Holstein (Rasser et al. 2008; Knox et al. in press). Here the Bastrup Formation was adopted to represent Lower Miocene fluvio-deltaic sands of Burdigalian age, based on a study of the Kasseburg cored borehole near Hamburg (Karl Gurs personal communication 2006; Rasser et al. 2008; Knox et al. in press).
In the North Sea lithostratigraphy it correlates with the upper part of the Hordaland Group (Deegan & Scull 1977; Hardt et al. 1989).

Name. After the town Ribe.

Type and reference section. The type section for the Ribe Group is in the gravel pit at Voervadsbro, where both marine sand and fluvial sand and gravel are exposed (Fig. 13). The group is outcropping at Klintinghoved in southern Jylland, at Rønshoved, Hagenør, Børup, Hindsgavl, Galsklint, Hvidbjerg, Brejning, Sanatoriet, Fakkegrav, Dykær and Jensgård in eastern Jylland, at Addit, Salten, Isenvad, ?Tandskov and Abildå in central Jylland and at Gyldendal, Søndbjerg, Lyby, Skyum Bjerge, Skanderup and Lodbjerg in the Limfjorden area. The reference section is the interval from 3–219 m (md. 3–220 m) in the borehole at Store Vorslunde (DGU no. 104.2325) (Fig. 13).

Thickness. The thickness is 217 m in the reference borehole. A thickness of c. 200 m is common in the Norwegian–Danish Basin and in most places on the Ringkøbing–Fyn High. In the Tinglev borehole (DGU no. 168.1378) located in the Tønder Graben more than 200 m has been penetrated without reaching the lower boundary of the group. Reduced thicknesses are seen in the eastern part of Jylland, which is partly due to erosion during the Pleistocene.

Lithology. The group consists of three cycles of alternating mud and sand rich units with some intercalation of coal beds, especially in the upper cycle (Odderup Formation). Each unit, 50 to 100 m thick, represents coarsening upwards cycles.

The sands are typically medium- to coarse-grained, quartz-rich sand with various amount of mica. Various types of cross-bedding including tabular, trough, hummocky and swaley cross-stratified sands characterise the sand-rich units. The sand grains are normally sub- to well- rounded. Well-rounded clasts of quartz, quartzite and chert up to 4 cm in size commonly occur in the upper part of the units and are sometimes associated with thick clinoformal packages. Fossils occur sporadically, especially, in the lower part of the sand-rich units.

The micaceous mud-rich part is homogeneous with some intercalation of laminated mud intervals as well as some incursion of discrete sand layers. These sand layers are commonly hummocky cross-stratified or characterised by tidal rhythmits. The clay mineral association is dominated by illite and kaolinite (Rasmussen 2005). Pyrite is a very common authigenic mineral.

The coal beds are found both associated with cross-stratified fluvial sands and mud and on top of shoreface/beach sand and lagoonal mud. The coal beds are limited to the Norwegian–Danish Basin where the beds typically reach thicknesses of 2 to 3 m. The thickest succession has been recorded in the Fasterholt area, where a cumulative thickness of c. 9 m of coal has been found.

Log characteristics. The typical gamma-ray pattern is characterised by three cycles of decreasing gamma-ray response upwards (Fig. 13). The gamma-ray is generally characterised by a serrated pattern, but distinct gamma-ray spikes are common in the lower part of each cycle and for the upper cycle (the Arnum and Odderup Formations) high gamma-ray spikes occur throughout the succession. In the northern part and also locally in the southern part a decreasing gamma-ray response commonly occur in the upper part of each cycle. For more detailed descriptions see descriptions below for each formation and member.

Fossils. Molluscs occur abundantly in the marine and nearshore deposits and plant fossils are locally abundant in the terrestrial deposits. See more detailed descriptions below in the definition of formations and members.

Depositional environment. The Ribe Group has been deposited by delta systems prograding from the N and NE towards the S and SW. The deposition of the first cycle (Billund Formation) was strongly controlled by the topography formed during the Early Miocene inversion tectonism (Rasmussen & Dybkjær 2005; Hansen & Rasmussen 2008; Rasmussen 2009a). During the deposition of this cycle, the so-called Ringkøbing and Brande lobes were concentrated to structural lows, the Brande Trough and the Rødding Graben (Hansen & Rasmussen 2008). East of the main delta lobes, spit and barrier-complexes developed due to along-shore transport of sand that was delivered from the river months of the delta systems (Rasmussen & Dybkjær 2005; Hansen & Rasmusen 2008). Fluvial sand interpreted as fluvial braided system deposits (Hansen 1985; Jesse 1995; Rasmussen et al. 2006) dominates in the northern part.

The second cycle (Bastrup Formation) shows a more evenly distributed progradational pattern across Jylland. Due to lack of outcrops of this part of the Miocene succession any detailed sedimentology has not been carried out, but from borehole data there are no indication of widespread spit and barrier complexes. Similarly, as for the first cycle, fluvial systems dominates the upper part of the succession. Log data and seismic data (Rasmussen et al. 2007; Rasmussen 2009b) indicate that a meandering fluvial system was widespread although local or periodical development of braided fluvial systems may have taken place.

The third and final cycle (the Odderup Formation) was deposited in a prograding coastal plain with widespread coal formation within the Norwegian–Danish Basin, whereas clean fluvial sand dominates the Ringkøbing–Fyn High area.

Boundaries. The lower boundary is often sharp separating greenish to brownish, glaucony-rich clay and mud from darkbrown, organich-rich mud. The boundary may be marked by a gravel lag or sand bed. Due to heavy bioturbation the boundary may be locally blurred. In central east Jylland the boundary is commonly characterised by a marked change from the sand deposits of the Øksenrade Member to darkborwn clayey silt of the Vejle Fjord Formation of the Ribe Group. The upper boundary; see the definition of the Måde Group.

Distribution. The Ribe Group is present in most parts of Jylland. The northern and eastern boundary follow closely the lower boundary of the Miocene deposits (Fig. 3)

Geological age. Aquitanian–early Langhian, Early Miocene – earliest Middle Miocene from 23.3 Ma – approximately 15 Ma.

Subdivision. The Ribe Group is divided into six formations: The Aquitanian Vejle Fjord Formation and Billund Formation, the uppermost Aquitanian – lower Burdigalian Klintinghoved Formation and Bastrup Formation and the upper Burdigalian – lower Langhian Arnum Formation and Odderup Formation (Fig. 6).

Vejle Fjord Formation

Redefined

History. The Vejle Fjord Formation was defined by Larsen & Dinesen (1959). The formation was originally defined from the base of the Brejning Clay Member to the top of the Vejle Fjord Sand Member. For stratigraphical and practical reasons the Brejning Clay Member is excluded from the Vejle Fjord Formation (see discussion of the Brejning Formation above). A redefinition of the Vejle Fjord Formation has been undertaken on the basis of the huge amount of data aquired during the last decade, which has shed new light on the depositional system (Dybkjær & Rasmussen 2000; Rasmussen & Dybkjær 2005).

Name. The formation is named after the Vejle Fjord in East Jylland.

Type and reference section. The type section is found at Dykær near Juelsminde (Fig 14). Other exposures in the Vejle Fjord area are the Brejning Hoved, Sanatoriet, Fakkegrav and Jensgård. It is further exposed at Hindsgavl near Middelfart, and is outcropping at Skyum Bjerge, Lyby, Mogenstrup, and Skanderup (Mors) in the Limfjord area. The reference section is the interval from 166–219 m (md. 167–220 m) in the borehole Store Vorslunde (DGU no. 104.2325) (Fig. 14).

Thickness. The formation is c. 6 m thick at the type locality (Fig. 14). In the western part of Jylland it may reach a thickness of up to c. 100 m, e.g. in the Holstebro borehole (DGU no. 64.613).

Lithology. The Vejle Fjord Formation consists of darkbrown clayey silt (Fig. 15). In some areas it is dominated by laminated, greenish-grey sand and dark-brown clayey silt. Sand stringers up to a few centimetres may occur. Locally, the formation is composed of wave-influenced heterolithic mud and sand with hummocky cross-stratification (Figs. 16, 17).

Log characteristics. The formation is characterised by medium gamma-ray readings (Fig. 14). The log pattern is highly serrated and show both decreasing and increasing upwards trends throughout the succession.

Fossils. The Vejle Fjord Formation contains an impoverished mollusc fauna (Ravn 1907; Eriksen 1937; Schnetler & Beyer 1987, 1990). Also the foraminifer fauna (Larsen & Dinesen 1959; Laursen & Kristoffersen 1999) and the dinocyst flora (Dybkjær 2004 a,b; Rasmussen & Dybkjær 2005) are impoverished within this formation. However, the abundance of dinocysts are locally very high based on few species.

Depositional environment. The Vejle Fjord Formation was deposited in a brackish to fully marine depositional environment. The brackish water conditions predominate within the Norwegian–Danish Basin in the early phase of deposition as a consequence of the elevated Ringkøbing–Fyn High (Rasmussen & Dybkjær 2005; Rasmussen 2009). As the sea level rose during the Early Miocene fully marine conditions prevailed and the depositional depth was c. 100 m in the Norwegian–Danish Basin and probably less than 30 m on the Ringkøbing–Fyn High. Most of the Vejle Fjord Formation was deposited in a prodelta environment. The thickest part of the formation is associated with an inter-lobe depositional environment.

Boundaries. The lower boundary is most commonly sharp characterised by a change from greenish darkbrown, glaucony-rich clayey silt to drakbrown clayey silt. A gravel layer is commonly found at the lower boundary. At the type locality, the lower boundary is recognised by a distinct decrease in the content of glaucony (Larsen & Dinesen 1959). The scattered glaucony grains found in the Vejle Fjord Formation are reworked (Rasmussen 1987). In central east Jylland the boundary is commonly characterised by a marked change from the sand deposits of the Øksenrade Member to darkborwn clayey silt of the Vejle Fjord Formation.

Distribution. The formation is present in most parts of Jylland except from the southern and western most part (Fig. 9B). The northern and eastern extent of distribution follows closely the general outline of the Miocene deposits (Fig. 3)

Biostratigraphy. The *Chiropteridium galea* and the *Homotryblium* spp. Dinocyst Zones of Dybkjær & Piasecki (submitted) are recorded in the Vejle Fjord Formation.

Geological age. The age of the Vejle Fjord Formation is early Aquitanian, earliest Early Miocene.
The absolute age of the formation is from 23.03 Ma to approximately 21.6 Ma. The duration of the deposition is then approximately 1.4 My.

Subdivision. The Vejle Fjord Formation includes the Skansebakke Member.

Skansebakke Member

New member

History. The Skansebakke Member was formerly defined as the Vejle Fjord Sand Member by Larsen & Dinesen (1959).

Name. The name is after the outcrop of the type section at Skansebakke, Brejning, at the south coast of Vejle Fjord.

Type and reference section. The type section is the outcrop at Skansebakke. It is further exposed at Brejning Hoved, Sanatoriet, Fakkegrav and Dykær. The reference section is the interval from 79–91.10 m (md. 79–92 m) in the Andkær borehole (DGU no. 125.2017) (Fig. 18).

Thickness. The thickness at Skansebakke is c. 7 m, at Brejning Hoved c. 12 m and at Sanatoriet 7 m.

Lithology. The Skansebakke Member consists of alternating layers of fine-grained, wellsorted, yellowish sand and brownish clay (Fig. 19). The sand beds are sharp based and homogenous to evenly laminated. The sand beds are commonly capped by wave- and current-ripples.

Log characteristics. The member is characterised by low gamma-ray readings with a serrated pattern (Fig. 18).

Fossils. The Skansebakke Member contains an impoverished mollusc fauna (Ravn 1907; Eriksen 1937). Also the foraminifer fauna (Larsen & Dinesen 1959) and the dinocyst flora (Dybkjær 2004 a,b; Rasmussen & Dybkjær 2005) are impoverished within this member.

Depositional environment. The Skansebakke Member is interpreted as having been deposited in a lagoonal depositional environment (Larsen & Dinesen 1959; Friis et al 1998; Rasmussen & Dybkjær 2005). The sand beds were deposited as washover fans on a backbarrier flat during the main degradation of minor spit and barrier systems formed along elevated parts of the Ringkøbing–Fyn High.

Boundaries. The lower boundary is placed where the first occurrence of an extensive sand layer occurs.

Distribution. The Skansebakke Member is restricted to central east Jylland and is especially exposed along the coast of Vejle Fjord (Fig. 9B).

Biostratigraphy. The *Chiropteridium galea* and the *Homotryblium* spp. Dinocyst Zones of Dybkjær & Piasecki (submitted) are recorded in the Skansebakke Member.

Geological age. The age of the Skansebakke Member is early Aquitanian, earliest Early Miocene.
The absolute age of the formation is between 23.03 Ma and 21.6 Ma, but the duration of the deposition is possibly much shorter.

Billund Formation

New formation

Name. The Billund Formation is named after the town Billund.

Type and reference section. The type section of the Billund Formation is the interval from 184 m to 235 m (md. 185–235 m) in the Billund borehole (DGU no. 114.1857). The reference section is the interval from 126–166 m (md. 128–167 m) in the Store Vorslunde borehole (DGU no. 104.2325) (Fig. 20).

Thickness. In the Billund borehole (DGU no.114.1857), the thickness is 51 m and the maximum thickness of 70 m has been found in the Isenvad borehole (DGU no. 86.2056). The thickness of the Billund Formation is 28 m in the Vandel Mark borehole (DGU no. 115.1371).

Lithology The Billund Formation is composed of fine- to coarse-grained sand (Fig. 21). Pebbly horisons are common in the upper part and at the base of fluvial channels. Clasts of up to 4 cm occur associated with erosional scours or down dip of steep clinoforms. The fine-grained sand which is commonly hummocky cross-stratified, occurs in the lower part of the formation or in distal lobes. In the northern area the formation is dominantly composed of cross-bedded sand with various size of cross bedding. Soft sediment deformation structures are commonly seen. Fine-grained wave-rippled sand, mud and coal are sandwiched between two sand bodies with an overall sheet geometry. Root horizons and tree stumps are locally present (Weibel 1996; Rasmussen *et al.* 2007). In the eastern area where the formation is outcropping, the sands are characterised by hummocky and swaley cross-stratification and homogeneous to laminated sand beds commonly capped by wave ripples. Tidal bundles are also present here (Fig. 22). The interbedded muds and heteroliths are darkbrown in the northern part due to a high content of organic matter. In the southern area the mud is light brown and distinctly thinner.

Log characteristics. The formation is characterised by low gamma-ray readings. In some boreholes the lower part is characterised by a serrated lower part with generally higher gamma-ray responses. At the type borehole the Billund Formation shows constantly low gamma-ray readings (Fig. 20).

Fossils. The Billund Formation contains fossil wood (Weibel 1996), leaves and seeds (Ravn 1907) but also marine molluscs (e.g. in the "Brøndum Blokke"). Foraminifers and dinocysts can be found locally (Laursen & Kristoffersen 1999; Rasmussen *et al.* 2006).

Depositional environment. The Billund Formation was deposited as a delta system prograding from the N and NE towards the S and SE. The progradation took place in association with an Early Miocene inversion phase (Rasmussen 2009a). The distribution of the delta lobes were consequently strongly controlled by the antecedent topography. Two overall lobes; the Ringkøbing and Brande lobes have been mapped by Hansen & Rasmussen (2008). The Billund delta complex was deposited as wave-dominated deltas (Rasmussen & Dybkjær 2005; Hansen & Rasmussen 2008; Rasmussen 2009b). The SE-ward along shore currents that prevailed during the Early Miocene resulted in deposition of spit- and barrier complexes SE of the main delta lobes. The most coarse-grained part was deposited in steeply dipping clinoformal packages deposited during falling sea-level (Hansen & Rasmussen 2008; Rasmussen 2009b).

Boundaries. The lower boundary is defined where a change from clayey, organic-rich silty sediments of the Vejle Fjord Formation is superimposed by sand. Locally, e.g. at Billund, the sand is overlying Eocene Søvind Marl.

Distribution. The Billund Formation is distributed in central Jylland (Fig. 9C). A depositional lobe of the formation is present in the North Sea (Hansen & Rasmussen 2008).

Biostratigraphy. The *Chiropteridium galea* and the *Homotryblium* spp. Dinocyst Zones of Dybkjær & Piasecki (submitted) are recorded in the Billund Formation.

Geological age. The age of the Billund Formation is early Aquitanian, earliest Early Miocene.
The absolute age of the formation is from 23.03 Ma to approximately 21.6 Ma. The duration of the deposition is then approximately 1.4 My.

Subdivision. The Billund Formation is divided into two members: the Hvidbjerg Member and the Addit Member.

Hvidbjerg Member

New member

History. The white sand at Hvidbjerg was studied by Larsen & Dinesen (1959). The Hvidbjerg Sand was not included in the Vejle Fjord Formation due to a different heavy mineral association.

Name. The Hvidbjerg Member is named after the outcrop at Hvidbjerg Strand on the south coast of Vejle Fjord.

Type and reference section. The type section of Hvidbjerg Member is the exposure at Hvidbjerg Strand on the south coast of Vejle Fjord (Figs. 23,24). Other exposures are at Sanatoriet, Fakkegrav and Dykær in the Vejle Fjord area, at Pjedsted west of Fredericia and at Hindsgavl, Børup and Rønshoved in the Lillebælt area. The sand crops out at two localities in the Limfjord area, at Søndbjerg and Lyby. The reference section is the interval from 58–79 m (md. 58–79 m) in the Andkær borehole (DGU no. 125.2017) (Fig. 23).

Thickness. The thickness is 24 m at Hvidbjerg (Fig. 23). In the Lillebælt area it reaches 13 m, but at most outcrops it is rarely thicker than 6 m.

Lithology. The Hvidbjerg Member consists of white, fine- to medium-grained sand with a few pebble layers (Fig. 24). The sand beds are dominated by sharp based, homogenous to evenly laminated sand capped by wave ripples. Hummocky and swaley cross-stratification are common in the southern part (Fig. 25). Trough and tabular cross-stratified sand beds occur locally as well as tidal bundles. The cross-bedding indicates bi-polar current directions towards the NE and SW. Thin, light brown clay layers dominate in the southern part. North of Hvidbjerg a dark-brown, mud dominated unit up to 3 m thick is common. This mud is locally capped by wood debris.

Log characteristics. The formation is characterised by low gamma-ray readings (Fig. 23). High gamma-ray response occurs where clay-rich, lagoonal deposits occur.

Fossils. A relatively rich dinocyst assemblage occurs in the Hvidbjerg Member (Dybkjær 2004; Rasmussen & Dybkjær 2005). Trace fossils of *Ophiomopha* and *Scolihtos* occur locally.

Depositional environment. Deposition took place in a storm dominated shoreface environment associated with spit development SE of main Billund delta lobes. The core of a spit system is outcropping at Hvidbjerg. North of Hvidbjerg, shoreface sands are alternating with mud-rich lagoonal deposits. Tidal inlets deposits are found at Dykær and Pjedsted where a flood and ebb dominated system is found respectively (Fig. 22).

Boundaries. The formation overlies the Vejle Fjord Formation and the lower boundary is marked by a change from black, organic-rich clayey silt to white sand. At Hvidbjerg the lower boundary is erosive.

Distribution. The Hvidbjerg Member is present in east Jylland and has also been found at Søndbjerg in north-west Jylland (Fig. 9C).

Biostratigraphy. The *Chiropteridium galea* and the *Homotryblium* spp. Dinocyst Zones of Dybkjær & Piasecki (submitted) are recorded in the Hvidbjerg Member.

Geological age. The age of the Hvidbjerg Member is early Aquitanian, earliest Early Miocene.
The absolute age of the formation is from 23.03 Ma to approximately 21.6 Ma. However, the duration of the deposition is probably much less than the full duration of this time interval.

Addit Member

New member

History. Sand-rich fluvial and coal bearing deposits in the Silkeborg area were first studied by Hartz in 1898 (Hartz 1909). He correlated the succession with Lower Miocene coal bearing deposits in Schleswig-Holstein. Rasmussen (1961) indicated that the fluvio-deltaic sediments in the Silkeborg – Skanderborg area could be of similar age as the Ribe Formation penetrated in the Arnum-1 well in southern Jylland. Studies of the succession in gravel pits south of Silkeborg were carried out during the 1970th and -80th focusing on the depositional environment and diagenesis (Friis 1976, 1995; Hansen 1985; Hansen 1995; Jesse 1995). These studies referred the deposits to the Middle Miocene Odderup Formation. However, Friis (1995) was aware of the problematic correlation with the Odderup Formation (see discussion at the end of the paper). The Salten inland cliff and the gravel pits at Addit and Voervadsbro were visited in 2004 and re-studied (Rasmussen et al. 2006). New biostratigraphic datings based on dinocysts revealed that the succession is Early Miocene in age and should be correlated with the Vejle Fjord Formation/Billund Formation.

Name. The member is named after the village Addit

Type and reference section. The type section for the Addit Member is the Dansand gravel pit at Addit (Fig. 26). The member is further exposed in the gravel pit of Voervadsbro and at Salten inland cliff. The reference section is the interval from 51–117 m (md. 51–118 m) in the Addit Mark borehole (DGU no. 97.928) (Fig. 26).

Thickness. The member is 50 m thick at Addit and up to 70 m thick in the borehole at Addit Mark (DGU no. 97.928; Fig. 26).

Lithology. The succession is composed of two sand- and gravel rich units separated by fine-grained sandy and clayey sediments with varying intercalation of coal layers (Fig. 27). The two sand-rich units are characterised by fining upward successions with sheet geometry. The lower part of each unit consists of trough cross-stratified coarse-grained sand and gravel alternating with large scale cross-stratified sand (Fig. 28). Upwards the unit is progressively dominated by tabular, co-sets of cross-stratified sand. The sand-rich succession may be capped by fine-grained cross-bedded sand showing lateral accretion. The coal bearing fine-grained sand and clay layer is dominated by cross-bedded sand and alternating thin rippled, fine-grained sand and clay layers. Wood fragments totally dominate certain horizons and petrified wood are common at Voervadsbro (Weibel 1996).

Log characteristics. The formation is characterised by low gamma-ray readings, especially in the lower part (Fig. 26). The sand-rich part is often characterised by a slightly upward increase in gamma-ray readings. High gamma-ray response often characterise the middle part of the member where it is associated with clay-rich and coal bearing deposits.

Fossils. The Addit Member contains fossil wood (Weibel 1996), leaves and seeds (Ravn 1907).
Dinocysts occur very sporadic in the Addit Member (Dybkjær 2004a,b; Rasmussen et al. 2006).

Depositional environment. The deposition occurred as migrating 3-D dunes (main channel) and migrating unit and compound bars in a braided fluvial system (Hansen 1985; Hansen 1995; Rasmussen 2006). The upper part of the member was deposited as migrating 2-D dunes. Several sedimentary structures as cross-bedded sand beds with bottom sets and normal graded foresets indicate a tidal influence (Pontén & Plink-Björklund 2007). The upper part of the sand succession showing lateral accretion was laid down in a point bar of a meandering fluvial system. The fine-grained part of the member was deposited in a flood plain and lake environment that was occasionally flooded by the sea as indicated by the presence of dinocysts.

Boundaries. In most places the lower boundary is marked by a sharp change from dark-brown, silty clay or clayey silt to grey coarse-grained sand and gravel. In places where the Addit Member is overlying the Hvidbjerg Member the boundary is marked by an erosional boundary where white, fine to medium sand is overlain by gravel (Fig. 21).

Distribution. The Addit Member is found in the central and northern parts of Jylland. It is especially well developed in the area south of Silkeborg, in an elongated lobe striking from Resen (southwest of Viborg) to the area between Herning and Ikast (Fig. 5, 9C).

Biostratigraphy. The *Homotryblium* spp. Dinocyst Zone of Dybkjær & Piasecki (submitted) is recorded in the Addit Member.

Geological age. The age of the Addit Member is early Aquitanian, earliest Early Miocene.
The absolute age of the formation is from 22.36 Ma to approximately 21.6 Ma. The duration of the deposition is then approximately 0.8 My.

Klintinghoved Formation

Redefined

History. The Klintinghoved Formation was included in the stratigraphy of Rasmussen (1961), however, the formation was never defined formally. Sorgenfrei (1940) described the mollusc fauna of the Klintinghoved Clay and briefly mentioned Klintinghoved Formation in a later publication (Sorgenfrei 1958).

Name. The formation is named after Klintinghoved cliff at Flensborg Fjord.

Type and reference section. The type section is the outcrop at Klintinghoved cliff (Fig. 29, 30). The reference section is designated in the cored borehole at Sdr. Vium (DGU no. 102.948) from 288–194 m (Fig. 29).

Thickness. At Klintinghoved the section is 3.5 m thick. In the nearby borehole at Høruphav (DGU no.170.50d) the thickness is 3.5 m. In the borehole at Sdr. Vium (DGU no. 102.948) the thickness is 94 m.

Lithology. The formation consists of darkbrown, silty clay with some intercalation of sand (Fig. 31, 32). The sand beds are sharp based and homogenous to finely laminated. There is some indication of double clay layers. In the cored borehole at Sdr. Vium (DGU no. 102.948) the formation is dominated by darkbrown mud with some intercalation of sand beds (Fig. 33). The sand beds are characterised by a sharp lower boundary. The sand beds are commonly homogeneous in the lower part passing upward into laminated sand.

Log characteristics. The formation is characterised by medium to high gamma-ray readings (Fig. 29). The log pattern is highly serrated and shows a general decrease in gamma-ray response upwards.

Fossils. The Klintinghoved Formation contains a rich mollusc fauna (Sorgenfrei 1958). Shark teeths also occur and marine microfossils such as foraminifers (Laursen & Christoffersen 1999) and dinocysts (Dybkjær & Rasmussen 2000; Dybkjær 2004; Rasmussen & Dybkjær 2007) are abundant and diverse.

Depositional environment. The Klintinghoved Formation was deposited in a shelf, delta slope to lower shoreface environment. Water depths were in the order of 15 to 60 m, but locally up to 100 m based on the height of clinoforms seen on seismic data. The depositional environment was under strong influence of storms and tidal processes.

Boundaries. The lower boundary is placed at the change from sand-rich deposits of the Billund Formation to the predominantly darkbrown, silty clay of the Klintinghoved Formation. The boundary is often erosive and overlain by a gravel lag or sand layer showing a fining upward trend.

Distribution. The Klintinghoved Formation is distributed in the northern part of central Jylland and in western and southern Jylland (Fig. 9D).

Biostratigraphy. The *Thalassiphora pelagica* and *Sumatradinium hamulatum* Dinocyst Zones of Dybkjær & Piasecki (submitted) occur in the Klintinghoved Formation.

Geological age. The age of the Klintinghoved Formation is late Aquitanian to early Burdigalian, Early Miocene. The absolute age of the formation is from 21.1 Ma to 19.0 Ma. The duration of the deposition is then approximately 2.1 My.

Subdivision. The Klintinghoved Formation includes the new Kolding Fjord Member and the new Resen Member.

Kolding Fjord Member

New member

History. Sand and organic-rich clayey sediments exposed at Lillebælt were studied by Radwanski et al. (1975), Rasmussen (1995) and Friis et al. (1998). These studies inferred that the sediments were a part of the Vejle Fjord Formation. However, a biostratigraphic study by Dybkjær & Rasmussen (2000) revealed that the sediments were significantly younger than the Vejle Fjord Formation and of the same age as the Klintinghoved Formation (Rasmussen 1961).

Name. The Kolding Fjord Member is outcropping at a number of localities along Lillebælt and Kolding Fjord. It is named after Kolding Fjord at which the type locality Rønshoved is exposed.

Type and reference section. The type section is the exposure at Rønshoved on the southern side of Kolding Fjord (Fig. 34). Other localities where the member is exposed are: Hagenør, Børup, Galsklint and Fænø in the Lillebælt and Kolding Fjord area. A minor outcrop is also found at Gyldendal, Limfjorden. The reference section is the outcrop at Hagenør (Fig. 34).

Thickness. The Kolding Fjord Member is 12 m thick at Rønshoved and 8 m at Hagenør. The member rarely exceeds 10 m (Fig. 34).

Lithology. The member is composed of white to yellow, fine- to medium-grained sand with a few thin, brown clay layers. The basal part of the member consists of a gravel layer up to 1 m thick. The sandy part of the member is dominated by hummocky and swaley cross-stratified silt and fine-grained sand (Fig. 35). The more clayey part is dominated by heterolithic mud which shows hummocky cross-stratification and clear rhythmicity i.e. double clay layers and alternating sand- and mud-rich units. Layers of up to 2 m of darkbrown, organic-rich, clayey silt may be intercalated in the sand (Fig. 36, 37). Homogeneous capped by wave-ripples are also common (Fig. 38).

Log characteristics. The member is characterised by low to medium gamma-ray readings. The log pattern is serrated and shows high gamma-ray readings where lagoonal, clay-rich deposits dominate.

Fossils. The Kolding Fjord Member contains a dinocyst assemblage of variegating richness (Dybkjær & Rasmussen 2000, 2005).

Depositional environment. Deposition took place at a storm dominated coast in a lower and upper shoreface environment (Friis et al. 1998; Rasmussen & Dybkjær 2005). The fine-grained part was deposited in a lagoonal environment with some tidal influence. The upper part of the member was deposited as washover fans on the backbarrier flat during the final degradation of the barrier complex.

Boundaries. The lower boundary is erosive and characterised by a distinct change from the sandy deposits of the Billund Formation to gravel dominated layers of the basal part of the Kolding Fjord Member.

Distribution. The formation is found in east Jylland and southwest of Holstebro in west Jylland (Fig. 9D).

Biostratigraphy. The *Thalassiphora pelagica* and *Sumatradinium hamulatum* Dinocyst Zones of Dybkjær & Piasecki (submitted) occur in the Kolding Fjord Member.

Geological age. The age of the Kolding Fjord Member is late Aquitanian to early Burdigalian, Early Miocene. The absolute age of the formation is from 21.1 Ma to 20.0 Ma. The duration of the deposition is then approximately 1.1 My.

Bastrup Formation

New formation

Name. The formation is named after the village Bastrup southwest of Kolding.

Type and reference section. The type section is the interval from 80–107 m (md. 80–110 m) in the Bastrup borehole (DGU no. 133.1298) (Fig. 39). The reference section is the interval from 111–164 m (md. 111–164) in the borehole at Almstok (DGU no. 114.1858) (Fig. 39).

Thickness. The thickness of the Bastrup Formation is 26 m in the Bastrup borehole, but the formation is commonly 50 meter thick. A maximum thickness of 80 m has been penetrated in the borehole at Stakroge (DGU no. 103.1654).

Lithology. The Bastrup Formation consists predominantly of grey, medium- to coarse-grained sand with intercalated gravel layers. Locally dark brown, organic-rich silty clay is present. The upper part is commonly characterised by a 30 to 15 m fining upward succession consisting of coarse-grained to fine-grained sand.

Log characteristics. The formation is characterised by low gamma-ray readings (Fig. 39). The log pattern is serrated and show both decreasing and increasing upwards trends through the succession. The upwards decreasing trend of gamma-ray readings is associated with delta progradation and the upwards increasing trend of gamma-ray response is associated with channel fill deposits, e.g. point bars which are commonly found in the upper part.

Fossils. A sparse foraminifer assemblage occurs in the distal part of the Bastrup Formation (Laursen & Kristoffersen 1999). The dinocyst flora is rich in some levels and very sparse/impoverished in other levels (Dybkjær 2004a; Dybkjær & Piasecki submitted).

Depositional environment. Deposition took place in deltaic and fluvial environments. Well developed point bars and fluvial channels are common in the upper part (Rasmussen et al. 2007; Rasmussen 2009). The intercalated mud represents flood-plain deposition.

Boundaries. The lower boundary is either sharp, e.g. in the Bastrup borehole (DGU no. 133.1298) or gradational as in the Almstok borehole (DGU no. 114.1858)(Fig. 39). In the Bastrup borehole, the lower boundary is placed where grey mud is sharply overlain by grey medium-grained sand. In boreholes where a more gradational development occurs, the boundary is marked by the change from alternating bed of sand and mud to clean sand. A gravel layer is also common at the base of the Bastrup Formation. In the Bastrup borehole the lower boundary is characterised by a distinct decrease in gamma-ray response. In other boreholes the lower boundary may be represented by a minor decrease in gamma-ray response followed by a consistent decrease in gamma-ray response upwards e.g. in the Almstok borehole (DGU no. 114.1858).

Distribution. The formation is present in southern and central Jylland. Towards the north-east the formation is truncated and it pinches out towards the south-west (Fig. 9E).

Biostratigraphy. The *Sumatradinium hamulatum* and *Cordosphaeridium cantharellus* Dinocyst Zones of Dybkjær & Piasecki (submitted) occur in the Bastrup Formation.

Geological age. The age of the Bastrup Formation is early Burdigalian, Early Miocene. The absolute age of the formation is from 20.0 Ma to 18.4 Ma. The duration of the deposition is then approximately 1.6 My.

Subdivision. The Bastrup Formation includes the new Resen Member.

Resen Member

New Member

Name. The Resen Member is named after the village Resen south of Skive where a brown coal pit was excavated.

Type and reference section. The type section is the interval from 70–121 m (md. 71 – 125 m) in the borehole at Hammerum (DGU no. 85. 2429) (Fig. 40). The reference section is the interval from 67–103 m (md. 67–105 m) in the Egtved Borehole (DGU no. 124.1159) (Fig. 40).

Thickness. The thickness of the member is 26 m in the Bastrup borehole (DGU no. 133.1298) but the member is commonly 50 meter thick. A maximum thickness of 80 m has been penetrated in the Stakroge borehole (DGU no.103.1654).

Lithology. The member consists of grey, medium- to coarse-grained sand with intercalated gravel layers. Dark brown, organic-rich silty clay with some coal is present locally. The member is typically characterised by a 30 to 15 m fining upward succession.

Log characteristics. The member is characterised by low gamma-ray readings. The log pattern is serrated and shows an increasing trend upwards. The increasing gamma-ray response upward is associated with channel fill deposits.

Fossils. The dinocyst flora is rich in some levels and very sparse/impoverished in other levels (Dybkjær 2004a; Dybkjær & Piasecki submitted).

Depositional environment. Deposition took place in fluvial environments and well-developed point bars and fluvial channels are common (Rasmussen *et al.* 2007; Rasmussen 2009). The intercalated mud represents flood-plain deposition and some marine influence has also been recognised, especially in the southern part. The most extensive coal formation was within freshwater lakes developed around salt diapir rims, e.g. the Sevel and Mønsted salt structures south of Skive (Japsen & Langtofte 1991).

Boundaries. The lower boundary is sharp and placed where darkbrown clayey silt of the Klintinghoved Formation is sharply overlain by grey, medium- to coarse-grained sand. A basal gravel layer is common within erosional lows.

Distribution. The member is present in southern and central Jylland (Fig. 9E). Towards the north-east the member is truncated and it pinches out towards the south-west.

Biostratigraphy. The *Sumatradinium hamulatum* and *Cordosphaeridium cantharellus* Dinocyst Zones of Dybkjær & Piasecki (submitted) occur in the Resen Member.

Geological age. The age of the Resen Member is early Burdigalian, Early Miocene. The absolute age of the formation is from 20.0 Ma to 18.4 Ma. The duration of the deposition is then approximately 1.6 My.

Arnum Formation

Revised.

History. The Arnum Formation is defined by Sorgenfrei (1958) to comprise the dark micaceous marine clay above the "Ribe Formation".

Name. The Arnum Formation is named after the village Arnum in southern Jylland.

Type and reference section. The Arnum Formation was penetrated in two boreholes at Arnum (DGU no.150.13) and (DGU no.150.25b) from 40–107 m and 40–107.5 m respectively (Sorgenfrei 1958). The interval from 60.90–153.75 m in the cored borehole, Sdr. Vium (DGU no. 102.948) is designated as the type section (Fig. 41). The reference section is the interval from 37–56 m (md. 39–56 m) in the Store Vorslunde borehole (DGU no. 104.2325) (Fig. 41).

Thickness. The thickness is c. 93,0 m in the type borehole, but 150 m Arnum Formation has been penetrated in the Borg-1 borehole (DGU no. 158.760). Generally the thickest succession is found in southwest Jylland.

Lithology. The Arnum Formation consists of dark brown, silty clay with occasional shell beds. Thin laminated fine-grained sand beds are common. The sand beds are often characterised by having a sharp lower boundary succeeded by laminated and low angle cross bedded sand capped by wave laminated sand. Micro hummocky cross-stratification is common. Some of the wave rippled sand beds have a sharp erosive upper boundary which is overlain by mud (Fig. 42). Thin sand beds and silt layers may have a high content of heavy minerals. A thin layer of glaucony, c. 1 mm thick, has been found in the Sdr. Vium borehole (DGU no. 102.948; Fig. 42).

Log characteristics. The formation is characterised by high gamma-ray readings (Fig. 41). The log pattern is serrated and shows a decreasing trend upwards. Distinct gamma-ray peaks are related to silt and sand beds rich in heavy minerals.

Fossils. The Arnum Formation contains a rich assemblage of molluscs (Sorgenfrei 1958; Rasmussen 1961). Also rich foraminifer and dinocyst assemblages occur in this formation (Laursen & Kristoffersen 1999; Dybkjær & Piasecki submitted).

Depositional environment. The Arnum Formation was deposited in a fully marine shelf environment. The water depth is unknown, but the concentration of heavy minerals and scour of wave rippled sand may indicate rather shallow water with frequently reworking and sorting of sediments.

Boundaries. The lower boundary is defined by a sharp transition from grey and white sand of the Billund Formation to dark brown silty clay of the Arnum Formation.

Distribution. The formation is distributed in Jylland southwest of a line from Struer to Horsens (Fig. 9F).

Biostratigraphy. The *Cordosphaeridium cantharellus*, *Exochosphaeridium insigne*, *Cousteaudinium aubryae* and *Labyrinthodinium truncatum* Dinocyst Zones of Dybkjær & Piasecki (submitted) occur in the Arnum Formation.

Geological age. The age of the Arnum Formation is Burdigalian to early Langhian, Early to Middle Miocene. The absolute age of the formation is from 18.4 Ma to 14.8 Ma. The duration of the deposition is then approximately 3.6 My.

Subdivision. The Arnum Formation includes the new Vandel Member.

Vandel Member

New member

Name. The Vandel Member is named after the village Vandel, east of Billund.

Type and reference section. The type section is the interval from 102–114 m (md. 102–112 m) in the Vandel Mark borehole (DGU no.115.1371). The reference section is the interval from 97–100 m (md. 97–100 m) in the Grindsted borehole (DGU no. 114.2038) (Fig. 43).

Thickness. The thickness rarely exceeds the 15 m recorded in the borehole at Vandel Mark (DGU no. 115.1371).

Lithology. The Vandel Member is composed of grey to white silt with a high content of heavy minerals. It may contain clasts of reworked reddish Eocene clay.

Log characteristics. The formation is characterised by high gamma-ray readings.

Fossils. No fossils have been recorded.

Depositional environment. The depositional setting is unclear but the member is capping fluvio-deltaic deposits of the Bastrup Formation. The absence of fossils could point towards a flood plain depositional environment.

Boundaries. The lower boundary is defined by a sharp transition from grey sand to grey and white silt.

Distribution. The member is distributed in central Jylland with maximum thicknesses in the area around Herning – Ikast, south of Silkeborg and north of Billund (Fig. 9F).

Biostratigraphy. The Vandel Member is barren of dinocysts, but the *Cordosphaeridium cantharellus* Dinocyst Zone (Dybkjær & Piasecki submitted) occurs in the lithostratigraphic units below and above.

Geological age. The age of the Vandel Member is early Burdigalian (late Early Miocene). The absolute age is between 19.0 Ma and 18.4 Ma, but the duration of the deposition is possibly much shorter.

Odderup Formation

Redefined

History. The Odderup Formation was defined by Rasmussen (1961). The borehole at Odderup Brickwork (DGU no.103.150) was designated as the type section where the browncoal and quartz sand from 28.2–40.3 m was defined as the type section (Rasmussen 1961). A redefinition is proposed here, including the sand, often rich in heavy minerals, that was deposited at the lower shoreface and offshore transition zone of the prograding shoreline.

Name. The Odderup Formation is named after the village Odderup on the basis of a boring (DGU no. 103.150) at the Odderup Brickwork.

Type and reference section. The formation is exposed at Abild Browncoal Museum near Ørnhøj but only the browncoal bearing Fasterholt Member is present here. The type section is the interval from 3–37 m (md. 3–39 m) in the borehole at Store Vorslunde (DGU no. 104.2325). The reference section is the intervals from 41–90 m (md.

42–90 m) and 110–118 m (md. 111–118 m) in the Rødding borehole (DGU no. 141.1141) (Fig. 44).

Thickness. The formation is 34 m thick at the type section but in central Jylland it commonly exceeds 40 m.

Lithology. The formation consists of fine- to coarse-grained sand with some intercalation of clay beds and browncoal. The sand is characterised by low angle cross-bedding, dipping towards the southwest and is enriched in heavy minerals (Fig. 45). The fine-grained part of the formation is dominated by hummocky cross-stratified sand. Some sand layers show rhythmic bedding with synsedimentary faults.

Log characteristics. The formation is characterised by a low to medium gamma-ray response (Fig. 44). However, an overall upwards decreasing gamma-ray trend is typical.

Fossils. Marine molluscs as well as dinocysts occur in the most distal parts of the Odderup Formation (Stauning Member). Foraminifers reported in more proximal settings may be referred to caving from higher strata. Fossil seeds, leaves and wood occur abundantly in the terrestrial deposits in coal beds and lacustrian deposits (Fasterholt Member).

Depositional environment. The Odderup Formation was deposited in the lower to upper shoreface and swash zone of a prograding coastal plain. The coal is interpreted as deposited in freshwater lakes and lagoonal swamps (Koch 1989).

Boundaries. The lower boundary is defined at the boundary between the succession of fossiliferous, alternating darkbrown silty clay and fine-grained sand layers and the first significant occurrence of grey fine-grained sand commonly with a high content of heavy minerals.

Distribution. The Odderup Formation is distributed in west, central and southern Jylland (Fig. 9G).

Biostratigraphy. The *Cordosphaeridium cantharellus*, *Exochosphaeridium insigne*, *Cousteaudinium aubryae* and *Labyrithodinium truncatum* Dinocyst Zones of Dybkjær & Piasecki (submitted) occur in the marine settings of the Odderup Formation.

Geological age. The age of the Odderup Formation is Burdigalien to earliest Langhian, Early Miocene to earliest Middle Miocene. The absolute age is from approximately 18.4 Ma to 16 Ma, i.e. a duration of deposition of approximately 3 My.

Subdivision. The Odderup Formation includes the new Stauning Member and the Fasterholt Member (Koch 1989).

Stauning Member

New member

History. The Stauning Member was recognised as fine-grained sand layers with a high content of heavy minerals interbedded in the Arnum Formation in a number of boreholes in south and central Jylland (Knudsen et al. 2005). On gamma-ray logs, the sand beds are characterised by extreme high gamma-ray readings. Exploitation for these sands with heavy minerals was intensive during the last part of the decade of 1990 in the Stauning area.

Name. The Stauning Member is named after the village Stauning where the member is subcropping Quaternary deposits at relatively shallow depths.

Type and reference section. The type section of the Stauning Member is found in the intervals from 62–72 m and 78–97 m (md. 64–72 m and 77–97 m) respectively in the Vandel Mark borehole (DGU no. 115.1371), where a complete succession of the member is penetrated (Fig. 46). The reference section is the intervals from 66–90 m (md. 67–90 m) and 110–118 m (md. 111–118 m) respectively in the Rødding borehole (DGU no. 141.1141) (Fig. 46).

Thickness. The thickness is commonly below 10 m but up to 100 m has been found in the extreme southern part, e.g. Tinglev borehole (DGU no. 168.1378).

Lithology. The member is composed of grey to white fine-grained sand, with a high content of heavy minerals (Fig. 47). The sand beds are intercalated in dark brown clayey silt. Sedimentary structures are dominantly hummocky cross-stratified, fine-grained sand.

Log characteristics. The formation is characterised by highly serrated gamma-ray readings. Extreme high gamma-ray readings are found in association with concentrations of heavy minerals.

Fossils. Marine molluscs occur in the Stauning Member (Knudsen 1998) as well as foraminifers and dinocysts (Laursen & Kristoffersen 1999; Dybkjær & Piasecki submitted).

Depositional environment. The Stauning Member was deposited as storm sand layers on the inner shelf.

Boundaries. The lower boundary is defined at the base of the first significant fine sand layer with a high content of heavy minerals.

Distribution. The Stauning Member is found in southern, central and western Jylland (Fig. 9G).

Biostratigraphy. The *Cordosphaeridium cantharellus*, *Exochosphaeridium insigne*, *Cousteaudinium aubryae* and *Labyrithodinium truncatum* Dinocyst Zones of Dybkjær & Piasecki (submitted) occur in the Stauning Member.

Geological age. The age is Burdigalien to earliest Langhian, Early Miocene to earliest Middle Miocene. The absolute age is from approximately 19 Ma to 16 Ma, i.e. a duration of deposition of approximately 3 My.

Fasterholt Member

History. The Fasterholt Member was defined by Koch (1989). Brown coal bearing layers was mentioned in Forchhammer's "Geology of Denmark" (Forchhammer 1835) and brown coal beds outcropping in banks of the Skjern Å (river) was reported by Dalgas (1868) and Hartz (1909). Extensive mining of brown coal occurred during the two world wars and large prospecting programs were carried out in connection with the demands for local energy resources (Milthers 1939; Milthers 1949).

Name. The Fasterholt Member is named after the village Fasterholt.

Type and reference section. The formation was exposed in several brown coal pits in central and western Jylland and the Fasterholt brown coal pit is the type locality (Fig. 48). The only place where it is exposed today is in a small pit at Abildå near Ørnhøj. The reference section is defined in the Store Vorslunde borehole from 13–15 m (md. 13–15 m; Fig. 48).

Thickness. The member is 10 m thick in central Jylland but wedges out towards the southwest.

Lithology. The Fasterholt Member consists of sand, clay and browncoal. It commonly consists of 3 sedimentary units showing a fining upward trend from a basal sandy lower part passing upward into silty clay and capped by a browncoal layer (Fig. 48).

Fossils. Marine fossils are absent but spores and pollen, fossil seeds, leaves and wood occur abundantly in the terrestrial deposits in lacustrian sediments and coal beds (Christensen 1975, 1976; Friis 1975, 1979; Koch 1977, 1989; Koch & Friedrich 1960; Koch *et al.* 1973; Wagner & Koch 1974).

Depositional environment. The member is interpreted to be deposited in a lacustrine depositional environment (Koch 1989). The concentration of browncoal in the Norwegian–Danish Basin and especially around old faults indicates a structural control on the deposition.

Boundaries. The lower boundary is characterised by a dense root horizon with tree stumps.

Distribution. The distribution of the Fasterholt Member is restricted to central Jylland (Fig. 9G).

Biostratigraphy. The Fasterholt Member cannot be dated on the basis of marine fossils, as they are absent, but the unit is stratigraphically enclosed by the *C. aubryae* and *L. truncatum* Dinocyst Zones of Dybkjær & Piasecki (submitted).

Geological age. Due to the absence of marine fossils, the Fasterholt Member is dated indirectly by the dinocyst stratigraphy of the under- and overlying marine strata. The age of the Fasterholt Member is Burdigalian to earliest Langhian, Early Miocene to earliest Middle Miocene. The absolute age is in between 17.8 Ma and 14.8 Ma, but the duration of deposition was probably much shorter.

Måde Group

History. The Måde Group was first mentioned by Rasmussen (1961) as the "Måde serien". The terminology is used for the marine, clay-dominated younger Miocene deposits. The succession is characterised by a basal gravel layer which is overlain by black, mica-rich mud followed by a thin greenish, glaucony-rich clay, grey clay and finally by fine- to medium-grained sand. In the North Sea lithostratigraphy, the Måde Group correlates with the Nordland Group (Deegan & Scull 1977; Hardt et al. 1989).

Name. The name is after a local area west of Esbjerg renown for its brickworks based on Upper Miocene clay. The last brick factories were closed in the 1970th.

Type and reference section. The Måde Group is exposed at Gram Claypit where both the Gram and Marbæk Formations can be seen. At Ørnhøj, Lille Spåbæk, the Hodde and Ørnhøj Formations are exposed and the Marbæk Formation is outcropping at the coastal cliffs at Sjelborg and Marbæk, northwest of Esbjerg. The interval from 24–52 m in the cored borehole Sdr. Vium (DGU no. 102.948) is designated as the type section (Fig. 49). The reference section is found in the Tinglev borehole (DGU no. 168.1378) from 49–197 m (md. 49–197 m; Fig. 49).

Thickness. The thickness is commonly 25 m in the western part of Jylland, but in the extreme southern Jylland, e.g. in the Tinglev borehole (DGU no.168.1378) 147 m has been penetrated.

Lithology. The Måde Group is dominated by darkbrown, organic-rich mud (Fig. 50). The lower part is composed of alternating fine-grained sand and silty clay with a basal gravel layer. Upwards the succession is getting more fine-grained with scattered incursions of glaucony. This is succeeded by greenishbrown glaucony-rich clay, typically 3 m thick. In the upper part of the glaucony-rich section goethification of glaucony grains is common (Dinesen 1976). This is overlain by brown clay rich in pyrite. Upwards this part is getting more silty, and thin c. 5 cm thick, fine-grained storm sand beds occur in the upper part. The uppermost Måde Group is fine- to medium-grained sand.

Log characteristics. The formation is characterised by medium to high gamma-ray readings (Fig. 49). In the lower part extreme high gamma-ray readings are common, the upper part show a gradual decrease in gamme-ray readings.

Fossils. The Måde Group contains rich and diverse mollusc faunas, crustaceans and vertebrates. Shark teeth are common. Foraminifers and dinocysts are abundant (see details in the desciption of the specific units)

Depositional environment. The Måde Group was deposited on the shelf. When the maximum flooding of land occurred during the deposition of the glaucony-rich Ørnhøj Formation and the lower part of the Gram Formation the water depth was over 100 m (Laursen & Kristoffersen 1999). The upper part of the group was deposited in front of a prograding coastline in an offshore to shoreface setting.

Boundaries. The lower boundary is sharp, marked by a thin gravel layer separating the white, fine-grained sand of the Ribe Group from the darkbrown mud of the Måde Group. The upper boundary is a sharp erosional boundary separating mud and fine-grained sand of the Måde Group from Quaternary deposits often characterised by a distinct change in lithology and colour of the deposits.

Distribution. The Måde Group is restricted to the western and southern part of Jylland (Fig. 9H). Locally it is found around Herning and in the Brande–Give area.

Geological age. The age of the Måde Group is early Langhian to latest Tortonian, early Middle Miocene to Late Miocene.

Subdivision. The Måde Group is divided into four formations: the Hodde, Ørnhøj, Gram and Marbæk Formations.

Hodde Formation

History. The Hodde Formation was defined by Rasmussen (1961).

Name. The formation is named after the village Hodde where the formation was shortly exposed in connection with the construction of Karlsgårde Channel.

Type and reference section. The formation is exposed at Lille Spåbæk near Ørnhøj, south of Holstebro. The type section is the interval from 44.80–52 m in the cored borehole at Sdr. Vium (DGU no. 102.948). The reference section is found in the Føvling borehole (DGU no. 132.1835) from 39–50 m (Fig. 51).

Thickness. The formation is 9.6 m thick (13.8 – 23.4 m) in the Hodde-1 borehole (DGU no.113.33), but more than 40 m has been penetrated in the Tinglev borehole (DGU no. 168.1378).

Lithology. The Hodde Formation consists of darkbrown, organic-rich, silty clay with thin sand lenses (Figs. 52–53). The pyrite content is high. The basal part of the formation is composed of a thin gravel layer. In the upper part of the formation laminated, silty clay are common and glaucony may occur.

Log characteristics. The formation is characterised by medium to high gamma-ray readings (Fig, 51). The log pattern is characterised by a gradual upward increase in gamma-ray response. Locally, the upper part shows low gamma-ray readings, e.g. the Føvling borehole (DGU no. 132.1835).

Fossils. The typical Hodde Formation contains a limited fauna of marine molluscs (Rasmussen, 1966) but a richer fauna occurs locally in shell-beds associated with the basal gravel bed. Trace-fossils are described from the basal bed into the underlying strata (Asgaard & Bromley 1974). Marine microscopic fossils as foraminifers and dinocysts occur abundantly (Laursen & Kristoffersen 1999; Piasecki 1980, 2005).

Depositional environment. The depositional environment is interpreted as fully marine (Rasmussen 1961). The Hodde Formation represents the most widespread transgression during the Miocene (Rasmussen 2004b; Knox *et al.* in press). The basal transgressive lag indicates deposition on a marine shoreface during the initial transgressive phase. The increase in glaucony in the upper part indicates an almost secession of sediment influx to this part of the North Sea in the Serravallian.

Boundaries. There is a marked change in lithology from the white, fine to medium-grained sand of the Odderup Formation to the darkbrown, clayey silt of the Hodde Formation. The lower boundary is sharp and is characterised by a gravel layer, the base of which forms the boundary.

Distribution. The Hodde Formation is distributed in southern and western Jylland (Fig. 9H). The Formation is locally distributed as far east as Bording and Give in central Jylland in depressions associated with salt structures.

Biostratigraphy. The upper *Labyrinthodinium truncatum* and the *Unipontidinium aquaeductum* Dinocyst Zones of Dybkjær & Piasecki (submitted) are recorded in the Hodde Formation.

Geological age. The age of the Hodde Formation is early Langhian to mid-Serravallian, Middle Miocene. The absolute age is from approximately 15 Ma to 13.2 Ma, and the duration of the deposition is approximately 1.8 My.

Ørnhøj Formation

New formation

History. Formerly referred to the "glauconitic clay", which constituted the lower part of the Gram Formation (Rasmussen 1956; 1961).

Name. Named after the village Ørnhøj where the formation still is exposed in some of the old browncoal pits in the neighborhood.

Type and reference section. The formation is partly exposed at Lille Spåbæk west of Ørnhøj. The type section is the interval from 41–44.80 m in the cored borehole at Sdr. Vium (DGU no. 102.948). The reference section is the interval from 34–40 m (md. 36–42 m) in the Føvling borehole (DGU no. 132.1835; Fig. 54).

Thickness. The thickness is ca. 4 m in the type borehole, but it rarely exceeds more than 2 m in thickness.

Lithology. The Ørnhøj Formation is composed of green and brown clay (Fig. 55). High concentrations of green pellets in the size of fine-grained sand occur commonly. In the upper part goethification of glaucony is common.

Log characteristics. The formation is characterised by high gamma-ray readings.

Fossils. The Ørnhøj Formation is barren of macro- and microscopic, calcareous fossils but a diverse assemblage of dinocysts is present (Piasecki 1980, 2005).

Depositional environment. The Ørnhøj Member was deposited in a fully marine, sediment starved depositional setting, which favoured the formation of glaucony. The goethification of glaucony in the upper part is interpreted as a result of a sea-level fall (Dinesen 1986; Eder *et al*. 2007) and probably a result of wave action at the sea floor. Concentration of glaucony in depositional bars at Ørnhøj (Jens Frederiksen personal communication 2009) supports the interpretation of wave action at the sea floor.

Boundaries. The lower boundary is often marked by a sharp change from darkbrown clayey silt of the Hodde Formation to greenish brown clay of the Ørnhøj Formation (Fig. 55).

Distribution. The Ørnhøj Formation is distributed in southern and western Jylland. The Formation is locally distributed as far east as Bording and Give in central Jylland in depressions associated with salt structures (Fig. 9H).

Biostratigraphy. The *Achomosphaera andalousiense* and *Gramocysta verricula* Dinocyst Zones of Dybkjær & Piasecki (submitted) are recorded in the Ørnhøj Formation.

Geological age. The age of the Ørnhøj Formation is late Serravallian, Middle Miocene. The absolute age is from 13.2 Ma to 11.4 Ma, and the duration of the deposition is approximately 1.8 My. This is supported by strontium isotope datings of molluscs from the overlying Gram Formation at Gram clay pit (Tor Eidvin personal communication 2009).

Gram Formation

Redefined

History. The Gram Formation was defined by Rasmussen (1956). In the original definition of the Gram Formation, the formation includes three members: The Glauconite Clay, the Gram Clay and the Gram Sand.

Name. The Gram Formation is named after the town Gram.

Type and reference section. The type section is at the old pit of Gram brickwork, currently the Midtsønderjyllands Museum of Gram, where a 13.1 m thick section of Gram Formation is exposed (Fig. 56). The reference section is the interval from 24–41 m in the cored borehole Sdr. Vium (DGU no. 102.948) (Fig. 56).

Thickness. The thickness is c. 25 m but in the borehole of Tinglev (DGU no.168.1378) 119 m was penetrated.

Lithology. The Gram Formation consists of darkbrown clay, which is getting more silty upwards. In the upper part a few fine-grained sand layers, c. 5 cm thick, are intercalated in the formation (Fig. 57). Siderite concretions are common in the lower part of the formation. Pyrite is common both as pyritified pellets and in trace fossils.

Log characteristics. The formation is characterised by medium gamma-ray readings (Fig. 56). The log pattern is highly serrated and shows a general decreasing upwards trends in gamma-ray response through the succession.

Fossils. Abundant and diverse mollusc faunas characterise the Gram Formation in association with marine vertebrates (whales, sharks and dolphins) and crustaceans (crabs) in concretionary nodules (e.g. Bendix-Almgreen 1983; Hoch 2008; Schnetler 2005; Steeman, 2009**).** Foraminifers and dinocysts are abundant (Laursen & Kristoffersen 1999; Piasecki 1980, 2005).

Depositional environment. The Gram Formation was laid down in a fully marine depositional environment with water depths of c. 100 m (Laursen & Kristoffersen 1999). The incursion of storm beds in the upper part is interpreted as having formed during progradation of the shoreline (Rasmussen & Larsen 1989).

Boundaries. The lower boundary is defined by the change from greenishbrown and brown, glaucony-rich clay to darkbrown clay. At the boundary there is an abrupt change from glauconified pellets and shells to pyritified pellets.

Distribution. The Gram Formation is distributed in southern and western Jylland (Fig. 9H). The Formation is locally distributed as far east as Bording and Give in central Jylland in depressions associated with salt structures.

Biostratigraphy. The *Amiculasphaera umbracula* and *Hystrichosphaeropsis obscura* Dinocyst Zones of Dybkjær & Piasecki (submitted) are recorded in the Gram Formation.

Geological age. The age of the Gram Formation is Tortonian, Late Miocene. The absolute age is from 11.4 Ma to approximately 7.6 Ma, and the duration of the deposition is then approximately 3.8 My (Piasecki 1980, 2005; Dybkjær & Piasecki submitted).

Marbæk Formation

New formation

History. Sands outcropping at Sjelborg and Marbæk cliffs, northwest of Esbjerg and sandy sediments in the upper part of the Sæd borehole (DGU no. 167.445) was with some uncertainty referred to the Pliocene (Jørgensen 1945). New studies of these sections (Piasecki 2003) however, indicate that these deposits are Tortonian in age. The sand was informally named the Gram Sand by Rasmussen (1956).

Name. The Marbæk Formation is named after the coastal cliff at Marbæk, northwest of Esbjerg.

Type and reference section. The type section is the exposure at Marbæk cliff. The reference section is the interval from 50–65 m (md. 49–65 m) in the Tinglev borehole (DGU no.168.1378) (Fig. 58).

Thickness. The Marbæk Formation is c. 16 m thick at Marbæk cliff. At the Gram Brickwork pit 1.5 m of the formation is exposed at the bank of the brook. In the Tinglev borehole (DGU no.168.1378) the thickness is 15 m (Fig. 58).

Lithology. The formation consists of white and reddish fine- to medium-grained sand with few intercalations of thin coarse-grained sand or gravel layers (Fig. 59). The sand shows parallel lamination with subordinate cross-bedding and hummocky cross-stratified beds are common (Fig. 60). Double clay layers may occur. The uppermost white sand consists of homogenous sand capped by wave-ripples (Fig. 61).

Fossils. Rare, poorly preserved molluscs have been found in the Marbæk Formation (Jørgensen 1945). Dinocysts occur in the lower part of the formation but disappears upwards (Piasecki *et al.* 2003).

Depositional environment. The formation was deposited in a storm dominated environment within the upper and lower shoreface. Double clay layers indicate some tidal influence.

Boundaries. The lower boundary is defined where alternating thin clay and sand layers are overtaken by amalgamated sand beds.

Distribution. The extension is limited to extreme western and southern Jylland.

Biostratigraphy. The *Hystrichosphaeropsis obscura* Dinocyst Zone of Dybkjær & Piasecki (submitted) is recorded in the lower part of the Marbæk Formation.

Geological age. The lower part of the Marbæk Formation is of Tortonian, Late Miocene age, equivalent to the uppermost part of the Gram Formation. The absence of fossils in the upper formation prevents precise dating of this part. The fossiliferous interval is deposited between 8.8 and 7.6 Ma (Piasecki *et al*. 2003).

Stratigraphic architecture

The overall stratigraphic architecture of the Miocene succession is revealed by seismic data and to some extent by outcrops and borehole data. Especially, the knowledge obtained by the interpretation of the seismic data, which include information in between the boreholes, is used in the construction of correlation panels.

Inspection of seismic sections (Figs 62–64) reveals that the lower part of the Miocene succession is composed of two discrete progradational successions (Fig. 62). The two successions correlate with the Vejle Fjord, Billund, Klintinghoved and Bastrup Formations. These packages are often characterised by an oblique parallel and sigmoidal clinoformal seismic reflection pattern. The height of clinoforms varies between 60–100 m and dips of the clinoforms between 3^0 and 10^0 are commonly found (Fig. 62). Clinoformal packages may alternate with units of more or less transparent seismic character (Fig. 63). This part of the succession is interpreted to represent prograding delta lobes with alternating sand-rich and mud-rich units (Rasmussen *et al.* 2007; Hansen & Rasmussen 2008; Rasmussen 2009b). On top of each prograding unit erosional valleys and channels occur and some channels are characterised by having a shingled reflection pattern (Rasmusssen 2009b). These features are formed by incision and are commonly filled with sand. The shingled reflection pattern is interpreted as point bars of meandering river systems (Rasmussen *et al.* 2007; Rasmussen 2009b). In between these delta lobes, seismic data indicate areas that are characterised by a parallel, often low amplitude reflection pattern (Fig. 63). This is interpreted as mud dominated inter-lobe deposits (Hansen & Rasmussen 2008). In northern and central Jylland there is a successive southward migration of delta lobes. These may be characterised by an ascending shoreline trajectory (Fig. 63) indicating progradation under rising sea level (e.g. Helland-Hansen & Gjelberg 1994). In the northern part of the study area, this part of the Miocene is dominated by a parallel to subparallel reflection pattern capping the clinoforms (Fig. 64). Boreholes penetrating this part of the succession indicate alternating mud- and sand-rich units (Fig. 64). Gravel pits and outcrops around Silkeborg indicate a dominance of braided fluvial systems here (Hansen 1985; Jesse 1995; Hansen 1995; Rasmussen *et al.* 2007). The dominance of braided fluvial systems is found in northern Jylland and parts of central Jylland from Addit to Hammerum. In a narrow NW – SE striking belt across central Jylland the seismic reflection pattern is dominated by a parallel clinoformal reflection pattern. This represent progradation during falling sea level (Hansen & Rasmussen 2008, Rasmussen 2009b). In southern Jylland there is a tendency of an aggradation stacking pattern.

Above these two progradational units of the Billund/Vejle Fjord – and Klintinghoved/Bastrup Formations, a parallel to subparallel reflection pattern dominates the Miocene succession (Fig. 62). This part correlates with the Arnum and Odderup Formations. The change in seismic character indicate a change in depositional environment from prograding "Gilbert type" deltas to aggrading shelf and coastal plain deposits. This is illustrated on correlation panels by progressively south-westward progradation of the Odderup Formation contemporaneously with deposition of marine the Arnum Formation.

Two representative correlation panels is shown in figure 65.

Palaeogeography

The Late Oligocene was characterised by a warm climate and thus a period with high sea level (Utscher *et al.* 2000; Utscher 2009; Zachos *et al.* 2001; Larsson *et al.* 2006; Larsson-Lindgren 2009). The North Sea was located in the northern westerly wind belt (Galloway 2002) and consequently the north-eastern part that is covered by present day Denmark, was dominated by wave processes due to the long fetch across the North Sea (Fig. 1). Most part of the present day Denmark was covered by the sea in the Late Oligocene and the deposition of the fully marine Brejning Formation took place. There is no evidence of the northern position of the coastline at that time, but structural elements as the Sorgenfrei–Tornquist Zone or the Norwegian mountains must have been important features in shaping the shoreline. The position of the coastline is here conservatively placed in the fringe area of the Fennoscandian Shield (Fig. 66). Partly due to climatic deterioration and initial uplift of the Norwegian–Danish Basin at the end of the Oligocene (Rasmussen 2009a; Rasmussen in prep.) more shallow water conditions prevailed at the Oligocene–Miocene transition. This resulted in deposition of the Øskenrade Member which was deposited in shallow water on the Ringkøbing-Fyn High. At Dykær subaerial conditions prevailed for a period as indicated by deposition of a gravel layer with clasts up to 2 cm (Rasmussen & Dybkjær 2005).

The transition from the Oligocene to the Miocene was characterised by a short, but marked sea-level fall associated with ice cap growth on Antartica (Miller *et al.* 1996). Coincident with this, inversion of the Norwegian–Danish Basin and reactivation of the Sorgenfrei–Tornquist Zone and the Ringkøbing–Fyn High commenced (Rasmussen 2009a). This resulted in a marked change in the depositional regime in the eastern North Sea Basin from deposition of dominantly fully marine clay-rich sediments deposited at the basin floor and toe of shelf slope to sedimentation of coarse-grained sand-rich shallow marine deltaic deposits (Larsen & Dinesen 1959; Rasmussen 1961; Spjeldnæs 1975; Friis *et al.* 1998; Michelsen *et al.* 1998; Rasmussen 1996; 2004a,b).

At the boundary the sea level was low partly due to eustatic lowstand of sea level and partly because the Norwegian-Danish Basin were uplifted due to the inversion tectonism. The palaeogeography was at that time controlled by structural highs and lows (Fig. 67). Elevated parts of the Ringkøbing–Fyn High formed a barrier across the present day southern Jylland. Salt diapirs within the Norwegian–Danish Basin acted as core of minor islands. Therefore a large silled basin formed north of the Ringkøbing–Fyn High where brackish water conditions prevailed. Reworking of sands laid down during the lowstand of sea level at the Miocene boundary, was transported along the structures and deposited as spits and barrier islands east of the structures (Fig. 67). In this brackish water basin the lower part of the Vejle Fjord Formation was deposited. The rising sea level in the early Aquitanian resulted in flooding of the Ringkøbing–Fyn High. This resulted in degradation of the barrier complexes and deposition of the Skansebakke Member. During the complete flooding, the shoreline withdrew to a position north of Århus in the east and Thisted in the north-west. The high sediment supply to the North Sea Basin, however, resulted in progradation of delta complexes from the north and north-east, elucidated in the deposition of the Billund Formation (Fig. 68). The sediments were conveyed through three major river systems (Olivarius 2009). The western river was probably connected to the Setesdal valley in present day Norway and was the source for the sediments deposited in the delta located off the present day west coast of

Denmark, the so-called Ringkøbing lobe (Hansen & Rasmussen 2008). The central river was sourced from the north, probably southern Norway and the northern part of present day central western Sweden. The eastern river drained the area covered by the present day central Sweden. The central and eastern river system merged in central Jylland and resulted in the deposition of the Brande lobe (Hansen & Rasmussen 2008). The river systems were characterised by braided rivers, the deposits of which are referred to as the Addit Member. At the sea, sands were deposited in wave dominated deltas (Rasmussen & Dybkjær 2005; Hansen & Rasmussen 2008). Some of the sand at the delta mouth was reworked and transported eastward by along shore currents and was deposited as spit and barrier complexes of the Hvidbjerg Member (Fig. 68). Development of lagoonal environments was common during this time. Due to a global climatic deterioration in the late Aquitanian, sea level began to fall and the delta complexes were forced south-westward and deposition of a coastline characterised by amalgamated beach ridges took place (Fig. 69).

A resumed transgression occurred at the beginning of the Burdigalian. This transgression was the result of a global warming. According toTorsten Utescher (personal communication 2008), the local climate rose 2^0. Widespread barrier island complexes formed east of the main delta systems due to strong erosion of the main delta and eastward transport of erosional materials. These barrier island complexes correspond to the Kolding Fjord Member (Fig. 70). During maximum flooding of the sea and associated with the progradation of the succeeding delta complex, mud was deposited in the Danish area. This is referred to as the Klintinghoved Formation (Fig. 71). The succeeding delta complex, the Bastrup Formation, prograded south-westward (Fig. 72) and periodically this progradation occurred during a sea-level fall. Here the coastline was dominated by beach ridges (Fig. 73). In mid Burdigalian times the delta complexes of the Bastrup Formation reached the southern part of Denmark (Fig. 74). During the sedimentation of the Bastrup Formation the river systems has changed to be dominated by meandering rivers, especially in the late part of progradation. Sand deposits of these rivers are referred to as the Resen Member.

At the end of the Early Miocene (late Burdigalian) a distinct global climatic warming commenced (Zachos *et al*. 2001). This resulted in a sea-level rise and a new transgression. The mud laid down under this transgression and in front of the succeeding prograding coastline is the Arnum Formation (Fig. 75). At the maximum flooding, the coastline was located across the northern part of the present day north-west Jylland and continued south-eastwards through central Jylland. Even though the climate was subtropical (Friis 1975) during the latest part of Early and early Middle Miocene resumed progradation occurred (Fig. 76). This was due to tectonism and uplift of the hinterland and consequently increased sediment supply to the North Sea Basin (Rasmussen 2004b). Sand of the prograding coastline is referred to as the Odderup Formation (Fig. 77). Fine-grained storm sand layers deposited in front of the coastline is named the Stauning Member. As a consequence of the prograding coastline of the Odderup Formation and coincident rising sea level due to the warmer climate, optimal conditions for coal formation existed. A preliminary study (Torsten Utecher personal communication, 2009) indicates that the widespread coal formation also was associated with increased precipitation in the area. The coal was formed in lagoons and lakes in the land area especially adjacent to older faults (Koch 1989) and predominantly north of the Ringkøbing–Fyn High. These widespread coal layers compose the Fasterholt Member (Koch 1989).

Due to the overall rising sea level during the so-called Mid Miocene climatic optimum and partly due to auto retreat (Muto & Steel, 2002) a major transgression occurred in the middle Langhian, early Middle Miocene. The transgression was further amplified by increased subsidence of the North Sea Basin during the Middle and Late Miocene (Koch 1989; Michelsen *et al* 1998; Clausen *et al*. 1999; Rasmussen 2004b; Rasmussen *et al*. 2005). Mud rich sediments of the Hodde Formation were deposited during this transgression. There is no evidence of formation of barrier-island complexes associated with the transgression and this probably indicate a very rapid flooding of the low relief landscape of the coal-rich Odderup Formation. Despite a global climatic deterioration in the early Serravallian, Middle Miocene (Zachos *et al*. 2001), the flooding of this part of the North Sea Basin continued as a consequence of the accelerating subsidence of the basin. During the most widespread flooding of the area, glaucony-rich sediments of the Ørnhøj Formation were formed indicating a far distance to the coastline. The location of the coastline during this maximum transgression is uncertain. Boreholes in central Jylland do not indicate any influx of coarse-grained siliciclastic deposits, so at a minimum, the coastline was displaced to the southern boundary of the Fennoscandian Shield (Fig. 78). Parts of the shield may, however, have been flooded during the highest rate of the sea-level rise. Coincident with the subsidence of the North Sea Basin, the Norwegian mainland was uplifted (Løseth & Henriksen 2005; Rundberg & Eidvin 2005; Eidvin & Rundberg 2007; Rasmussen *et al*. 2008). This resulted in enhanced sediment supply into the basin and progradation took place. Mud of the Gram Formation was deposited in an open shelf environment (Fig. 79). In the upper part thin storm sand layers are intercalated in the Gram Formation indicating an approaching coastline (Rasmussen & Larsen 1989). Near the end of the Tortonian, Late Miocene, shoreface sediments of the Marbæk Formation were deposited in the central-western part of present day Denmark (Fig. 80).

The progradation of the coastline continued through the Late Miocene and a delta/coastline was formed in the central part of the Central Graben area (Rasmussen 2005; Møller *et al*. 2009). The termination of the Miocene was characterised by a sea-level fall of c. 90 m, which is indicated by deep incision of this delta complex.

Discussion

The first lithostratigraphy of the Danish Miocene by Rasmussen (1961) has a bipartite subdivision of the sand-rich fluvio-deltaic systems, namely the Ribe and Odderup Formations (Fig. 4). At the time, when Rasmussen (1961) established the Miocene lithostratigraphy, no high-quality boreholes penetrated the entire Miocene succession. During the last decade more than 50 boreholes have been drilled. The location of many of these boreholes has been made in order to resolve the development of the Miocene succession and thus strategically placed. A systematically study of all outcrops with Miocene deposits has been undertaken by the group during the same period (Rasmussen & Dybkjær 2005; 2009; Piasecki *et al.* 2003; Rasmussen *et al.* 2007). High-resolution seismic data, with a resolution less than 10 m, have been aquired. Consequently, a combination of seismic lines provides now a full coverage across the succession from north to south and from east to west (Fig. 5).

Furthermore, the development of a dinocyst stratigraphy for the Miocene in Denmark (Dybkjær & Piasecki 2008; submitted) has resulted in a much higher biostratigraphic resolution of the Miocene succession than formerly used biostratigraphic techniques. These steps have resulted in a quite robust stratigraphic framework. Recent developments within dinocyst stratigraphy (de Verteuil & Norris 1996; Williams *et al.* 2004; Powell & Brinkhuis 2004) combined with Strontium isotope datings (written communication, Tor Eidvin 2009) on selected samples has made it possible to suggest absolute ages of the lithostratigrapic units and to correlate regionally/globally (see further in Dybkjær & Piasecki 2008,submitted).

Some of the early results of the study of the Miocene succession revealed that the succession in question was more complex than indicated by the lithostratigraphy of Rasmussen (1961). The sequence stratigraphic framework of Rasmussen (2004a) indicated for the first time that the lower Miocene could be subdivided into three distinguished prograding sand-rich units. Changes has however, occurred; i) the Ribe Formation (now Bastrup Formation) was wrongly correlated between central and southern Jylland (Rasmussen 2004b), ii) The fluvial deposits at Addit and Voervadsbro was formerly referred to as the Odderup Fm. Friis (1995), however, stressed that the correlation of sand deposits near Silkeborg with the Odderup Formation was uncertain and that a stratigraphical tool was highly needed to solve this problem. New biostratigraphy indicates that these sections should be correlated with the Billund Fm (Rasmussen *et al.* 2006).

Although that L.B. Rasmussen made his bipartite subdivision of the sand-rich Miocene formation, the Ribe and Odderup Formations (Fig. 4), it is, however, interesting that he mentioned the Vejle Fjord Clay Member (now Vejle Fjord Formation) and Vejle Fjord Sand Member (Skansebakke Member) in the text about the Miocene formations, but he did not include these in the stratigraphic scheme where they in justice belongs to, as shown in the new stratigraphic scheme (Fig. 6). Larsen & Dinesen (1959) also noticed the "white, probably marine sand", at Hvidbjerg, but excluded this sand-rich succession, because of the different content of heavy minerals (Larsen & Dinesen 1959). Larsen & Dinesen (1959) were, however, aware that the Hvidbjerg sand could be of Miocene in age. The sand-rich deposits at Hvidbjerg constitute the Hvidbjerg Member of the new Billund Formation, which forms the lowermost fluvio-deltaic formation of the Ribe Group. Consequently, a tripartite subdivision of the lower part of the Miocene succession was very close to be established 40 years ago.

The lower and upper shoreface deposits of the new Marbæk Formation, which indicates a fourth and probably final progradation of fluvio-deltaic deposits at the end of the Miocene were neither included in the scheme of Rasmussen (1961). The deposits were interpreted as Pliocene by Jørgensen (1945), but redated to Late Miocene by Piaseki *et al*. (2003). A Miocene age of the Marbæk Formation is confirmed by a study of the Neogene succession in the North Sea, which clearly shows that the Pliocene is truncated several tenth of kilometres off the Danish west coast (Rasmussen *et al*. 2005).

Finally, the palaeogeographical reconstruction of the Miocene succession has formerly been difficult to resolve due to the presence of only small and scattered outcrops in the study area. A lagoonal–barrier complex was suggested by Larsen & Dinesen (1959) to represent the overall depositional setting. Their study, based on only two closely spaced outcrops at Brejning, Vejle Fjord did not allow them to reconstruct the trend of the coastline. The lagoonal–barrier model was adopted and elaborated by Friis *et al.* (1998). They suggested a NE – SW trending coastline for the Lillebælt area turning into a N-S striking coastline in the Vejle Fjord and Horsens Fjord area. These considerations were based on their interpretation of facies associations and sedimentary structures of sand-rich deposits interpreted as shoreface and beach deposits. Especially, weakly SE dipping cross-bedding of sands interpreted to be deposited in the swash zone of a beach was interpreted to represent a beach facing a lagoon. This reasoning was based on the general idea that the Miocene shoreline had a general N-S trend (Friis *et al.*1998). Reinterpretation by Rasmussen & Dybkjær (2005), however, changed the strike of the coastline to be trending NW–SE. This interpretation was based on the strike of the crest of coarse-grained wave ripples, dip of cross-bedding of ebb and flood dominated dunes and the development of facies associations based on a sequence stratigraphic framework including biostratigraphy. A NW–SE orientation of the shoreline was subsequently confirmed by high-resolution seismic data acquired across Jylland, which clearly show a dominance of S to SW-wards progradation of delta systems (Rasmussen *et al.* 2004; Rasmussen & Dybkjær 2005). This is also in concert with the sediment source area that was located in the present day Telemark area in Norway and western central Sweden (Olivarius 2009).

Den rumlige geologiske model for Miocæn

Den rumlige geologiske model for den miocæne lagserie opstilles med udgangspunkt i de stratigrafiske tolkninger, som er udført i forbindelse med den nationale grundvandskortlægning.

Der er fokuseret på at modellere de 3 niveauer med gode sandede formationer; Billund, Bastrup og Odderup, samt de mellemliggende mere lerede formationer; Vejle Fjord, Klintinghoved og Arnum. De lerede sedimenter fra Måde gruppen (Hodder, Ørnhøj og Gram) er slået sammen i modellen.

Nøgleboringer i 3D-tolkningen af den miocæne lagserie er boringer fra stratigrafiske korrelations-paneler opstillet i forbindelse med den nye lithostratigrafi. Disse er blevet suppleret med boringer fra korrelations-paneler i tidligere rapporter fra kortlægningen af miocæne grundvandsmagasiner. Der er således i alt anvendt omkring 130 nøgleboringer som er tolket med baggrund i den opstillede lithostratigrafi. Flere boringer på de tidligere paneler er blevet retolket efterhånden som der er kommet nye stratigrafiske undersøgelser til. Især er tolkninger i det sønderjyske område revideret. Det drejer sig blandt andet om den tidligere tolkede Ribe Formation, der nu tolkes som Bastrup formationen. Endvidere var der i det sydvestlige Jylland flere steder tolket Billund Formation på de tidligere paneler, hvor der nu tolkes Bastrup Formation.

I den rumlige geologiske model er de enkelte lag navngivet således, at navnet fortæller mest muligt om alderen og aflejringsmiljøet. Lagene er inddelt i lag, der er afsat under henholdsvis regressive og transgressive perioder. Nogle er afsat i flodsystemer som fluviatile aflejringer, nogle er afsat i strandzonen, nogle er afsat på soklen på 60-100 meter's vanddybde som deltalober, og nogle er afsat under marine forhold som lerede aflejringer.

Under den miocæne epoke blev hovedparten af de sandende sedimenter i Ribe gruppen (især i Billund og Bastrup Formationerne) aflejret som sandede deltalober adskilt af mere lerede indslag (Vejle Fjord og Klintinghoved Formationerne) som følge af variationer i havniveau. Den gradvise kystudbygning fra nordøst mod sydvest har bevirket, at eksempelvis Billund Formationen kan underinddeles i ca. 10 adskilte generationer af deltalober, hvor den ældste mod nordøst benævnes BDS1 (Billund Delta Sand 1) og de efterfølgende nummereres stigende mod sydvest, se figur 1.

I hele modelområdet er tolket gennemgående flader i den miocæne lagserie, som betegnes overordnede flader. Det drejer sig dels om Top Miocæn og Bund Miocæn, der udgør henholdsvis toppen og bunden af modellen og dels om de sekvensstratigrafisk definerede maximale regressive flader (MRS) som udgør toppen af henholdsvis Billund og Bastrup Formationen.

Mellem de overordnede flader er tolket en række underordnede enheder, der hver især har en begrænset udbredelse. De underordnede enheder navngives efter de formationer de tilhører (Vejle Fjord, Billund, Klintinghoved, Bastrup, Arnum og Odderup), se figur

2. Der arbejdes i alt med ca. 75 flader og lithologiske enheder i den rumlige geologiske model for miocænet.

I forbindelse med opstilling af den rumlige geologiske model er der udført kvalitetssikring og færdiggørelse af tolkningen af de overordnede lag Top Miocæn, Bund Miocæn, MRS Billund og MRS Bastrup på hele det seismiske datasæt i kortlægningsområdet. Som støtte til tolkningen i GeoScene 3D er der udført detailtolkning af de underordnede lag Vejle Fjord, Billund, Klintinghoved, Bastrup, Arnum og Odderup på en del af det seismiske datasæt.

Detailtolkningen er baseret på en samtolkning af seismik og boringer som er tolket med baggrund i den nye lithostratigrafi og er et forsøg på at afgrænse udstrækningen af sandede enheder på de seismiske profiler.

I nogle tilfælde er der tolket sandede enheder alene ud fra refleksionsmønsteret på profilerne. F.eks. er tilstedeværelsen af stejle skråtstillede reflektorer (parallel klinoform refleksionsmønster) med en hældning på 7° -10° internt i en enhed en indikation på at enheden består af mellem-grovkornet sand (Rasmussen et al. 2007; Hansen and Rasmussen 2008). Enheder med mindre stejle og mere kurvede skråtstillede reflektorer (sigmoidal klinoform refleksionsmønster) indikerer typisk vekslende sandede og lerede aflejringer (Hansen and Rasmussen 2008). Nedskårne dale og flod-kanaler kendetegnet som opad-konkave erosionsflader i de seismiske profiler er generelt antaget at repræsentere relativt grovkornet sand og grus (Rasmussen et al. 2007).

Hvor tilstedeværelsen af sand i boringer understøttes af refleksionsmønsteret i seismikken er der foretaget relativ sikker ekstrapolation og afgrænsning af de sandede enheder.

I tilfælde hvor en nærtstående boring viser tilstedeværelsen af tykke sandlag uden at det direkte underbygges af refleksionsmønsteret på de seismiske linier er der alligevel forsøgt foretaget en tolkning og afgrænsning af sådanne enheder ud fra en række forskellige kriterier. F.eks. er fraværet af egentlige interne refleksioner benyttet som en indikation på sandede aflejringer idet finkornede sedimenter aflejret ved lavt energiniveau typisk giver anledning til relativt svage, men sammenhængende parallelle horisontale (eller konforme med underlaget) interne reflektorer (Anstey 1982). Et andet eksempel er skråtstillede reflektorer med lavere hældning end nævnt ovenfor. Man skal i den forbindelse også være opmærksom på, at hvis en seismiske linie stryger skævt eller vinkelret på udbygningsretningen af et delta vil interne reflektorer fremstå med lavere eller ingen hældning.

I starten af projektet er der etableret en metodik til indlægning af seismiske data i GeoScene 3D. De seismiske data plottes til såkaldte cgm-filer som efterfølgende konverteres til jpg-filer med programmet Larson VizEx Pro v9.5.0 fra Larson Software Technology, Inc. Baseret på jpg-filerne beregnes en top og bundkote for hver enkelt seismisk profil. Langt de fleste anvendte seismiske linier er korrigeret for variationer i terrænhøjden langs profilet samt tilstedeværelsen af lavhastighedslag (dvs. lag med hastigheder væsentligt under 1500 m/s - typisk umættet sand med en hastighed på ca. 500 m/s). De har således et fladt seismisk datum, dvs. den kote som svarer til 0 ms i profilet. Flere af de seismiske profiler har imidlertid forskelligt seismisk datum og for en lang række linier svarer f.eks. 100 eller 200 ms til kote 0 m. For andre linier svarer 100 eller

200 ms til kote +40 m eller +60 m. Ved beregningen af top og bundkoter tages selvfølgelig højde for disse forskelle. Enkelte linier har terræn som seismisk datum og for disse linier er beregningen af top og bundkoter baseret på en gennemsnitskote for terrænet langs linien.

Som udgangspunkt anvendes en fast gennemsnitshastighed på 1800 m/s for hele det seismiske profil ved beregningen af top og bundkoter. Den anvendte hastighed på 1800 m/s vurderes i stor udstrækning at være repræsentativ for den miocæne lagpakke, men i realiteten varierer de seismiske lydhastigheder både med dybden og lateralt. I de øvre dele af de seismiske profiler kan den seismiske hastighed både være højere og lavere end 1800 m/s. Ukonsoliderede sedimenter af sand og ler kan typisk have seismiske hastigheder på 1500-1600 m/s og moræneaflejringer kan typisk have seismiske hastigheder på 2000-2200 m/s. I de dybere dele af de seismiske profiler, dvs. under de neogene og paleogene lagpakker, vil den reelle seismiske hastighed være væsentlig højere end de anvendte 1800 m/s og de koter hvori dybe reflektorer på profilerne optræder i GeoScene 3D kan således ikke tages for pålydende. Alligevel er det valgt at vise alle seismiske profiler til en tovejs-tids-dybde på 1200 ms for at nyttiggøre de strukturelle informationer som kan udledes af de dybere dele af de seismiske linier.

Selvom beregningen af top og bundkoter for de seismiske profiler beregnes med en fast gennemsnitshastighed for alle profiler og under hensyntagen til det aktuelle seismiske datum forekommer det at profiler som krydser hinanden ikke korrellerer fuldstændigt. Det kan skyldes, at der i forbindelse med processeringen af data er anvendt forskellige nmo-korrektionshastigheder eller at der ved korrektionen for terrænvariationer og/eller lavhastighedslag er anvendt forskellige hastigheder eller gjort forskellige antagelser.

Hvis det ved indlægning af et seismisk profil i GeoScene 3D viser sig at hele profilet generelt vil passe bedre med boringsoplysninger og/eller andre profiler ved at anvende en anden hastighed end 1800 m/s anvendes den hastighed som vil give den bedste korrelation.

I udarbejdelsen af den rumlige geologiske model er også anvendt geofysiske logs fra GERDA databasen. Det drejer sig om naturlige gammalogs der benyttes til lithologisk tolkning som supplement til prøvebeskrivelser i boringerne. Lerede sedimenter viser en relativt høj gammastråling, mens sand typisk har en relativt lav gammastråling. Grus og silt kan have en mellemhøj naturlig gammastråling.

Gammaloggene benyttes også til at skelne mellem f.eks. deltaaflejringer og fluviatile aflejringer. Kornstørrelsen i deltaaflejringer viser ofte en tendens til at grove-opad, hvilket afspejler sig som faldende gamma-niveau opad. Fluviatile aflejringer viser typisk en tendens til at fine-opad, afspejlet som stigende gamma-niveau opad.

Gammaloggene viser også ofte regionale markører som kan anvendes i en sekvensstratigrafisk tolkning. F.eks. kan strandzone sedimenter rige på tungmineraler give anledning til regionale markører, dvs. tynde horisonter med meget højt gamma-niveau.

Arbejdsgangen i opstilling af den rumlige geologiske model for miocænet har været først, at få sammentolket alle de stratigrafiske boringer og seismikken, der er udført i forbindelse med den nationale grundvandskortlægning. Derefter at udvide modellen med tolkning af andre boringer og de resterende seismiske data.

I forbindelse med GeoScene 3D projekter er der etableret et system hvor usikkerheden på de enkelte datapunkter registreres i bagvedliggende tabeller. Usikkerheden angives med talværdier mellem 1 og 4, hvor 1 angiver størst sikkerhed. F.eks. tildeles punkter tilknyttet stratigrafisk beskrevne boringer værdien 1 for stor sikkerhed. Usikkerhedsværdierne kan efterfølgende anvendes til, at fremstille kort for de enkelte flader og enheder, der viser hvor sikker tolkningen er i området.

I den bagvedliggende tabel for Bund Miocæn registreres navnet på det lag der udgør bunden (Søvind mergel, Brejning ler m.m.), hvis det er beskrevet i boringerne.

En rumlig geologisk model over lithostratigrafiske enheder i den miocæne lagserie kan hjælpe med, at udpege mulige nye vandindvindingsområder og forudsige de geologiske lag på nye borelokaliteter. Modellen kan også udgøre fundamentet i fremtidige hydrostratigrafiske modeller for området.

References

Asgaard, U. & Bromley, R.G. 1974: Sporfossiler fra den Mellem Miocæne transgression I Søby–Fasterholt området. Dansk Geologisk Forening, Årskrift 1973, 11–19.

Bendix-Almgreen, S.E. 1983: *Carcharodon megalodon* from the Upper Miocene of Denmark, with comments on elasmobranch tooth enameloid: coronoïn. Geological Society of Denmark Bulletin 32, 1–32.

Bertelsen, F. 1978: The Upper Triassic – Lower Jurassic Vinding and Gassum Formations of the Norwegian–Danish Basin. Danmarks Geologiske Undersøgelse Serie B **3**, 26 pp.

Berthelsen, A. 1992: Mobil Europe. In: Blundell, D.J., Mueller, St., Freeman, R. (eds.): A continent revealed: The European Geotraverse Project. Cambridge: Cambridge University Press, 153–164.

Beyrich, E. 1853: Die Conchylien des Norddeutschen Tertiär-gebirges. Zeitschrift der Deutsche Geologisches Gesellshaft **5,** 273–358.

Buchardt, B. 1978: Oxygene Isotope Palaeotemperatures from the Tertiary Period in the North Sea Area. Nature **275**, 121–123.

Buchardt-Larsen, B. & Heilmann-Clausen, C. 1988: The Danish Subbasin, Southern Jylland. In: Vinken R. (Compiler): The Southwest European Tertiary Basin; Results of the International Geological Correlation Program No 124. Geologisches Jahrbuch **100**, 83–91.

Christensen, L. & Ulleberg, K. 1974: Sedimentology and micropalaeontology of the Middle Oligocene sequence of Sofienlund. Bulletin of the Geological Society of Denmark **22**, 283–305.

Clausen, O.R., Gregersen, U., Michelsen, O. & Sørensen, J.C., 1999: Factors controlling the Cenozoic sequence development in the eastern parts of the North Sea. Jour. Geol. Soc., London. **156**, 809–816.

Dalgas, E. 1868: Geographiske Billeder fra Heden. Udgivet af det Danske Hedeselskab, H. **2**, 125 pp., København

de Verteuil, L. & Norris, G. 1996: Miocene dinoflagellate stratigraphy and systematics of Maryland and Virginia. Micropaleontology **42** (Supplement), 172 pp.

Deegan, C.E. & Schull, B.J. (compilers)1977: A standard lithostratigraphic nomenclature for the central and northern North Sea. Institute of Geological Science Report **77/25**, London: Her Majesty's Stationary Office, 36 pp.

Dinesen, B. 1976: Geochemical properties of the marine Younger Miocene at Gram, SW Jutland. Geological Survey of Denamrk, Årbog 1975, 5–29.

Doré, A.G., Lundin, E.R., Kusznir, N.J. & Pascal,C. 2008. Potential mechanisms for the genesis of Cenozoic domal stractures on the NE Atlantic margin: pros, cons and some new ideas. In: Johnson, H. Dore, A.G. Gatliff, R.W. Holdworth, R. Lundin, E.R. & Ritchie J.D.(eds.): The Nature and Origin of Compression in Passive Margins. Geological Society. London, Special Publications **306**, 1–26.

Dybkjær, K. 2004a: Dinocyst stratigraphy and palynofacies studies used for refining a sequence stratigraphic model–uppermost Oligocene to lower Miocene, Jylland. Denmark. Review of Palaeobotany and Palynology **131**, 201–249.

Dybkjær, K. 2004b: Morphological and abundance variations in *Homotryblium*-cyst assemblages related to depositional environments; Uppermost Oligocene - Lower Miocene, Jylland, Denmark. Palaeogeography, Palaeoclimatology, Palaeoecology **206**, 41–58.

Dybkjær, K. & Rasmussen E. S. 2000: Palynological dating of the Oligocene – Miocene successions in the Lille Bælt area, Denmark. Bulletin of the Geological Society of Denmark 47, 87–103.

Dybkjær, K. & Rasmussen, E.S. 2007: Organic-walled dinoflagellate cyst stratigraphy in an expanded Oligocene-Miocene boundary section in the Eastern North Sea Basin (Frida-1 well, Denmark) and correlation from basinal to marginal areas. Journal of Micropalaeontology **2f**, 1–17.

Dybkjær, K. & Piasecki, S. 2008: A new Neogene biostratigraphy for Denmark. Geological Survey of Denmark and Greenland Bulletin **15,** 29–32.

Dybkjær, K. & Piasecki, S. submitted: Neogene dinocyst zonation in the eastern North Sea Basin, Denmark. Review of Palaeobotany and Palynology.

Dybkjær, K. Piasecki, S. & Rasmussen, E.S. 1999: Dinoflagellat-zonering og sekvensstratigrafi i den miocæne lagpakke i Midt- og Sønderjylland. Danmark og Grønlands Geologiske Undersøgelse Rapport 1999/73, 33 pp.

Dybkjær, K,. Rasmussen, E.S. & Piasecki, S. 2001: Oligocæn–Miocæn stratigrafi i Vejle Amt. Danmark og Grønlands Geologiske Undersøgelse Rapport 2001/104, 37 pp.

Eder, V.G., Martín-Algarra, A., Sánchez-Navas,A., Zanin, Y.N., Zamirailova, G. & Lebedev, Y.N. 2007: Depositional controls on glaucony texture and composition, Upper Jurassic, West Siberian Basin. Sedimentology **54**, 1365–1387.

Edvin, T. & Rundberg, Y. 2007: Post-Eocene strata of the southern Viking Graben, northern North Sea; integrated biostratigraphic, strontium isotopic and lithostrastigraphic study. Norwegian Journal of Geology **87**, 391–450.

Eriksen, K. 1937: En foreløbig Meddelelse om Tertiæret ved Brejning paa Sydsiden af Vejle Fjord: Meddelelser fra Dansk Geologisk Forening **9**, 137–150.

Faleide, J. I., Kyrkjebø, R., Kjennerud, T., Gabrielsen, R.H., Jordt, H., Fanavoll, S., & Bjerke, M.D. 2002: Tectonic impact on sedimentary processes during Cenozoic evolution of the northern North Sea and surrounding areas. In: Dore, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P., White, N., (eds.): Exhumation of the North Atlantic Margin: Timing, Mechanism and Implications for Petroleum Exploration: Geological Society, London Special Publication **196**, 235–269.

Friis, E.M. 1975: Climatic implications of microcarpological analyses of the Miocene Fasterholt flora. Bulletin of the Geological Society of Denmark **24**, 179–191.

Friis, H. 1976: Weathering of a Neogene fluviatile fining-upwards sequence at Voervadsbro, Denmark. Bulletin of the Geological Society of Denmark **25**, 99–105.

Friis, H. 1994: Lithostratigraphy and sedimentary petrography of the Oligocene sediments from the Harre borehole, Denmark. In: Nielsen, O.B. (ed.): Danmarks geologi fra Kridt til i dag. Aarhus Geokompendier **1**, 35–43.

Friis, H. 1995: The role of faecal pellets in the deposition of marine muds — examples from the Danish Tertiary. Bulletin of the Geological Society of Denmark **42**, 68–75.

Friis, H., Mikkelsen, J. & Sandersen, P. 1998: Depositional environment of the Vejle Fjord Formation of the Upper Oligocene – Lower Miocene of Denmark: a back island/barrier-protected depositional complex. Sedimentary Geology **17**, 221–244.

Forchhammer, J. G., 1835: Danmarks geognostiske Forhold, forsaavidt som de ere afhængige af Dannelser der ere sluttede, fremstillede i et Indbydelsesskrift til Reformationsfesten den 14de November 1835: København, Kongelig og Universitets-Bogtrykker J.H. Schultz, 112 pp.

Galloway, W.E., 2002: Paleogeographic setting and depositional architecture of a sand-dominated shelf depositional system, Miocene Utsira Formation, North Sea: Journal of Sedimentary Research, **72**, 447–490.

Gabrielsen, R.H., Faleide, J.I., Pascal, C., Braathem, A., Nystuen, J.P., Etzelmuller, B. & O'Donnell, S. in press: Latest Caledonian to Present tectonomorphogical development of southern Norway. Marine and Petroleum Geology.

Christensen, E.F. "The Søby-Flora: Fossil Plants from the Middle Miocene Delta Deposits of the Søby-Fasterholt Area, Central Jutland, Denmark." *Geological Survey of Denmark, II Series* 103 (1975): 1–41.

Christensen, E.F. "The Søby-Flora; Fossil Plants from the Deltaic Deposits of the Søby-Fasterholt Area, Central Jutland, Denmark. Part Ii." *Geological Survey of Denmark, II Series* 108 (1976): 1–49.

Gradstein, F., Ogg, J., Smith, A., 2004. A Geological Time Scale. Cambridge University Press, Cambridge, U.K.

Gabroe, A., 1961a: Geologiens historie i Danmark. Fra myte til videnskab I, 283 pp.

Gabroe, A., 1961b: Geologiens historie i Danmark. Forskere og resultater II, 522 pp.

Hansen, J.Ø. 1985: En lithofacies undersøgelse af nogle kvartssandforekomster i Midt-jylland. Unpublished M. Sc. thesis, University of Aarhus. 126 pp.

Hansen, H.C. 1995: Tertiary fluvial deposits of Jylland, Addit area. In: Michaelsen O. (ed.): Proceeding of the 2nd Symposium on: Marine Geology Geological Survey of Denmark Series C **12**, 39–51.

Hansen, J.P.V. & Rasmussen, E.S. (2008): Distribution and thicknesses of reservoir sands in a wave-dominated delta, Billund delta, eastern Danish North Sea and Jylland. Sedimentary Research **78**, 130–146.

Hardt, T., Holtar, E., Isaksen, D., Kyllingstad, G., Lervik, K.S., Lycke, A.S. & Tonstad, K. 1989: Revised Tertiary lithostratigraphic nomenclature for the Norwegian North Sea. In: Isaksen, D. & Tonstad, K. (eds.): A revised Cretaceous and Tertiary lithostrati-graphic nomenclature for the Norwegian North Sea. Norwegian Petroleum Directorate (NDP) Bulletin **5**, 35–55.

Harzhauser, M. & Piller, W.E. 2007: Benchmark data of a changing sea – Palaeo-geography, Palaeobiogeography and events in the Central Paratethys during the Mio-cene. Palaeogeography, Palaeoclimatology, Palaeoecology **253**, 8–31.

Hartz, N., 1909: Bidrag til Danmarks Tertiære og Diluviale flora. Tekst og Atlas, 293 pp.

Heilmann-Clausen, C. 1995a: Palæogene aflejringer over Danskekalken. In: Nielsen, O.B. (ed.): Danmarks geologi fra Kridt til i dag. Aarhus Geokompendier **1**, 69–114.

Heilmann-Clausen, C. 1995b: Linde-1 borehole: Paleogene dinocysts, palynofacies and stratigraphy. EFP-92 Project: Basin development of the Tertiary of the Central Trough with emphasis on possible hydrocarbon reservoirs. Report 18, 23 pp.

Heilmann-Clausen, C., Nielsen, O.B. & Gersner, F. 1985: Lithostratigraphy and deposi-tional environments in the upper Palaeocene and Eocene of Denmark. Bulletin of the Geological Society of Denmark **33**, 287–323.

Helland-Hansen; W. & Gjelberg, J.G. 1994: Conceptual basis and variability in se-quence stratigraphy: a different perspective. Sedimentary Geology **92**, 31–52.

Heller, E. 1960: Keld Milthers´ arbejde med brunkulseftersøgningen: Meddelelser fra Dansk Geologisk Forening **14**, 447–453.

Hoch, E. 2008: Hvaler for 8 Millioner År Siden. Editeret af I. Adriansen, A. Blond, K. Furdal and A.B. Sørensen, Under Fælles Hat. Årbog for Museum Sønderjylland, 41–56.

Håkansson, E. & Pedersen, S.S. 1992: Geologisk kort over den danske undergrund. Varv.

Japsen, P. 1993: Influence of lithology and Neogene uplift on seismic velocities in Denmark: Implications for depth conversion of maps. Bulletin of American Association of Petroleum Geologists **77**, 194–211.

Japsen, P. & Langtofte, C. 1991: Geological map of Denmark, 1:400000 the Danish Basin. Geological Survey of Denmark, Map series 29, 2pp. and 3 maps.

Japsen, P. & Bidstrup, T. 2000: Quantification of late Cenozoic erosion in Denmark based on sonic data and basin modelling. Bulletin of the Geological Society of Denmark **46**, 79–99.

Japsen, P., Bidstrup, T. & Rasmussen, E.S. 2002: Comment on: "Cenozoic evolution of the eastern Danish North Sea" by M. Huuse, H. Lykke-Andersen and O. Michelsen, Marine Geology **186**, 571–575.

Japsen, P., Green, P., Nielsen, L.H., Rasmussen, E.S. & Bidstrup, T., 2007: Mesozoic–Cenozoic exhumation events in the eastern North Sea Basin: A multi-disciplinary study based on palaeothermal, palaeoburial, stratigraphic and seismic data. Basin Research **19**, 451–490.

Jesse, J. 1995: Arkitekturelementanalyse af aflejringer fra den mellem miocæne Odderup Formation. Geologisk Tidsskrift **2**, 95 pp.

Jørgensen, K. D. 1945: Marint Pliocæn? ved Esbjerg. Meddelelser fra Dansk geologisk Forening **10**, 460–467.

Knudsen, C. 1998: Heavy mineral exploration in Miocene sediments, Jylland. Denmark and Greenland. Geological Survey Report 1998/45, 44 pp.

Knudsen, C., Frei, D., Rasmussen, T., Rasmussen, E.S. & McLimans 2005: New methods in provenance studies based on heavy minerals: an excample from Miocene sands in Jylland, Denmark. In: M. Sønderholm and A.K. Higgins (eds): Review of Survey activities 2004, Geological Survey of Denmark and Greenland Bulletin **7**, 29–32.

Knox, R., Bosch, A., Rasmussen, E.S., Heilmann-Clausen, C., Hiss, M., de Lugt, I., Kasinski, J., King, C., Köthe, A., Słodkowska, B., Standke, G. & Vandenberghe, N. in press: Cenozoic. In: Doornenbal, J.C. and Stevenson, A.G. (eds): Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publications b.v.

Koch, B.E. 1989: Geology of the Søby–Fasterholt area. Danmarks Geologiske Undersøgelse Serie A **22**, 177 pp.

Koch, E. & Friedrich, W.L. 1970: Geologisch-Paläontologische untersuchung der Miozänen braunkohlen bei Fasterholt in Jütland. Geological Society of Denmark Bulletin **20**, 169–91.

Koch, E, Friedrich, W.L., Christensen, E.F. & Friis, E.M. 1973: Den Miocæne Brunkulsflora og dens geologiske miljø i Søby-Fasterholt området sydøst for Herning. Dansk geologisk Forening, Årsskrift for 1972, 1–57.

Larsen, G. & Dinesen, A. 1959: Vejle Fjord Formation ved Brejning: Sedimenterne og foraminiferfaunaen (oligocæn – miocæn). Danmarks Geologiske Undersøgelse, II Række **82**, 114 pp.

Larsen, G. & Kronborg, C. 1994: Geologisk set: Det mellemste Jylland, 272 pp. Geografforlaget Miljøministeriet, Skov- og Naturstyrelsen.

Larsson-Lindgren, L. 2009: Climate and vegetation during the Miocene – evidence from Danish palynological assemblages. Litholund theses No **19**, Paper III 20 pp. (unpaginated).

Larsson, L.M., Vajda, V. & Rasmussen, E.S. 2006: Early Miocene pollen and spores from Central Jylland, Denmark – environmental and climatic implications. Geologiska Föreningen Förhandlinger **128**, 261–272.

Laursen, G. & Kristoffersen, F.N. 1999: Detailed foraminiferal biostratigraphy of Miocene formations in Denmark. Contributions to Tertiary and Quaternary Geology **36**, 73–107.

Liboriussen, J., Aston, P. & Tygesen, T. 1987: The tectonic evolution of the Fennoscandian Border Zone in Denmark. Tectonophysics **137**, 21–29.

Lourens, L., Hilgen, F., Shackleton, N.J., Laskar, J. & Wilson, D. 2004: The Neogene Period. In: Gradstein, F., Ogg, J. & Smith, A. (eds.): A geological Time Scale 2004. Cambridge University Press, Cambridge, U.K., 509–440.

Løseth, H. & Henriksen, S. 2005: A Middle to Late Miocene compression phase along the Norwegian passive margin. In: Dore, A.G. & Vinding, B.A., (eds.): Petroleum geology: North-West Europe and global perspectives – Proceedings of the 6^{th} petroleum geology conference, 845–859. London: Geological Society.

Mai, D.B. 1967: Die Florenzonen, der Florenwechsel und die Vorstellung uber den Klimaablauf im Jungtertiar der DDR. Abhandlungen Zentral Geologische Institut **10**, 55–81, Berlin.

Martinsen, O.J., Bøen, F., Charnock, M.A., Mangerud, G. & Nøttvedt, A. 1999: Cenozoic development of the Norwegian margin 60-64^{0}N: sequences and sedimentary response to variable basin physiography and tectonic setting. In: Fleet A.J. & Boldy S.A.R. (eds.): Petroleum Geology of Northwest Europe: Proceedings of the 5^{th} Conference, 293–304. London: Geological Society.

Michelsen, O. 1994: Stratigraphic correlation of the Danish onshore and offshore Tertiary successions based on sequence stratigraphy: Bulletin of the Geological Society of Denmark **41**, 145–161.

Michelsen, O., Thomsen, E., Danielsen, M., Heilmann-Clausen, C., Jordt, H. & Laursen, G.V. 1998: Cenozoic sequence stratigraphy in the eastern North Sea. In: P. C. De Graciansky, T. Jacquin, & P. R. Vail, (eds.): Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. SEPM Special Publication, The Society for Sedimentary Geology **60,** 91–118.

Miller, K.G., Mountain, G.S., the Leg 150 Shipboard Party, and members of the New Jersey Coastal Plain Drilling project 1996: Drilling and dating New Jersey Oligocene-Miocene sequences: Ice volume, global sea level, and Exxon records. Science **271**, 1092–1095.

Miller, K.G., Wright, J.D., & Fairbanks, R.G. 1991: Unlocking the ice house: Oligocene-Miocene oxygen isotopes, eustacy, and marine erosion. Journal of Geophysical Research **96**, 6829–6848.

Miller, K.G., Mountain, G,S., Browning, J.V., Kominz, M.A., Sugarman, P.J., Christie-Blick, N Katz, M.E., & Wright, J.D. 1998: Cenozoic global sea level, sequences and the New Jersey transect: results from coastal plain and continental slope drilling. Review of Geophysics **36**, 569–601.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., Stephen F. & Pekar S.F. 2005: The Phanerozoic record of global sea-level changes. Science **310**, 1293–1298.

Milthers, K. 1949: Nogle hovedlinier i brunkullenes lejringsforhold.: Meddelelser fra Dansk Geologisk Forening **11**, 486 pp.

Mogensen, T. & Jensen, L.N. 1994: Cretaceous subsidence and inversion along the Tornquist Zone from Kattegat to the Egernsund Basin. First Break **12**, 211–222.

Mosar, J., Lewis, G. & Torsvik, T.H. 2002. North Arlantic sea-floor spreading rates: implication for the Tertiary development of inversion structures of the Norwegian–Greenland Sea. Journal of the Geological Society, London **159**, 503–515.

Muto, T. & Steel, R.J. 2002: Role of autoretreat and A/S changes in the understanding of deltaic shoreline trajectory: a semi-quantitative approach. Basin Research 14, 303–318.

Møller, L.K., Rasmussen, E.S. & Clausen, O.R. 2009: Clinoform migration patterns of a Late Miocene delta complex in the Central Graben; implications for relative sea-level changes. In: Henriksen, S., Hampson, G.J., Helland-Hansen, W. Johannessen, E.P. &. Steel, R.J (eds.): Trajectory Analysis in Stratigraphy. Basin Research **21**, 704–720.

Olivarius, M. 2009: Provenance and facies of Miocene sand successions in western Denmark based on bulk geochemistry, heavy minerals and zircon age datings. Unpublished Master Thesis, Department of Geography and Geology, University of Copenhagen, unpaginated.

Oszczypko, N. 2006. Late Jurassic-Miocene evolution of the Outer Carpatian fold-and-thrust belt and its foredeep basin (Western Carpatians, Poland). Geological Quarterly **50**, 169–194.

Piasecki, S. 1980: Dinoflagellate cyst stratigraphy of the Miocene Hodde and Gram Formations, Denmark. Bulletin of the Geological Society of Denmark **29**, 53–76.

Piasecki, S., Rasmussen, E.S. & Dybkjær, K. 2003: Neogene sedimenter ved Sjælborg og Marrebæk Klint, Esbjerg, Vestjylland. Danmarks og Grønlands Geologiske Undersøgelse, Rapport 2003/83, 18 pp.

Pontén, A. & Plink-Björklund, P. 2007: Depositional environments in an extensive tide-influenced plain, Middle Devonian Gauja Formation, Devonian Baltic. Sedimentology **54**, 969–1006.

Potter, P.E. & Szatmari, P. 2009. Global Miocene tectonics and the modern world. Earth-Science Reviews **96**, 279–295.

Powell, A.J. & Brinkhuis, H. 2004: Figure 21.2 In: Lourens, L., Hilgen, F., Shackleton, N.J., Laskar, J., Wilson, D., 2004, The Neogene Period. In: Gradstein, F., Ogg, J. and Smith, A. (eds.): A Geological Time Scale 2004. Cambridge Univ. Press, Cambridge, U.K., 409–440.

Prentice, M.L. & Matthews, R.K. 1988: Cenozoic ice-volume history: Development of a composite oxygen isotope record. Geology. **16**, 963–966.

Radwanski, A., Friis, H. & Larsen, G. 1975: The Miocene Hagenør-Børup sequence at Lillebælt (Denmark): its biogenic structures and depositional environment. Bulletin of the Geological Society of Denmark **24**, 229–260.

Rasmussen, E.S. 1987: En mineralogisk og geokemisk undersøgelse af Vejle Fjord Formationen (Ø. Oligocæn – N. Miocæn). Unpublished Master Thesis, Aarhus University, 223 pp.

Rasmussen, E.S. 1995: Vejle Fjord Formation: clay mineralogy and geochemistry. Bulletin of the Geological Society of Denmark **42**, 57–67.

Rasmussen, E.S. 1996: Sequence stratigraphic subdivision of the Oligocene and Miocene succession in South Jylland. Bulletin of the Geological Society of Denmark **43**, 143–155.

Rasmussen, E.S. 2004a: The interplay between true eustatic sea-level changes, tectonics,
and climatical changes: What is the dominating factor in sequence formation of the Upper Oligocene-Miocene succession in the eastern North Sea Basin, Denmark?. Global and Planatary Changes **41**, 15–30.

Rasmussen, E.S. 2004b: Stratigraphy and depositional evolution of the uppermost

Oligocene – Miocene succession in Denmark. Geological Society of Denmark Bulletin **51**, 89–109.

Rasmussen, E.S. 2005: The geology of the upper Middle – Upper Miocene Gram Formation in
the Danish area. Paleontos **7,** 5–18.

Rasmussen, E.S. 2009a: Neogene inversion of the north-eastern North Sea. Tectonophysic
465, 84–97.

Rasmussen, E.S., 2009b: Detailed mapping of marine erosional surfaces and the geometry of clinoforms on seismic data: a tool to identify the thickest reservoir sand. In: Henriksen, S., Hampson, G.J., Helland-Hansen, W. Johannessen E.P. &. Steel, R.J (eds.): Trajectory Analysis in Stratigraphy, Basin Research **21**, 721–737.

Rasmussen, E.S. & Dybkjær, K. 2005: Sequence stratigraphy of the Upper Oligocene – Lower Miocene of eastern Jylland, Denmark: role of structural relief and variable sediment supply in controlling sequence development. Sedimentology **52**, 25–63.

Rasmussen, E.S., Dybkjær, K, & Piasecki, S. 2006: Neogene fluvial and marginal marine deposits of the Salten section, Denmark. Bulletin of the Geological Society of Denmark **53**, 23–37.

Rasmussen, E.S. & Larsen, O.H. 1989: Mineralogi og geokemi i det Øvre Miocæne Gram Ler. Geological Survey of Denmark, Series D, **7**, 81 pp.

Rasmussen, E.S., Vangkilde-Pedersen, T. & Scharling, P. 2007: Prediction of reservoir sand in Miocene deltaic deposits in Denmark based on high-resolution seismic data. Geological Survey of Denmark and Greenland Bulletin **13**, 17–20.

Rasmussen, E.S**.,** Heilmann-Clausen, C., Waagstein, R., & Eidvin, T. 2008: Tertiary of Norden. Episodes **31**, 66–72.

Rasmussen, E.S**.,** Vejbæk, O.V., Bidstrup, T., Piasecki, S. & Dybkjær, K. 2005: Late Cenozoic depositional history of the Danish North Sea Basin: implications for the petroleum systems in the Kraka, Halfdan, Siri and Nini fields. In: Dore, A.G. & Vinding, B.A. (eds): Petroleum geology: North-West Europe and global perspectives - Proceedings of the 6th petroleum geology conference, 1347–1358. London: Geological Society.

Rasmussen, L. B. 1961: De Miocæne formationer i Danmark: Danmarks Geologiske Undersøgelse, IV Række **5**, 45 pp.

Rasmussen, L. B. 1966: Biostratigraphical studies on the marine younger Miocene of Denmark. Based on the molluscan faunas. Geological Survey of Denmark II series **88**, 358 pp.

Rasmussen, L. B. 1968: Molluscan Faunas and Biostratigraphy of the Marine Younger Miocene Formations in Denmark. Part II: Palaeontology. Danmarks Geologiske Undersøgelse, II Række **92**, 265 pp.

Rasmussen, L.B. 1975: Tertiærperioden. In: Nørrevang,A. & Meyer, T.J. (eds): Danmarks Natur, Bind 1, Politikens Forlag, 161–198.

Rasmussen, L. B. 1988: En jordisk krønnike. Træk af DGUs historie 1888-1988: København, Danmarks Geologiske Undersøgelse. Miljøministeriet, 114 pp.

Rasser, M.W., Harzhauser, M., (co-ordinators), A., O.Y., Anistrenko, V.V., Bassie, D., Belak,
M., Berger, J.-P., Bianchini, G., Cicic, S., Cosovic, V., Doláková, N., Drobne, K., Filipescu,
S., Gürs, K., Hladilová, S., Hrvatovic, H., Jelen, B., Kasinski, J.R., Kovac, M., Krajl, P.,
Marjanac, T., Márton, E., Mietto, P., Moro, A., Nagymarosy, A., Nebelsick, J.H., Nehyba,
S., Ogorelev, B., Oszczypko, N., Pavelic, D., Pavlovec, R., Pavsic, J., Petrova, P., Piwocki,
M., Poljak, M., Pugliese, N., Redzepovic, R., Rifelj, H., R., R., Skaberne, D., Sliva, L., G.,
S., Tunis, G., Vass, D., Wagreich, M., & Wesselingh, F. 2008: Palaeogene and Neogene:
In: Mccann, T., (Ed): The geology of Central Europe: Mesozoic and Cenozoic. Geological Society London, 1031–1138.

Ravn, J. P. J. 1906: Nogle Bemærkninger om de Oligocæne og Miocæne Aflejringer i Jylland: Meddelelser fra Dansk Geologisk Forening **12**, 1–6.

Ravn, J. P. J. 1907: Molluskfaunaen i Jyllands Tertiæraflejringer: Det Kongelige Danske Videnskabernes Selskabs Skrifter, 7. Række, Naturvidenskab og mathematisk Afdeling, III. 2, 217–385.

Ribero, A, Kullberg, M.C., Kullberg, J.C., Manuppellea, G. & Pripps, S. 1990: A review of Alpine tectonics in Portugal: Foreland detachment and cover rocks. Tectonophysics **184**, 357–366.

Rundberg, Y. & Eidvin, T. 2005: Controls on depositional history and architecture of the Oligocene-Miocene succession, northern North Sea Basin. In: Wandaas, B.T.G. *et al*. (eds.): Onshore-Offshore Relationships on the North Atlantic Margin. NPF Special Publication **12**, 207–239.

Salvador, A. 1994: International Stratigraphic Guide. A Guide to stratigraphic classification, terminology, and procedure. Boulder: The international Union of Geological Sciences, IUGS Secretariat, Trondheim and the Geological Society of America Inc. 214 pp.

Schiøler, P., Andsbjerg, J., Clausen, O.R., Dam, G., Dybkjær, K., Hamberg, L., Heilmann-Clausen, C., Johannessen, E.P., Kristensen, L.E., Prince, I. & Rasmussen, E S. 2007: Lithostratigraphy of the Palaeogene - Lower Neogene succession of the Danish North Sea. Geological Survey of Denmark and Greenland Bulletin 12, 77 pp.

Schnetler, K.I. 2005: The Mollusca from the Stratotype of the Gram Formation (Late Miocene, Denmark). Edited by F. Roth and K. Hoedemarkers. The Marine Gram Formation at Gram, Denmark.: Late Miocene Geology and Palaeontology. Palaeontos 7, 62–189.

Schnetler, K.I. & Beyer, C. 1987: A late Chattian (Chattian B) mollusc fauna from the clay-pit of Galten Brickworks at Nørre Vissing, Jylland, Denmark. Mededelingen van de Werkgroep voor Tertiaire en Kwartaire Geologie (Contributions to Tertiary and Quaternary Geology) **24**, 193–224.

Schnetler, K.I. & Beyer, C. 1990: A Late Oligocene (Chattian B) molluscan fauna from the coastal
cliff at Mogenstrup, North of Skive, Jutland, Denmark. Contribution to Tertiary and Quatenary Geology **27**, 39–81.

Steeman, M.E. (2009): A new baleen whale from the Late Miocene of Denmark and early mysticete hearing. Palaeontology **52**, 1169–1190.

Sorgenfrei, T. 1940: Marint Nedre-Miocæn i Klintingehoved paa Als: Danmarks Geologiske Undersøgelse, II. Række, **65**, 143 pp.

Sorgenfrei, T. 1958: Molluscan assemblages from the marine Middle Miocene of South Jutland and their environments. Danmarks geologiske Undersøgelse, Serie II, **79**, 503 pp.

Sorgenfrei, T. & Berthelsen, A. 1954. Geology and Water Well Boring. Geological Survey of Denmark, Serie III, **106**, 106 pp.

Spjeldnæs, N. 1975: Palaeogeography and facies distribution in the Tertiary of Denmark and surrounding areas. Norges Geologiske Undersøgelse **316**, 289–311.

Utescher, T., Mosbrugger, V. & Ashraf, A.R. 2000: Terrestrial climate evolution in Northwest Germany over the last 25 million years: Palaios **15**, 430–449.

Utescher, T., Mosbrugger, V., Ivanov, D. & Dilcher, D.L. 2009: Present-day climatic equivalents of European Cenozoic climates. Earth and Planetary Science Letters **284**, 544–552

Vejbæk, O.V. 1992: Geodynamic modelling of the Danish Central Trough. In: R.M. Larsen, H. Brekke, B.T. Larsen & E. Telleraas (eds.): Structural and Tectonic Modelling and its application to Petroleum Geology. Elsevier, Amsterdam, Norwegian Petroleum Society, Special Publication **1**, 1–17.

Vejbæk, O.V. 1997: Dybe strukturer i danske sedimentære bassiner. Geologisk Tidsskrift **4**, 1–21.

Vejbæk, O.V. & Andersen, C. 2002: Post mid-Cretaceous inversion tectonics in the Danish Central Graben – regionally synchronous tectonic events. Geological Society of Denmark, Bulletin **49**, 139–144.

Vinken, R. (ed.) 1988: The Northwest European Tertiary Basin. Geologische Jahrbuch A, 100, 7–508, Hannover.

Wagner, P. & Koch, B.E. 1974: Fossil roots of Sequoia type from two localities of the Miocene delta deposits of the Søby Area. Geological Society of Denmark Bulletin **23**, 134–58.

Weibel, R. 1996: Petrified wood from an unconsolidated sediment, Voervadsbro, Denamrk. Sedimentary Geology **101**, 31–41.

Williams, G.L., Brinkhuis, H., Pearce, M.A., Fensome, R.A. & Weegink, J.W. 2004: Southern ocean and global dinoflagellate cyst events for the latest Cretaceous-Neogene. In: Exon, N.F. *et al.* (eds.): Proceedings of the Ocean Drilling Program, Scientific Results **189**, 98 pp.

Zachos, J.C., Pagani, M., Sloan, L., Thomas, E. & Billups, K. 2001: Trends, rhythms, and aberrations in global climate 65 Ma to Present. Science **292**, 686–693.

Ziegler, P.A. 1982: Geological atlas of Western and central Europe. Amsterdam, Elsevier, 130 pp.

Ziegler, P.A. 1991: Geological atlas of Western and Central Europe. Geological Society Publication, Bath, UK. 239 pp.

Ziegler, P.A., Cloetingh, S., Van Wees, J.D. 1995: Geodynamics of intraplate compressional deformation: The Alpine foreland and other examples. Tectonophysics **252**, 7–59.

Figure captions

Fig. 1. Palaeogeographic reconstruction of the NW Europe during Early Miocene (modified from Rasmussen *et al.* 2008).

Fig. 2. Structural elements in the study area. Modified from Berthelsen (1992) and Håkansson & Pedersen (1992).

Fig. 3. Pre-Quaternary subcrop map of Denmark. Modified from Sorgenfrei & Berthelsen (1954)

Fig. 4. The Miocene lithostratigraphy for the Danish area defined by Rasmussen (1961).

Fig. 5. Map showing boreholes, outcrops and seismic data used in the study. Selected towns and villages are indicated.

Fig. 6. New lithostratigraphy of the Danish Miocene.

Fig. 7. Type and reference section for the Brejning Formation. The type section is the Dykær outcrop located southwest of Juelsminde and the reference section is the interval from 96,5–100,90 m in the Andkær borehole (DGU no. 125.2017). The accompanying legend is applicable for all outcrop logs and boreholes shown in this study.

Fig. 8. The Brejning Formation at Øksenrade showing the lower part of the formation and the lower boundary towards the light greenish-grey Eocene Søvind Marl Formation (Photo courtesy Peter Warna-Moors). Red foldknife for scale, c. 10 cm long.

Fig. 9. The distribution of latest Oligocene – Miocene formations and members in Denmark.

Fig. 10. Type and reference section for the Øksenrade Member. The type section is the Øksenrade outcrop located southwest of Middelfart. The reference section is the interval from 210–212 m in the Gadbjerg borehole (DGU no. 115.1474).

Fig. 11. Brejning Formation and the Øksenrade Member at the coastal cliff at Øksenrade Skov, southwest of Middelfart. This outcrop constitute the type section for the Øksenrade Member. Spade for scale.

Fig. 12. The boundary between Brejning Formation and Øksenrade Member by the distinct change from black, clayey silt to red sand. Lense cap for scale.

Fig. 13. Type and reference section for the Ribe Group. The type section is the gravel pit at Voervadsbro located southeast of Silkeborg. The reference section is the interval from 3–219 m in the StoreVorslunde borehole (DGU no. 104.2325) northeast of Vejle.

Fig. 14. Type and reference section for the Vejle Fjord Formation. The type section is the Dykær outcrop located southwest of Juelsminde. The reference section is the interval from 166–219 m in the Store Vorslunde borehole (DGU no. 104.2325) north-east of Vejle.

Fig. 15. The Vejle Fjord Formation at Skansebakke near Brejning. Spade for scale.

Fig. 16. Hummocky cross-stratified sand from the upper part of the Vejle Fjord Formation at Jensgård, east of Horsens. The ruler is 1 m.

Fig 17. Hummocky cross-stratified sand with burrows (*Echinocardium cordatum*?) from the Vejle Fjord Formation, at Skyum. Note that the sand layer is only burrowed in the upper part. Most of the Vejle Fjord Formation was deposited as alternating sand and clayey, silt layers, but due to bioturbation any stratification was later destroyed and only thicker storm sand layers were preserved. Knife blade for scale.

Fig. 18. Type and reference section for the Skansebakke Member. The type section is the Skansebakke outcrop located at Brejning east of Vejle. The reference section is the interval from 79–91.10 m in the Andkær borehole (DGU no. 125.2017).

Fig. 19. Alternating fine-grained sand and clay of the Skansebakke Member. The clay was deposited in a lagoon and the sand was deposited as washover fans during the degradation of a barrier island associated with an Early Miocene transgression. Spade for scale.

Fig. 20. Type and reference section for the Billund Formation. The type section is the interval from 184–235 m in the Billund borehole (DGU no. 114.1857) and the reference section is the interval from 126–166 m in the Store Vorslunde borehole (DGU no. 104.2325).

Fig. 21. Marine sand and fluvial gravel and sand of the Billund Formation exposed at Voervadsbro. Note the *Scolithos* burrows indicating a marine depositional environment. The lower boundary of the fluvial deposits (Addit Member) is at the base of the gravel layer. The section is 2 m high.

Fig. 22. Tidal bundles exposed at Pjedsted, southeast of Vejle. The cross-bedding is dipping towards the southwest and thus represent deposits formed by ebb currents. Note the clay drapes and bottom sets both in the right and left side of the photo. These parts of the succession were laid down during neap tide. Consequently, the cross bedded section represent a neap – spring – neap cycle (c. one and a half month). The section is 1,5 m high. Photo Ole Rønø Clausen

Fig. 23. Type and reference section for the Hvidbjerg Member. The type section is the Hvidbjerg outcrop located southeast of Vejle. The reference section is the interval from 58–79 m in the Andkær borehole (DGU no. 125.2017).

Fig. 24. The outcrop at Hvidbjerg exposes c. 26 m of white sand that was deposited in a spit system east of the main delta lobe of the Billund Formation. Note the stratification which is formed by the most bioturbated parts of the succession.

Fig. 25. Hummocky cross-stratified sand of the Billund Formation (Hvidbjerg Member) overlying alternating hummocky stratified sand and clay of the Vejle Fjord Formation at Hindsgavl near Middlefart.

Fig. 26. Type and reference section for the Addit Member. The type section is the Addit gravel pit located southeast of Silkeborg.The reference section is the interval from 51–117 m in the Addit Mark borehole (DGU no. 97.928).

Fig. 27. Addit Member at Addit gravel pit showing the two sand- and gravel-rich units and the intercalated coal horison. Each unit shows a fining upward trend. The height of the section is 40 m.

Fig. 28. Cross-bedded sand and gravel of the Addit Member deposited as a mid channel bar in a braided fluvial system. The height of the section is 3 m.

Fig. 29. Type and reference section for the Klintinghoved Formation. The type section is the outcrop at Klintinghoved east of Sønderborg. Here 3.5 m of the formation is exposed. The reference section is the interval from 194–288 m in the Sdr. Vium borehole (DGU no. 102.948).

Fig. 30. View of the Klintinghoved outcrop seen from the east. The cliff is c. 10 m high.

Fig. 31. Alternating clay and bioturbated and laminated sand of the Klintinghoved Formation. Note the double clay layers in the sand indicating a tidal influence on deposition.

Fig. 32. Laminated, darkbrown clayey silt and thin fine-grained sand of the Klintinghoved Formation.

Fig. 33. Darkbrown silty clay and sharp based sand beds of the Klintinghoved Formation. The sand beds are normaly graded and homogenous to weakly laminated in the lower part. Note the double clay layers indicating a tidal influence on sedimentation.

Fig. 34. Type and reference section for the Kolding Fjord Member. The type section is the exposure at Rønshoved, east of Kolding. The reference section is the outcrop at Hagenør.

Fig. 35. Heterolithic deposits of the Kolding Fjord Member sharply overlain by hummocky cross-stratified sand at the Rønshoved outcrop. The heterolithic succession is characterised by alternating hummocky cross-stratified sand and sandy clay and various types of ripple lamination. The section at the photo is 3 m high.

Fig. 36. The Kolding Fjord Member at Hagenør. The lower part of the Hagenør outcrop is characterised by two organic-rich, clayey, silt deposits separated by bioturbated sand. The upper part of the exposure is dominated by alternating sand and clay layers. The sand beds are typically sharp based, homogenous to weakly laminated in the lower part and capped by wave- or current-ripples. Persons for scale.

Fig. 37. Close-up of the lagoonal deposits at Hagenør. The light brown deposits capped by sand ripples sandwiched between the dark lagoonal clay represent at short period of marine incursion. The strik of the the crest of the rippled sand is northwest–southeast. The section is c. 2 m high.

Fig. 38. Close-up of the alternating sand and clay layers exposed in the upper part of the Hagenør section. Spade for scale.

Fig. 39. Type and reference section for the Bastrup Formation. The type section is from 84–107 m in the Bastrup borehole (DGU no. 133.1298). The reference section is from 111–164 m in the Almstok borehole (DGU no. 114.1858).

Fig. 40. Type section and reference borehole for the Resen Member. The section from 70–120 m in the Hammerum borehole (DGU no. 85.2429) is designated as the type section. The reference section is the interval from 67–101 m in the Egtved borehole (DGU no. 124.1159).

Fig. 41. Type and reference section for the Arnum Formation. The type section is the interval from 60.90–153.75 m in the cored borehole Sdr. Vium (DGU no. 102.948). The reference section is the interval from 37–56 m in the Store Vorslunde borehole (DGU no. 104.2325).

Fig. 42. Two cores from the Sdr. Vium borehole (DGU no. 102.948) showing typical lithologies of the Arnum Formation; A) bioturbated clay with a thin layer of glaucony, B) Dark brown clayey silt and hummocky cross-stratified sand.

Fig. 43. Type and reference section for the Vandel Member. The type section is the interval from 102–114 m in the Vandel Mark borehole (DGU no. 115.1371). The reference section is the interval from 97–100 m in the Grindsted borehole (DGU no. 114.2038).

Fig. 44. Type and reference section for the Odderup Formation. The type section is the interval from 3–37 m in the Store Vorslunde borehole (DGU no. 104.2325). The reference section is the intervals from 41–90 m and from 110–118 m in the Rødding borehole (DGU no. 141.1141).

Fig. 45. Low angle cross-bedded sand with heavy minerals from the Odderup Formation. The sand was deposited in the swash zone of a beach. The height of the section on the photo is 0.4 m.

Fig. 46. Type and reference section for the Stauning Member. The type section is the intervals from 62–72 m and from 78–97 m in the Vandel Mark Borehole (DGU no. 115.1371). The reference section is the intervals from 66–90 m and from 110–118 m in the Rødding borehole (DGU no. 141.1141).

Foto. 47. Typical lithologies of the Stauning Member: A) Hummocky cross-stratified sand interbedded in drak brown silty clay. B) Heterolithic deposits with some indication of double clay layers. Note the smale scale faulting of the succession. These might be associated with earth quakes.

Fig. 48. Type and reference section for the Fasterholt Member. The type section is the Fasterholt Brown Coal Pit northwest of Brande. The pit is closed now. Sediment section

is redrawn from Koch (1989). The reference section is the interval from 13–15 m m in the Store Vorslunde borehole (DGU no. 104.2325).

Fig. 49. Type and reference section for the Måde Group. The type section is the interval from 24–52 m in the cored Sdr. Vium borehole (DGU no. 102.948). The reference section is the interval from 50–197 m in the Tinglev Borehole (DGU no. 168.1378).

Fig. 50. Photo of the open pit at Lille Spåbæk, Ørnhøj where the Hodde, Ørnhøj and Gram Formations were exposed in the late 70th. These three formations and the Marbæk Formation constitutes the Måde Group. The cliff is c. 10 m high.

Fig. 51. Type and reference section for the Hodde Formation. The type section is the interval from 44.80–52 m in the cored Sdr. Vium borehole (DGU no. 102.948). The referece section is the interval from 39–50 m in the Føvling borehole (DGU no. 132.1835).

Fig. 52. The upper part of the Hodde Formation at Lille Spåbæk, Ørnhøj. Spade for scale.

Fig. 53. Close-up of the Hodde Formation. The Hodde Formation is composed of dark brown clayey silt. The yellowish stripes are due to weathering of pyrite. The section is 0.5 m high.

Fig. 54. The type and reference section for the Ørnhøj Formation. The type section is the interval from 41–44.80 m in the cored Sdr. Vium borehole (DGU no. 102.948). The reference section is the interval from 34–40 m in the Føvling borehole (DGU no. 132.1835).

Fig. 55. The Ørnhøj Formation at Lille Spåbæk, Ørnhøj. The lower boundary towards the Hodde Formation is seen in the lower part of the section. Knife for scale, c. 20 cm long.

Fig. 56. Type and reference section for the Gram Formation. The type section is at Gram Clay pit near Gram. Here 13.1 m of the formation is exposed. The reference section is the interval from 24–41 m in the cored Sdr. Vium borehole (DGU no. 102.948).

Fig. 57. Fine-grained, partly biotubated sand intercalated in the upper part of the Gram Formation. The sand beds are commonly wave-rippled. The section is 0.30 m high.

Fig. 58. Type and reference section for the Marbæk Formation. The type section is at the coastal clif at Marbæk northwest of Esbjerg. Here 15 m of the formation are exposed. The reference section is the interval from 50–65 m in the Tinglev borehole (DGU no. 168.1378).

Fig. 59. Oblique view of the Marbæk Formation at Marbæk, northwest of Esbjerg. Two persons in the upper right for scale.

Fig. 60. Hummocky cross-stratified sand of the Marbæk Formation. The section on the photo is 50 cm high.

Fig. 61. Glacial disturbed sand of the Marbæk Formation, but homogenous sand and wave-rippled sand typical for upper shoreface deposits can be seen. The section is 0.4 m high.

Fig. 62. N–S trending seismic section tying the Store Vorslunde, Billund and Almstok boreholes. Delta lobes characterised by oblique-parallel reflection pattern is indicated in yellow. This pattern correlates to sand-rich delta lobe deposits. Note the alternation of these sand-rich delta deposits and more clay-rich inter delta deposits which is so characteristic for the Vejle Fjord–Billund Formations and the Klintinghoved–Bastrup Formations. The upper part of section is dominated by a parallel to subparallel reflection pattern which is characteristic for the Arnum–Odderup Formation and indicate a change in sedimentation pattern of these formations.

Fig. 63. Seismic section close up at Store Vorslunde area where the sand-rich part of the deltas are indicated in yellow. Sand-rich fluvial deposits of the Addit and Resen Members are shown in red respectively.

Fig. 64. E–W striking Seismic section at Ikast. The section shows a cross-section of the Billund and Bastrup delta system as indicated by dipping reflectors both towards the west and east. In this area the fluvial systems of the Addit and Resen Members, shown in red, are particularly well developed.

Fig. 65. Two typical correlation panels showing the overall architecture of the Miocene succession in Denmark. A) North–south trending section from Resen to Løgumkloster. Note the characteristic shift of delta lobes that is so common during the progradation of the Billund and Bastrup Formations and the more regular and aggrading system of the Odderup Formation. B) East–west striking section from Morsholt to Stauning. Note that the main delta lobes are pinching out both to the east and to the west.

Fig. 66. Palaeogeographic reconstruction of the latest Late Oligocene Brejning Formation. The exact location of the shoreline is uncertain, but most of Jylland was marine at that time. Water depth in northern Jylland was over 200 m and formation of glaucony dominates indicating a certain distance to the shoreline.

Fig. 67. Palaeogeographic reconstruction of earliest Early Miocene (ealiest Aquitanian) Vejle Fjord Formation. Due to Early Miocene inversion reactivation of the Ringkøbing–Fyn High and salt structured a barrier between the eastern part of the Norwegian–Danish Basin and the North Sea Basin was formed. This resulted in brackish water environment northeast of the the Ringkøbing–Fyn High. Note that small spit systems developed east of these structures. The degradation of these spit systems during the Early Miocene transgression resulted in the formation of the Skansebakke Member.

Fig. 68. Palaeogeographic reconstruction of Early Miocene (Aquitanian) Billund and Vejle Fjord Formations. The sea level continued to rise during this phase and flooded the Ringkøbing–Fyn High. However, due to high sediment supply to the basin, the shoreline prograded southward. This favoured the formation of spit/barrier complexes southeast of the main delta lobes which consistute the Hvidbjerg Member of the The

Billund Formation. The river system during the Early Miocene was dominantly braided rivers.

Fig. 69. Palaeogeographic reconstruction of of Early Miocene (late Aquitanian) Billund Formation. During this period the relative sea-level fall and progradation of the shoreline is reflected by amalgamation of beach ridges along the coast. Distinct incision and formation of broad valleys commenced at the same time.

Fig. 70. Palaeogeographic reconstruction of Early Miocene (early Burdigalian) Klintinghoved Formation and Kolding Fjord Member. A global climatic warming resulted in a relative rise in sea level. The shoreline was characterised by eatuaries and associated barrier complexes and the formation of braided fluvial deposits occurred within incised valleys.

Fig. 71. Palaeogeographic reconstruction of Early Miocene (early Burdigalian) Klintinghoved Formation. During the most widespread flooding in the early Burdigalian most of western and central Jylland was covered by the sea and the deposition of the Klintinghoved Formation took place here.

Fig. 72. Palaeogeographic reconstruction of the Early Miocene (early Burdigalian) Bastrup Formation. The progradation occurred during rising relative sea level which formed optimal conditions for a shoreline dominated by lagoons and barrier islands. The fluvial system was dominated by meandering river systems.

Fig. 73. Palaeogeographic reconstruction of the Early Miocene (Burdigalian) Bastrup Formation. During this period the relative sea level fall and the prograding shoreline was characterised by amalgamation of beach ridges parallel to the coast. Distinct incision on land and formation of broad valleys commenced at the same time.

Fig. 74. Palaeogeographic reconstruction of the Early Miocene (Burdigalian) Bastrup Formation. During this part of the Miocene most parts of Jylland was land. The progradation took place during rising sea level.

Fig. 75. Palaeogeographic reconstruction of the late Early Miocene (late Burdigalian) Arnum Formation. The shoreline was located across the northern part of Jylland.

Fig. 76. Palaeogeographic reconstruction of the late Early Miocene (late Burdigalian) Odderup Formation. During this time period the climate became subtropical and the global sea level rose. High sediment supply, however, forced the shoreline to prograde. These condition favoured formation of lagoons and swamp lakes which were optimal for the formation of coal-rich deposits.

Fig. 77. Palaeogeographic reconstruction of the early Middle Miocene (early Langhian) Odderup Formation. During the maximum regression of the shoreline most of Jylland was land only the south western part was covered by the sea. Lagoonal–swamp conditions prevailed north of the Ringkøbing–Fyn High probably favoured by increased subsidence in this area.

Fig. 78. Palaeogeographic reconstruction of Middle Miocene (Serravallian) Ørnhøj Formation. Despite a climatic deterioration in the Middle Miocene most of Jylland was flooded and the shoreline was located in the northern part of Jylland. Due to a very low sedimentation rate optimal conditions excisted for the formation of glaucony.

Fig. 79. Palaeogeographic reconstruction of Late Miocene (Tortonian) Gram Formation. In the latest part of the Miocene distinct uplift of Scandinavian and the Alpine mountains resulted in extreme high sediment supply into the North Sea Basin. This resulted in marked progradation from both the north and south.

Fig. 80. Palaeogeographic reconstruction of Late Miocene (Tortonian) Marbæk Formation. The marked progradation of the shoreline during the Late Miocne resulted in subaerial conditions in most parts of Jylland and deposition of shoreface deposits in the extreme western part of Jylland. At the end of the Miocene the shoreline was located ca. 250 west of the present day west coast.

Fig. 81. Principskitse for udbygning af deltalober fra nordøst mod sydvest.

Fig.82. Principskitse for opbygningen af lithologiske enheder.

Fig. 1. *Palaeogeographic reconstruction of the NW Europe during Early Miocene (modified from Rasmussen et al. 2008).*

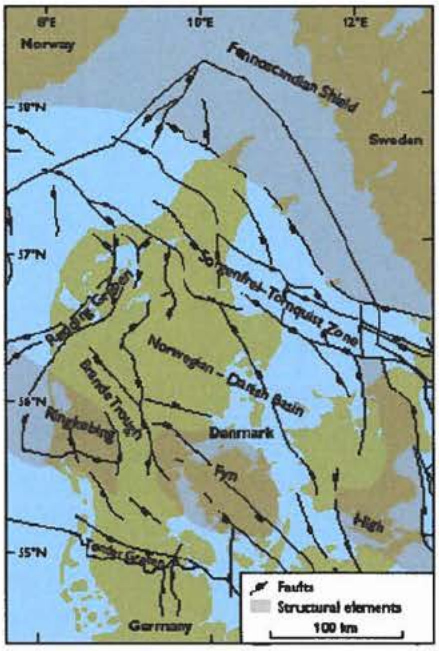

Fig. 2. *Structural elements in the study area. Modified from Berthelsen (1992) and Håkansson & Pedersen (1992).*

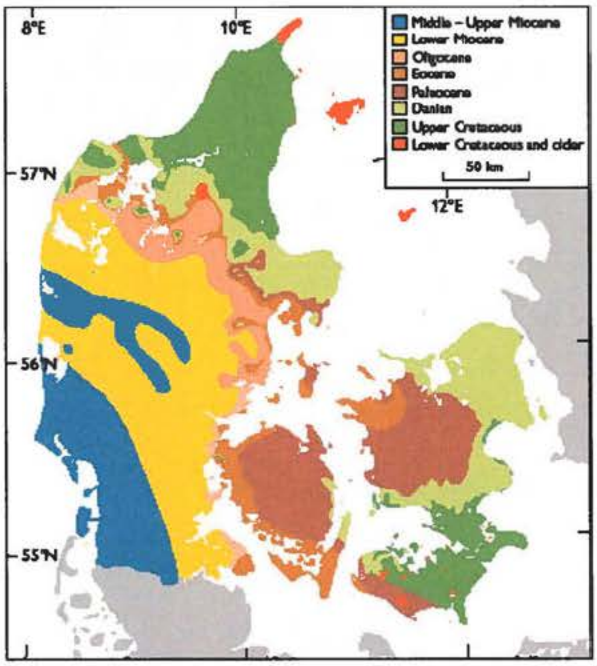

Fig. 3. *Pre-Quaternary subcrop map of Denmark. Modified from Sorgenfrei & Berthelsen (1954)*

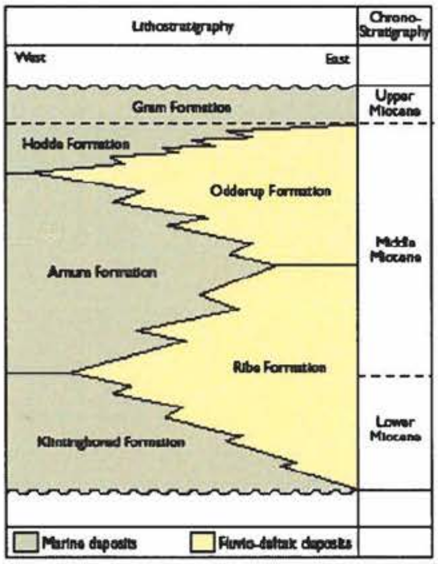

Fig. 4. *The Miocene lithostratigraphy for the Danish area defined by Rasmussen (1961).*

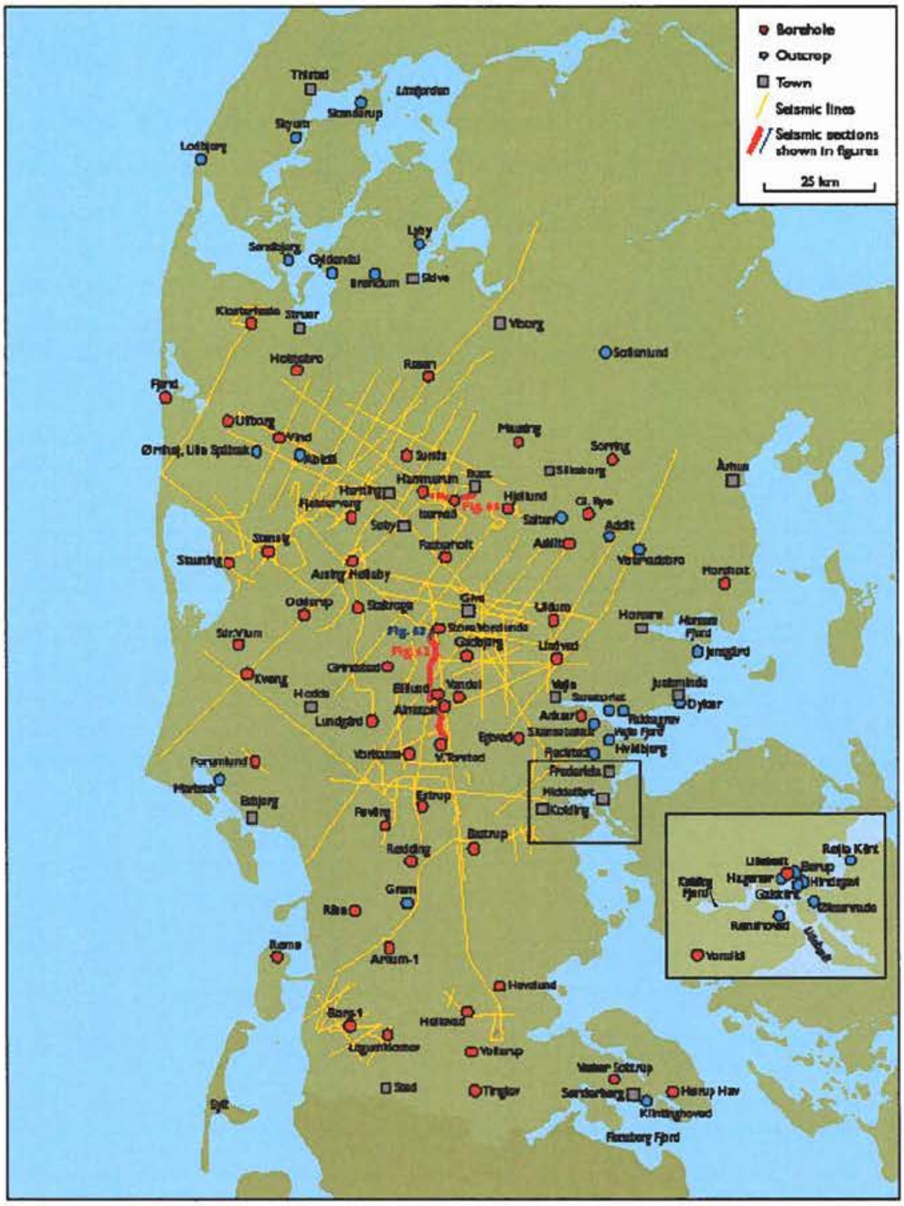

Fig. 5. *Map showing boreholes, outcrops and seismic data used in the study. Selected towns and villages are indicated.*

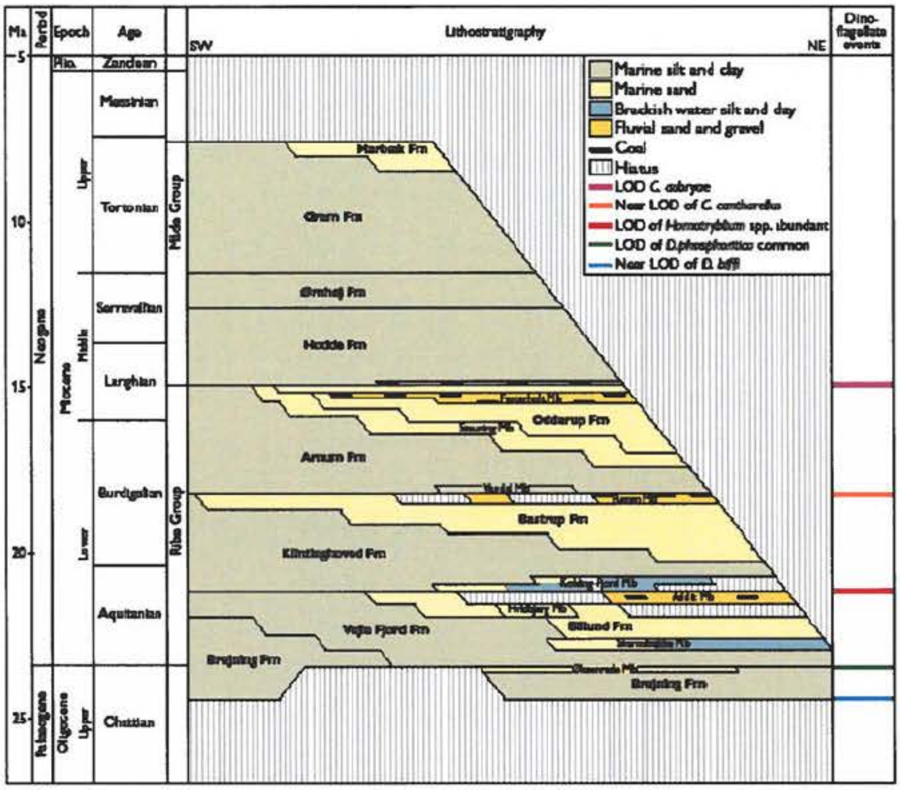

Fig. 6. *New lithostratigraphy of the Danish Miocene.*

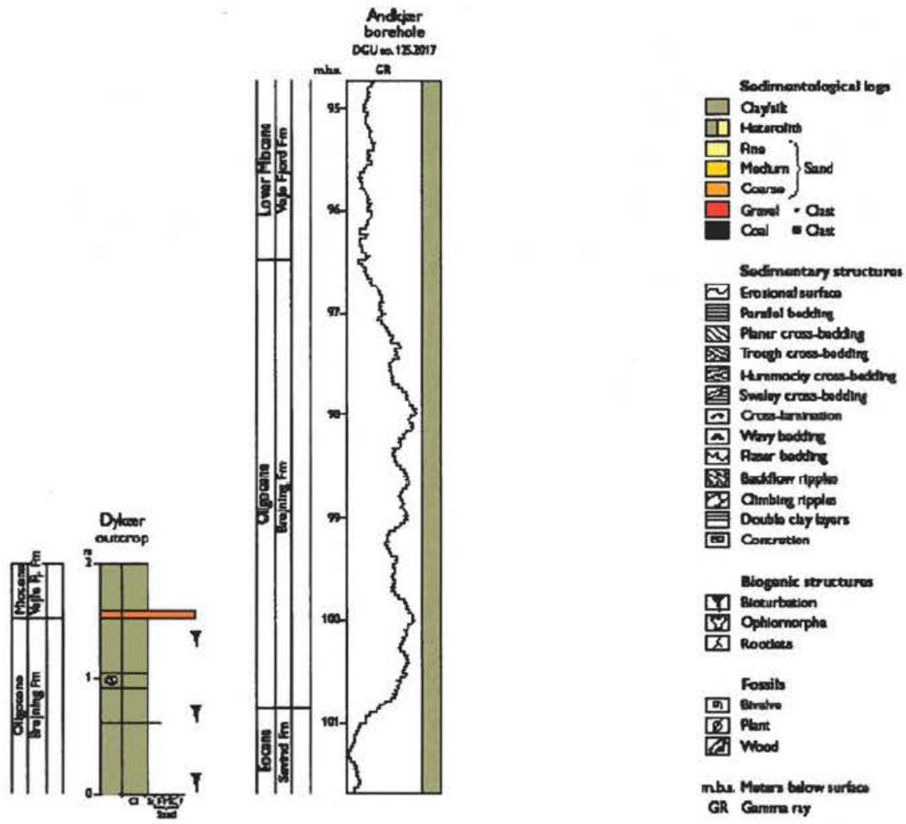

***Fig. 7.** Type and reference section for the Brejning Formation. The type section is the Dykær outcrop located southwest of Juelsminde and the reference section is the interval from 96,5–100,90 m in the Andkær borehole (DGU no. 125.2017). The accompanying legend is applicable for all outcrop logs and boreholes shown in this study.*

Fig. 8. *The Brejning Formation at Øksenrade showing the lower part of the formation and the lower boundary towards the light greenish-grey Eocene Søvind Marl Formation (Photo courtesy Peter Warna-Moors). Red foldknife for scale, c. 10 cm long.*

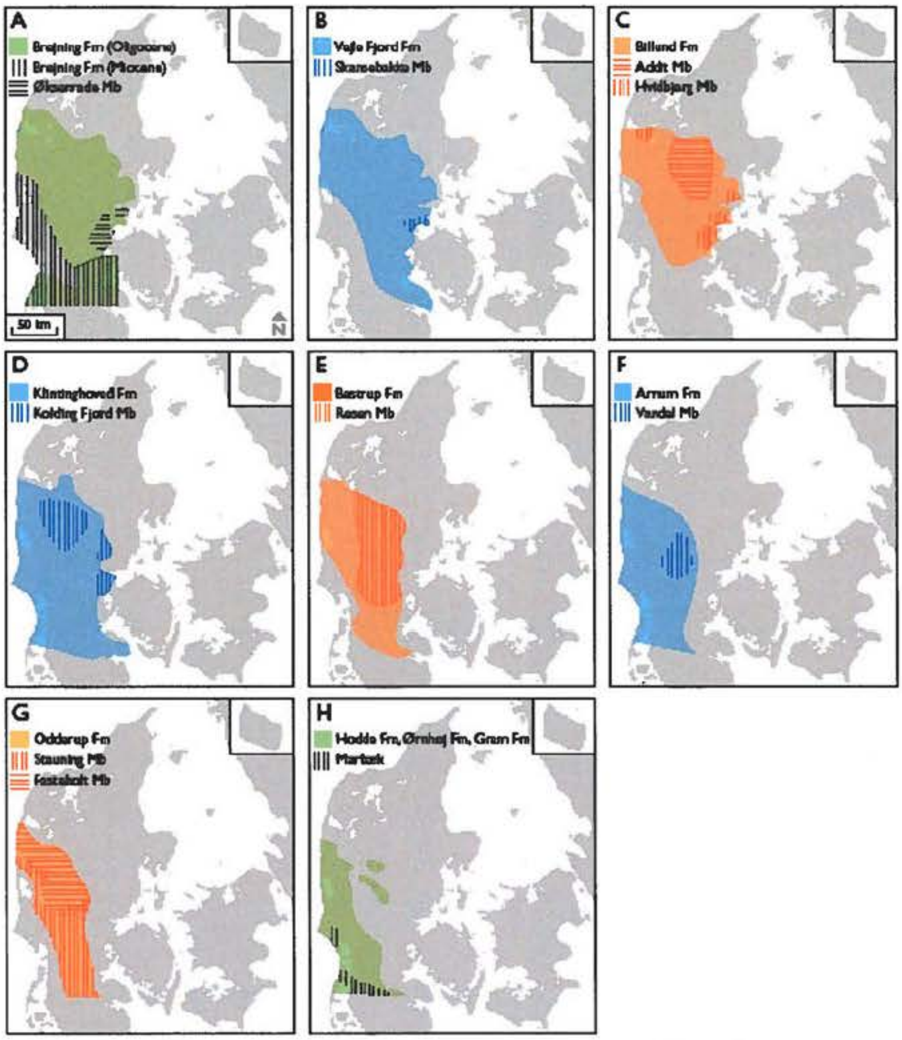

Fig. 9. *The distribution of latest Oligocene – Miocene formations and members in Denmark.*

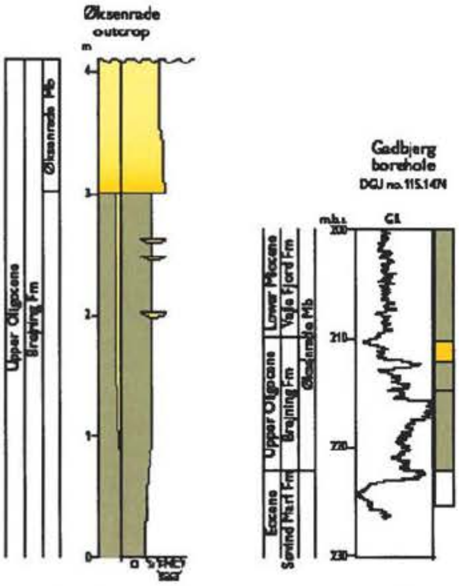

Fig. 10. *Type and reference section for the Øksenrade Member. The type section is the Øksenrade outcrop located southwest of Middelfart. The reference section is the interval from 210–212 m in the Gadbjerg borehole (DGU no. 115.1474).*

Fig. 11. *Brejning Formation and the Øksenrade Member at the coastal cliff at Øksenrade Skov, southwest of Middelfart. This outcrop constitute the type section for the Øksenrade Member. Spade for scale.*

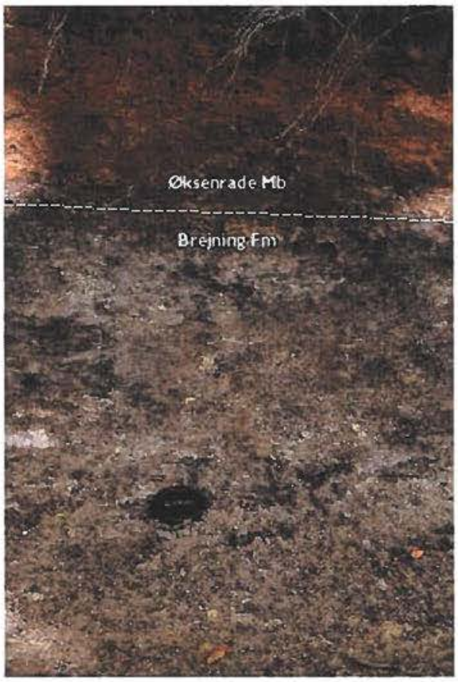

***Fig. 12.** The boundary between Brejning Formation and Øksenrade Member by the distinct change from black, clayey silt to red sand. Lense cap for scale.*

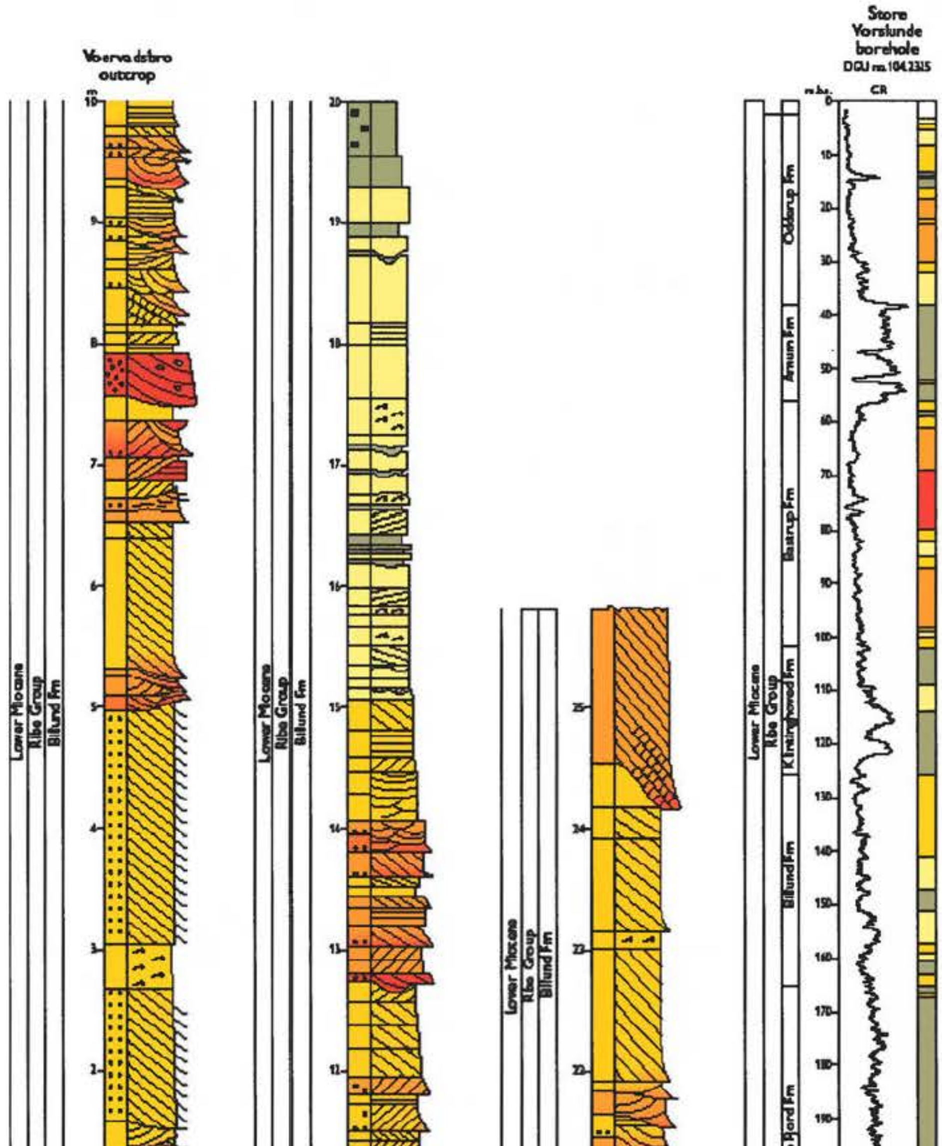

Fig. 13. *Type and reference section for the Ribe Group. The type section is the gravel pit at Voervadsbro located southeast of Silkeborg. The reference section is the interval from 3–219 m in the Store Vorslunde borehole (DGU no. 104.2325) northeast of Vejle.*

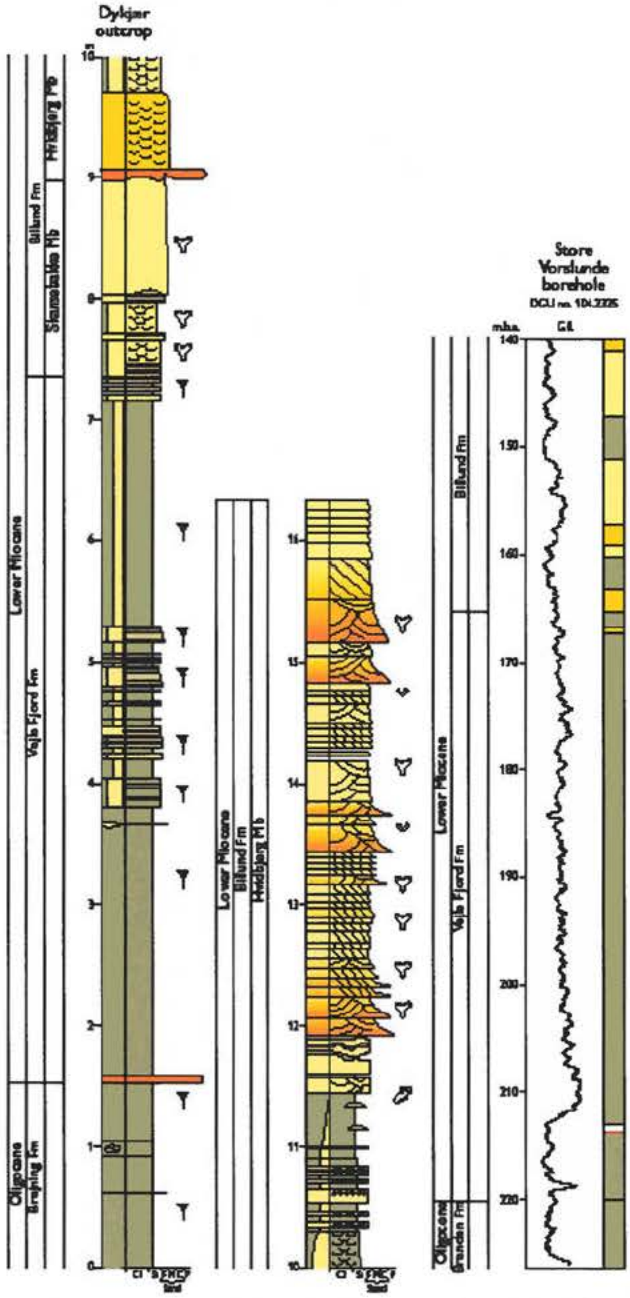

Fig. 14. *Type and reference section for the Vejle Fjord Formation. The type section is the Dykær outcrop located southwest of Juelsminde. The reference section is the interval from 166–219 m in the Store Vorslunde borehole (DGU no. 104.2325) north-east of Vejle.*

Fig. 15. The Vejle Fjord Formation at Skansebakke near Brejning. Spade for scale.

Fig. 16. *Hummocky cross-stratified sand from the upper part of the Vejle Fjord Formation at Jensgård, east of Horsens. The ruler is 1 m.*

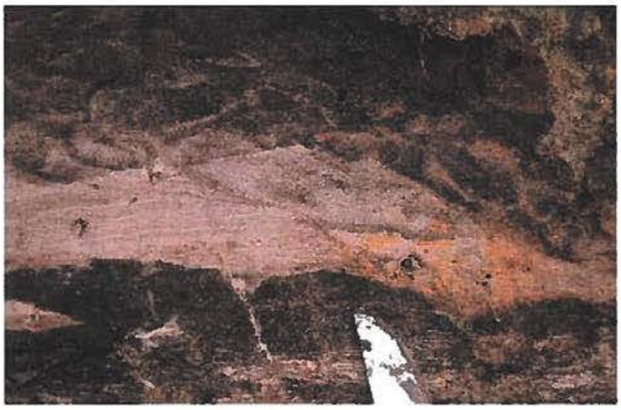

Fig 17. *Hummocky cross-stratified sand with burrows (Echinocardium cordatum?) from the Vejle Fjord Formation, at Skyum. Note that the sand layer is only burrowed in the upper part. Most of the Vejle Fjord Formation was deposited as alternating sand and clayey, silt layers, but due to bioturbation any stratification was later destroyed and only thicker storm sand layers were preserved. Knife blade for scale.*

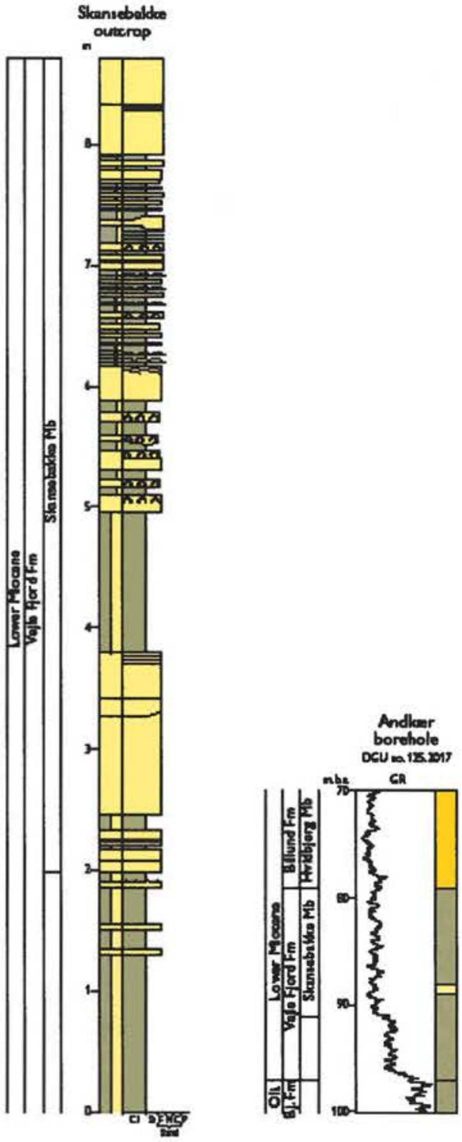

Fig. 18. *Type and reference section for the Skansebakke Member. The type section is the Skansebakke outcrop located at Brejning east of Vejle. The reference section is the interval from 79–91.10 m in the Andkær borehole (DGU no. 125.2017).*

Fig. 19. *Alternating fine-grained sand and clay of the Skansebakke Member. The clay was deposited in a lagoon and the sand was deposited as washover fans during the degradation of a barrier island associated with an Early Miocene transgression. Spade for scale.*

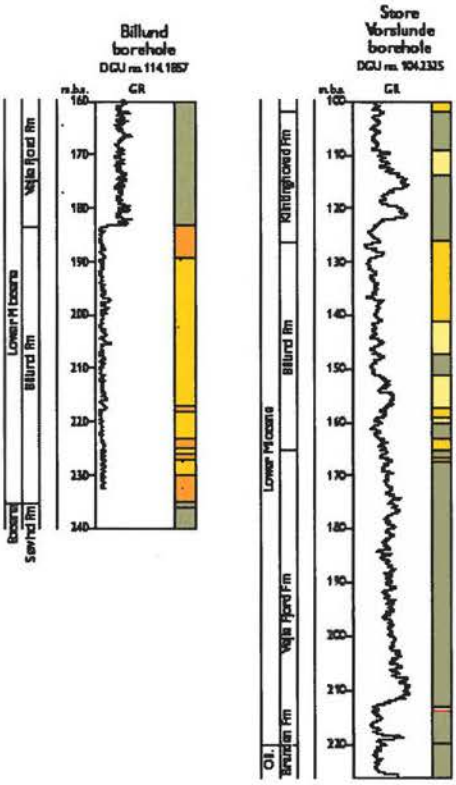

Fig. 20. *Type and reference section for the Billund Formation. The type section is the interval from 184–235 m in the Billund borehole (DGU no. 114.1857) and the reference section is the interval from 126–166 m in the Store Vorslunde borehole (DGU no. 104.2325).*

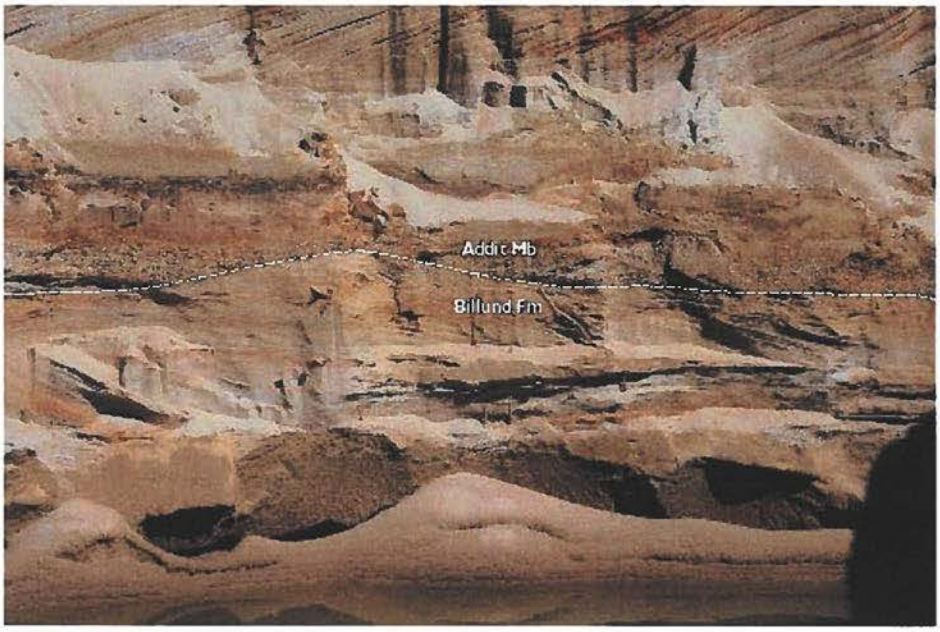

Fig. 21. *Marine sand and fluvial gravel and sand of the Billund Formation exposed at Voervadsbro. Note the Scolithos burrows indicating a marine depositional environment. The lower boundary of the fluvial deposits (Addit Member) is at the base of the gravel layer. The section is 2 m high.*

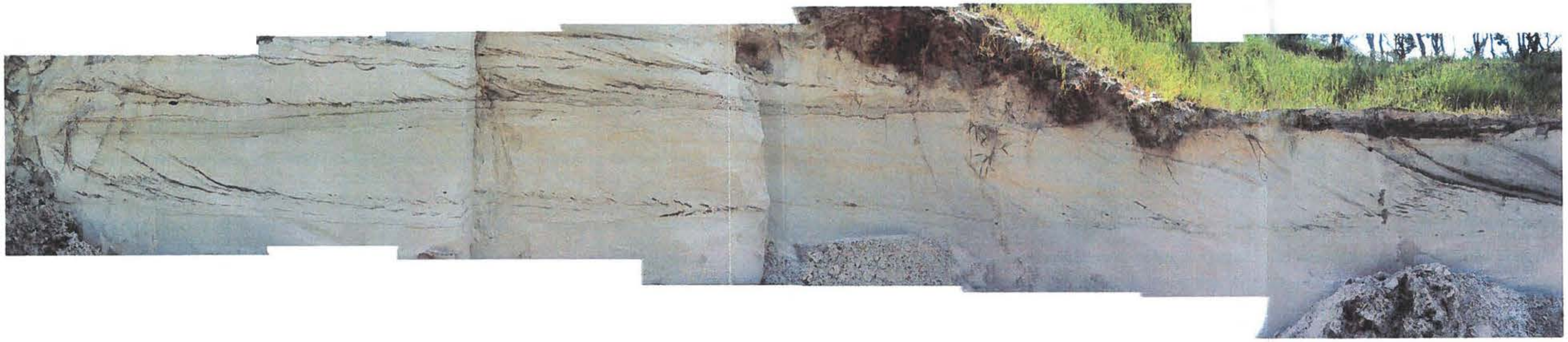

Fig. 22. *Tidal bundles exposed at Pjedsted, southeast of Vejle. The cross-bedding is* *ırrents. Note the clay drapes and bottom sets both in the right and left side of the photo. These parts of the succession were laid down during n* *- neap cycle (c. one and a half month). The section is 1,5 m high. Photo Ole Rønø Clausen*

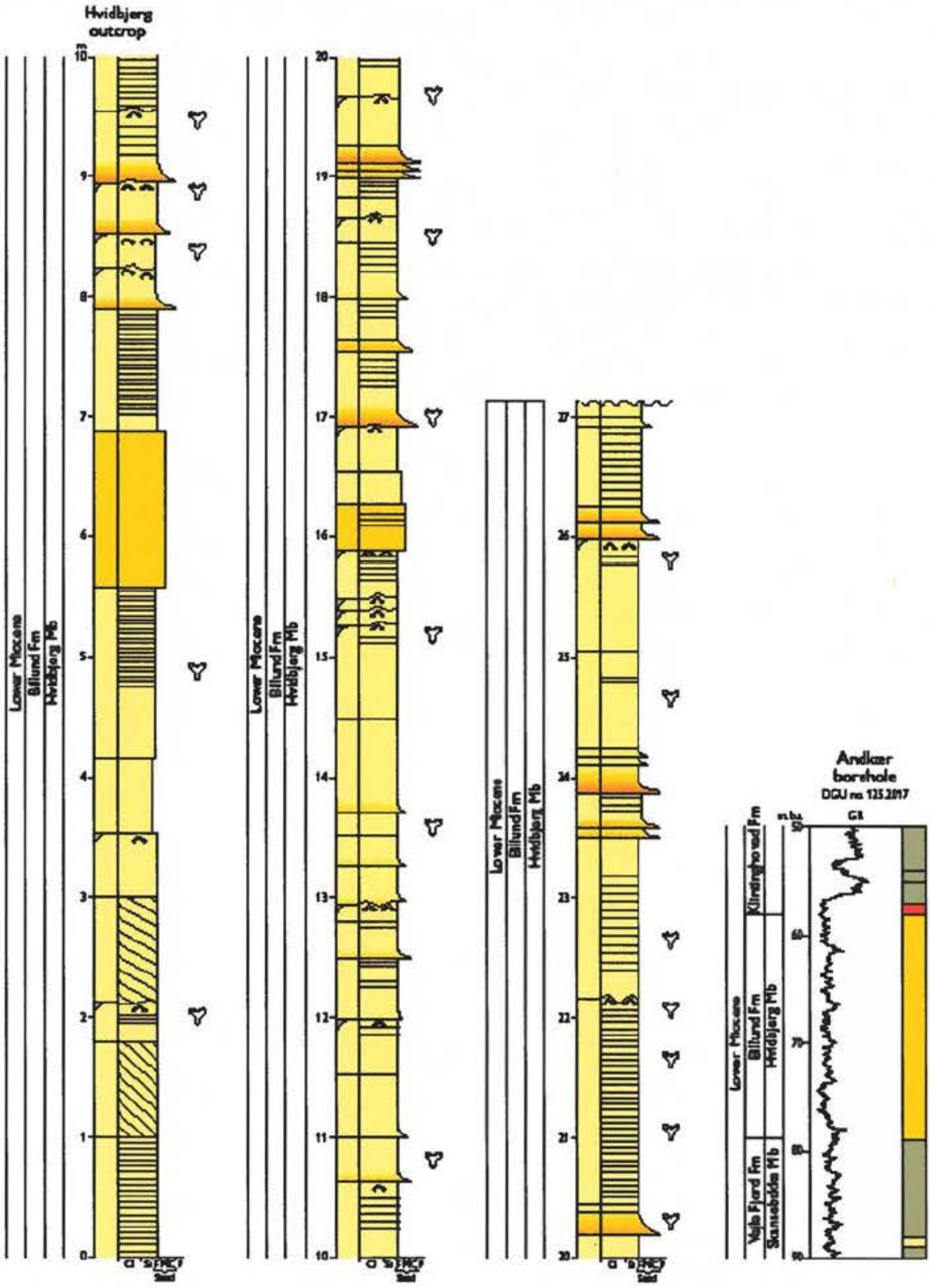

Fig. 23. Type and reference section for the Hvidbjerg Member. The type section is the Hvidbjerg outcrop located southeast of Vejle. The reference section is the interval from 58–79 m in the Andkær borehole (DGU no. 125.2017).

Fig. 24. *The outcrop at Hvidbjerg exposes c. 26 m of white sand that was deposited in a spit system east of the main delta lobe of the Billund Formation. Note the stratification which is formed by the most bioturbated parts of the succession.*

Fig. 25. *Hummocky cross-stratified sand of the Billund Formation (Hvidbjerg Member) overlying alternating hummocky stratified sand and clay of the Vejle Fjord Formation at Hindsgavl near Middlefart.*

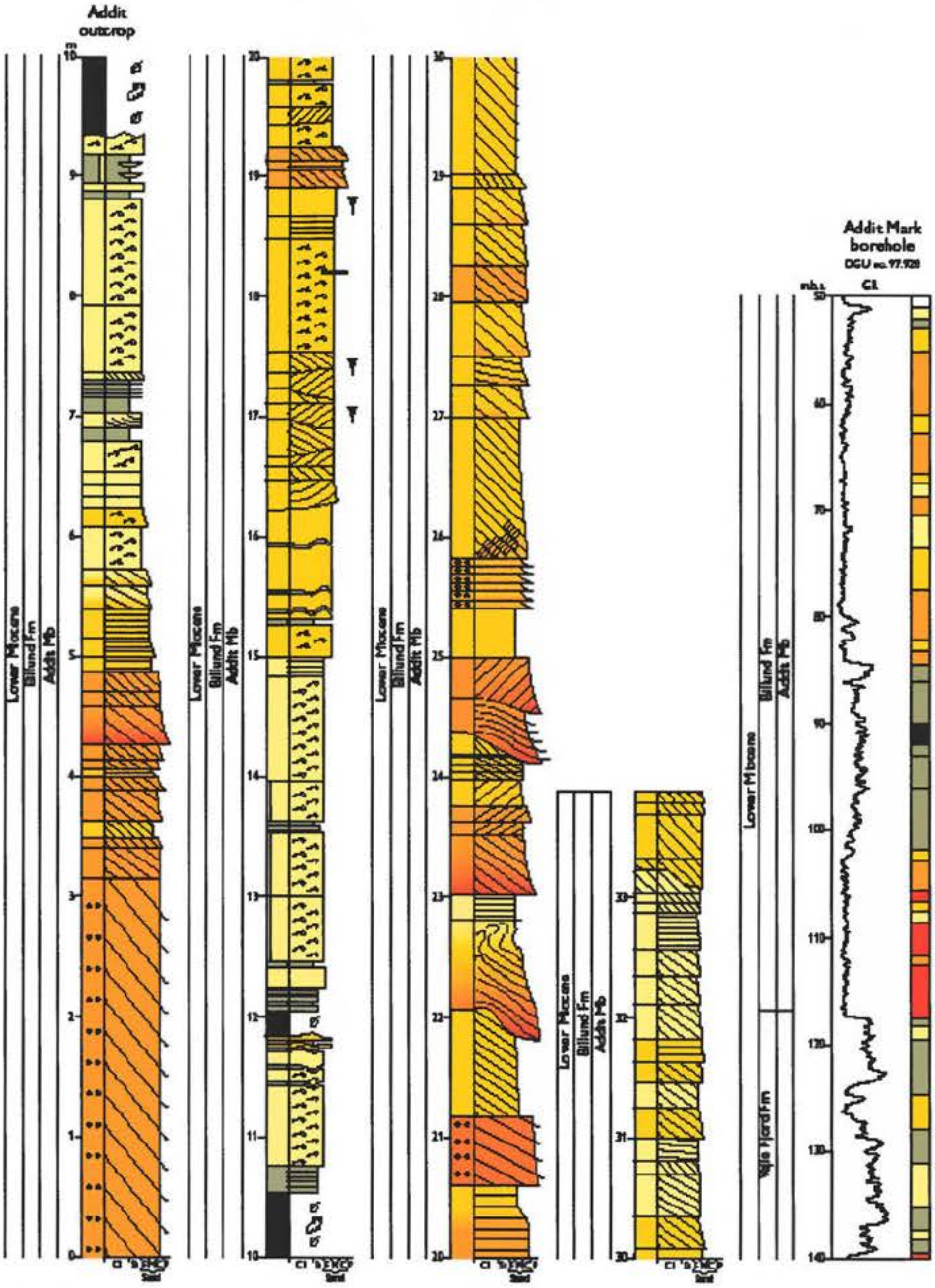

Fig. 26. *Type and reference section for the Addit Member. The type section is the Addit gravel pit located south-east of Silkeborg. The reference section is the interval from 51–117 m in the Addit Mark borehole (DGU no. 97.928).*

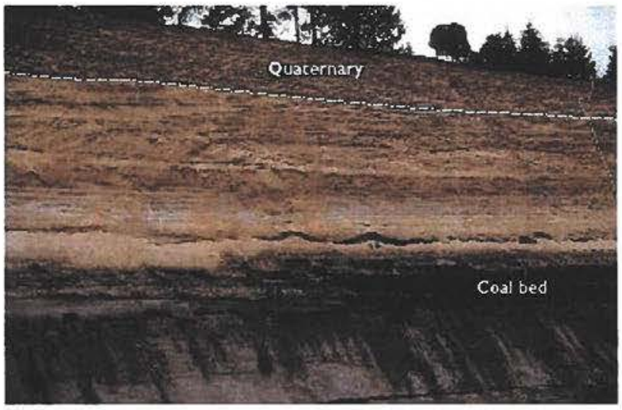

Fig. 27. Addit Member at Addit gravel pit showing the two sand- and gravel-rich units and the intercalated coal horison. Each unit shows a fining upward trend. The height of the section is 40 m.

Fig. 28. *Cross-bedded sand and gravel of the Addit Member deposited as a mid channel bar in a braided fluvial system. The height of the section is 3 m.*

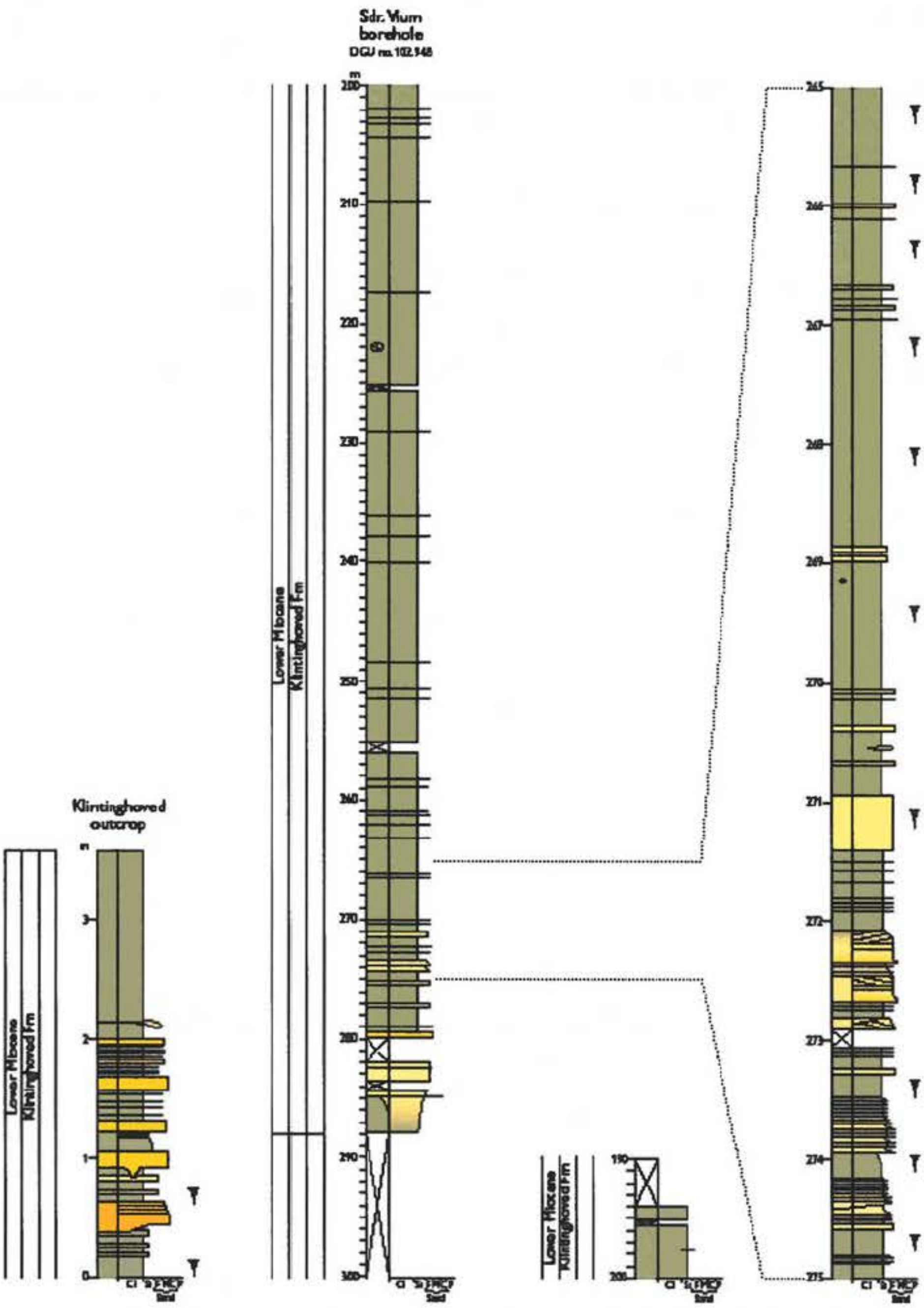

Fig. 29. Type and reference section for the Klintinghoved Formation. The type section is the outcrop at Klintinghoved east of Sønderborg. Here 3.5 m of the formation is exposed. The reference section is the interval from 194–288 m in the Sdr. Vium borehole (DGU no. 102.948).

Fig. 30. *View of the Klintinghoved outcrop seen from the east. The cliff is c. 10 m high.*

Fig. 31. ***Alternating clay and bioturbated and laminated sand of the Klintinghoved Formation. Note the double clay layers in the sand indicating a tidal influence on deposition.***

Fig. 32. *Laminated, darkbrown clayey silt and thin fine-grained sand of the Klintinghoved Formation.*

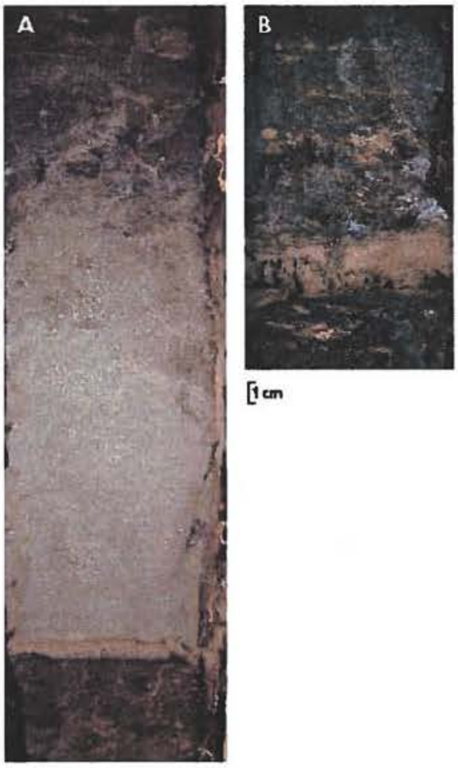

Fig. 33. Darkbrown silty clay and sharp based sand beds of the Klintinghoved Formation. The sand beds are normaly graded and homogenous to wealdy laminated in the lower part. Note the double clay layers indicating a tidal influence on sedimentation.

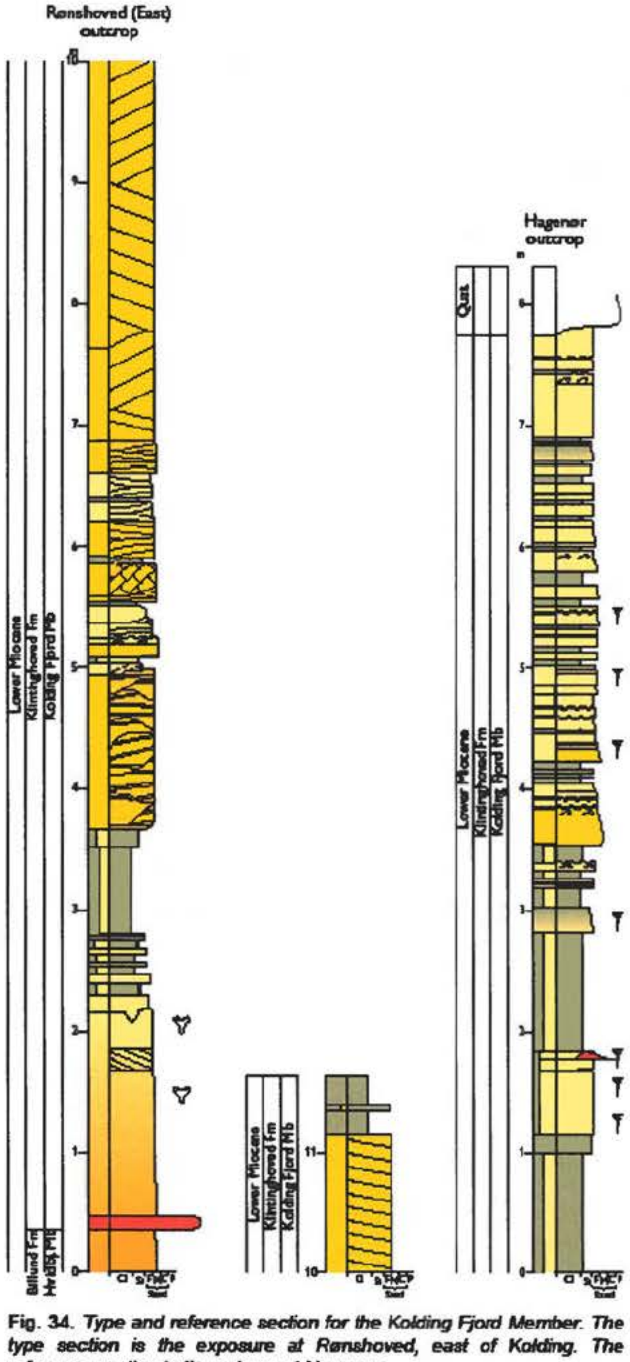

Fig. 34. Type and reference section for the Kolding Fjord Member. The type section is the exposure at Rønshoved, east of Kolding. The reference section is the outcrop at Hagenør.

Fig. 35. Heterolithic deposits of the Kolding Fjord Member sharply overlain by hummocky cross-stratified sand at the Rønshoved outcrop. The heterolithic succession is characterised by alternating hummocky cross-stratified sand and sandy clay and various types of ripple lamination. The section at the photo is 3 m high.

Fig. 36. The Kolding Fjord Member at Hagenør. The lower part of the Hagenør outcrop is characterised by two organic-rich, clayey, silt deposits separated by bioturbated sand. The upper part of the exposure is dominated by alternating sand and clay layers. The sand beds are typically sharp based, homogenous to weakly laminated in the lower part and capped by wave- or current-ripples. Persons for scale.

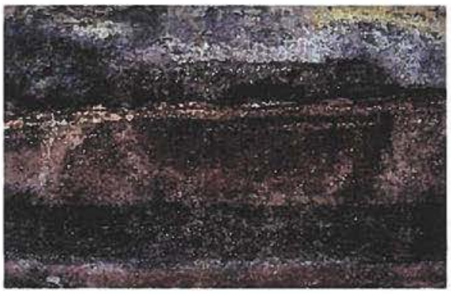

Fig. 37. Close-up of the lagoonal deposits at Hagenør. The light brown deposits capped by sand ripples sandwiched between the dark lagoonal clay represent at short period of marine incursion. The strik of the the crest of the rippled sand is northwest–southeast. The section is c. 2 m high.

Fig. 38. Close-up of the alternating sand and clay layers exposed in the upper part of the Hagenør section. Spade for scale.

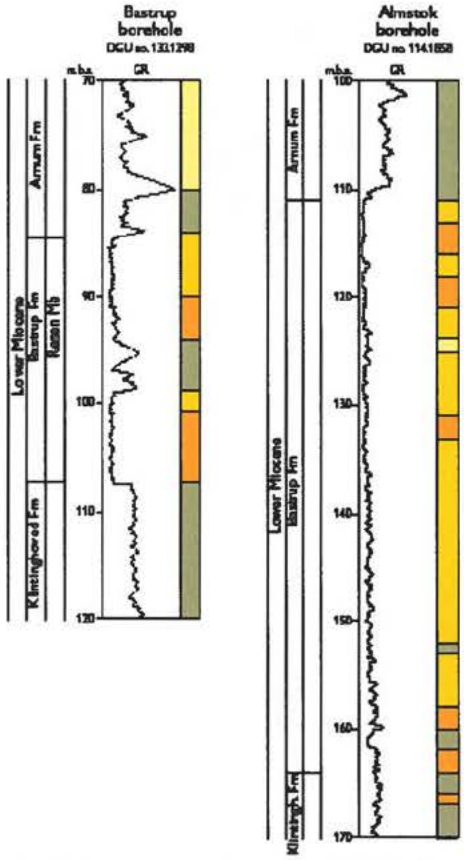

***Fig. 39.** Type and reference section for the Bastrup Formation. The type section is from 84–107 m in the Bastrup borehole (DGU no. 133.1298). The reference section is from 111–164 m in the Almstok borehole (DGU no. 114.1858).*

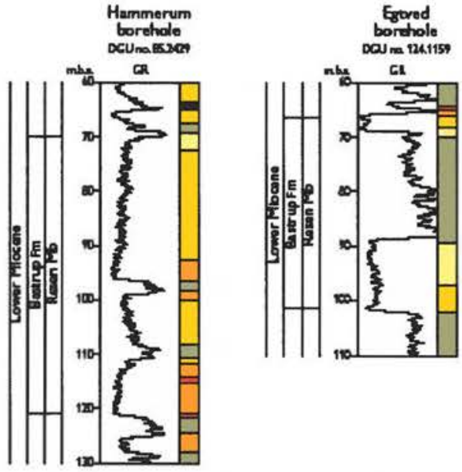

Fig. 40. *Type section and reference borehole for the Resen Member. The section from 70–120 m in the Hammerum borehole (DGU no. 85.2429) is designated as the type section. The reference section is the interval from 67–101 m in the Egtved borehole (DGU no. 124.1159).*

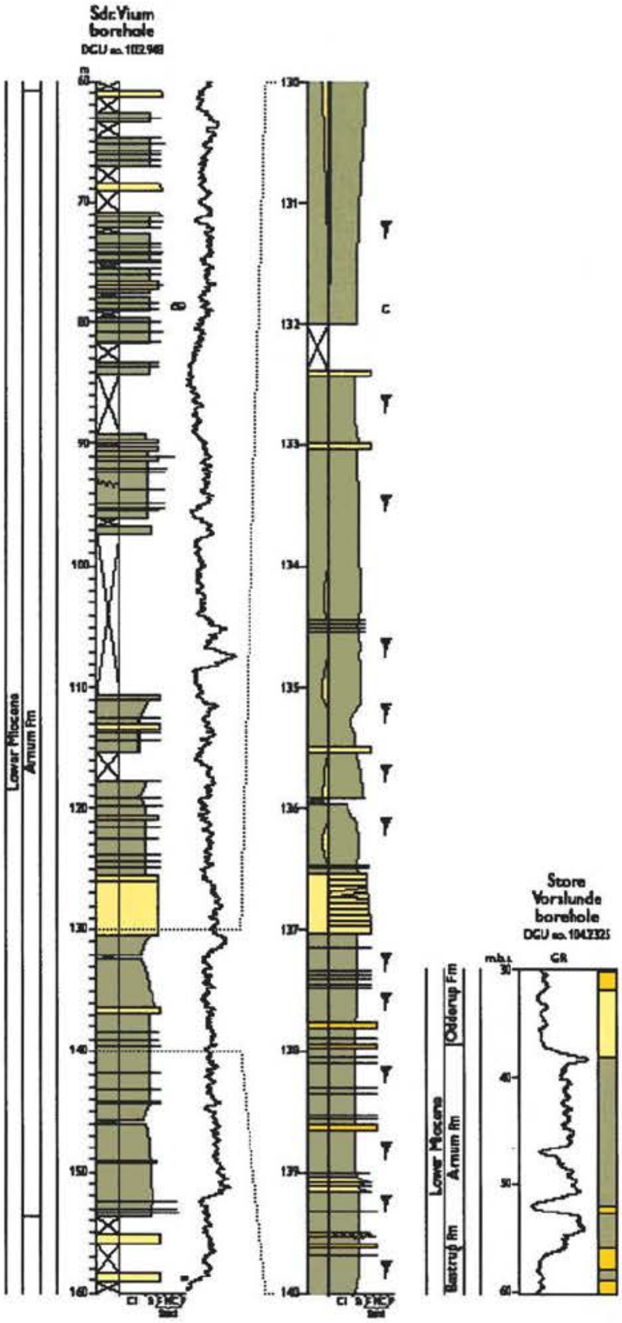

Fig. 41. *Type and reference section for the Arnum Formation. The type section is the interval from 60.90–153.75 m in the cored borehole Sdr. Vium (DGU no. 102.948). The reference section is the interval from 37–56 m in the Store Vorslunde borehole (DGU no. 104.2325).*

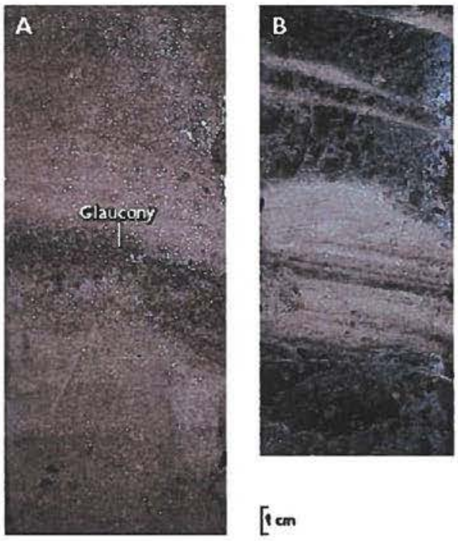

Fig. 42. *Two cores from the Sdr. Vium borehole (DGU no. 102.948) showing typical lithologies of the Arnum Formation; A) bioturbated clay with a thin layer of glaucony, B) Dark brown clayey silt and hummocky cross-stratified sand.*

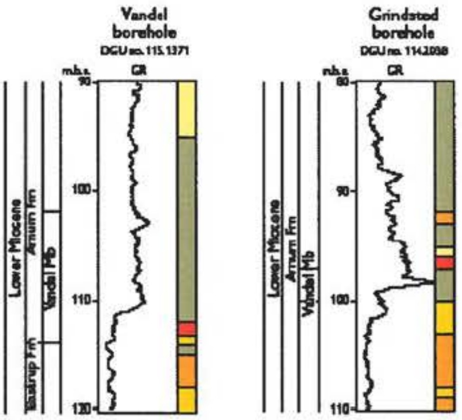

Fig. 43. *Type and reference section for the Vandel Member. The type section is the interval from 102-114 m in the Vandel Mark borehole (DGU no. 115.1371). The reference section is the interval from 97–100 m in the Grindsted borehole (DGU no. 114.2038).*

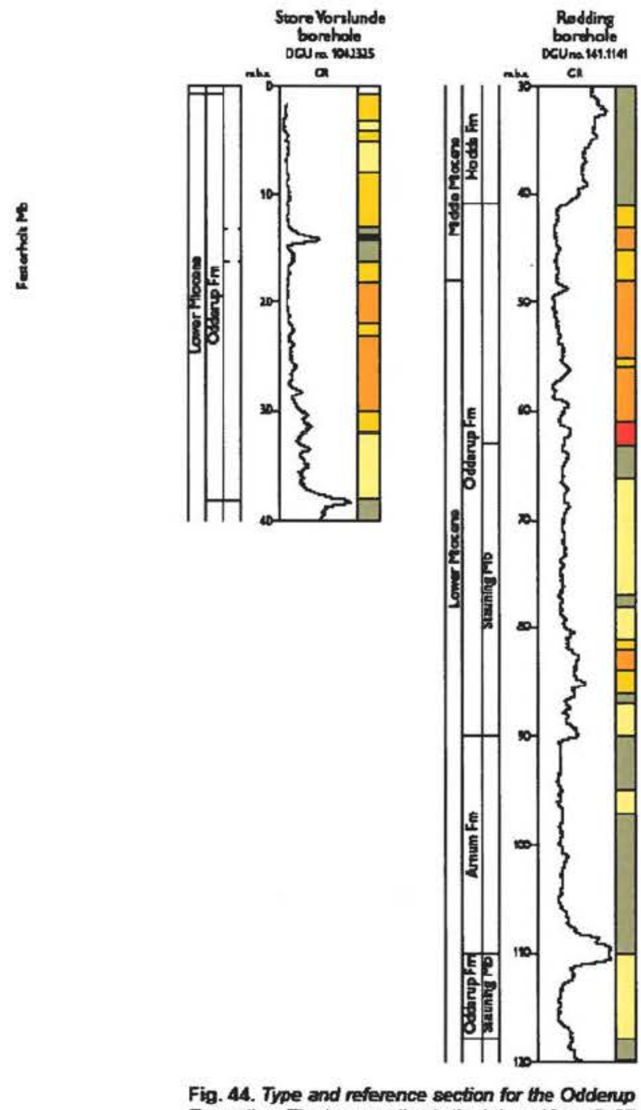

Fig. 44. *Type and reference section for the Odderup Formation. The type section is the interval from 3–37 m in the Store Vorslunde borehole (DGU no. 104.2325). The reference section is the intervals from 41–90 m and from 110–118 m in the Rødding borehole (DGU no. 141.1141).*

Fig. 45. *Low angle cross-bedded sand with heavy minerals from the Odderup Formation. The sand was deposited in the swash zone of a beach. The height of the section on the photo is 0.4 m.*

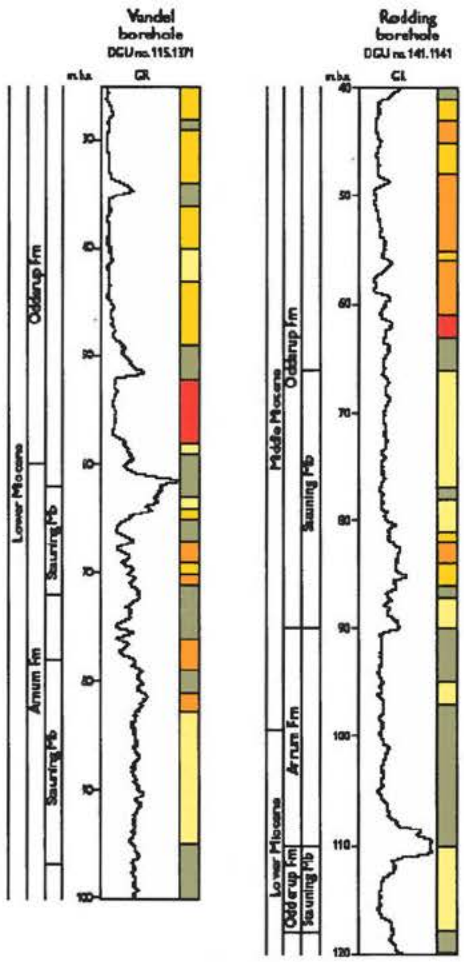

Fig. 46. *Type and reference section for the Stauning Member. The type section is the intervals from 62–72 m and from 78–97 m in the Vandel Mark Borehole (DGU no. 115.1371). The reference section is the intervals from 66–90 m and from 110–118 m in the Rødding borehole (DGU no. 141.1141).*

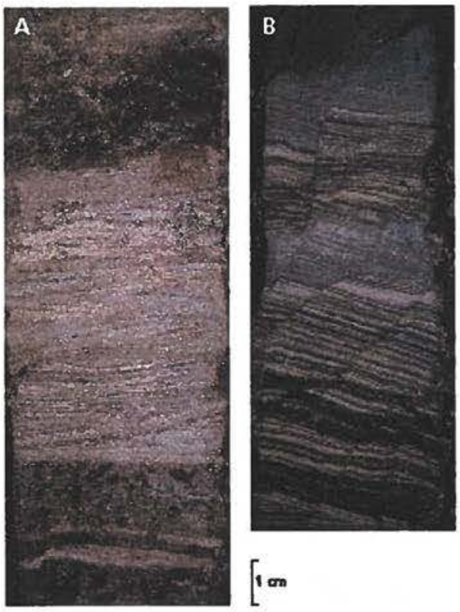

Fig. 47. *Typical lithologies of the Stauning Member: A) Hummocky cross-stratified sand interbedded in drak brown silty clay. B) Heterolithic deposits with some indication of double clay layers. Note the smale scale faulting of the succession. These might be associated with earth quakes.*

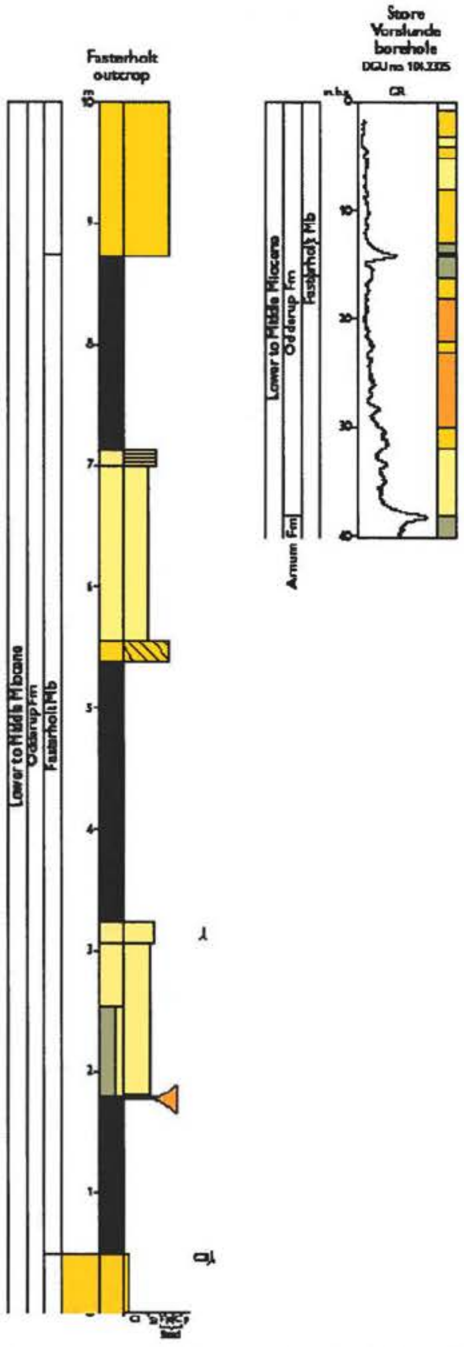

Fig. 48. *Type and reference section for the Fasterholt Member. The type section is the Fasterholt Brown Coal Pit northwest of Brande. The pit is closed now. Sediment section is redrawn from Koch (1989). The reference section is the interval from 13–15 m m in the Store Vorslunde borehole (DGU no. 104.2325).*

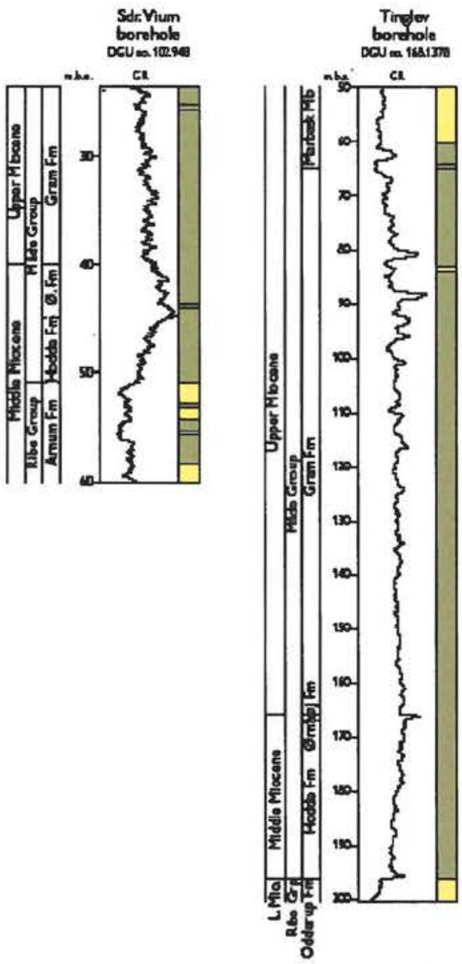

Fig. 49. *Type and reference section for the Måde Group. The type section is the interval from 24–52 m in the cored Sdr. Vium borehole (DGU no. 102.948). The reference section is the interval from 50–197 m in the Tinglev Borehole (DGU no. 168.1378).*

Fig. 50. Photo of the open pit at Lille Spåbæk, Ørnhøj where the Hodde, Ørnhøj and Gram Formations were exposed in the late 70th. These three formations and the Marbæk Formation constitutes the Måde Group. The cliff is c. 10 m high.

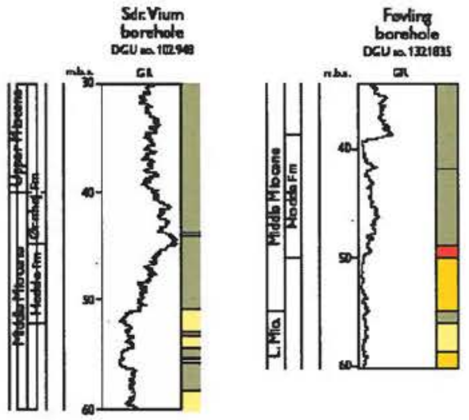

Fig. 51. Type and reference section for the Hodde Formation. The type section is the interval from 44.90–52 m in the cored Sdr. Vium borehole (DGU no. 102.948). The referece section is the interval from 39–50 m in the Fevling borehole (DGU no. 132.1835).

Fig. 52. *The upper part of the Hodde Formation at Lille Spåbæk, Ørnhøj. Spade for scale.*

Fig. 53. Close-up of the Hodde Formation. The Hodde Formation is composed of dark brown clayey silt. The yellowish stripes are due to weathering of pyrite. The section is 0.5 m high.

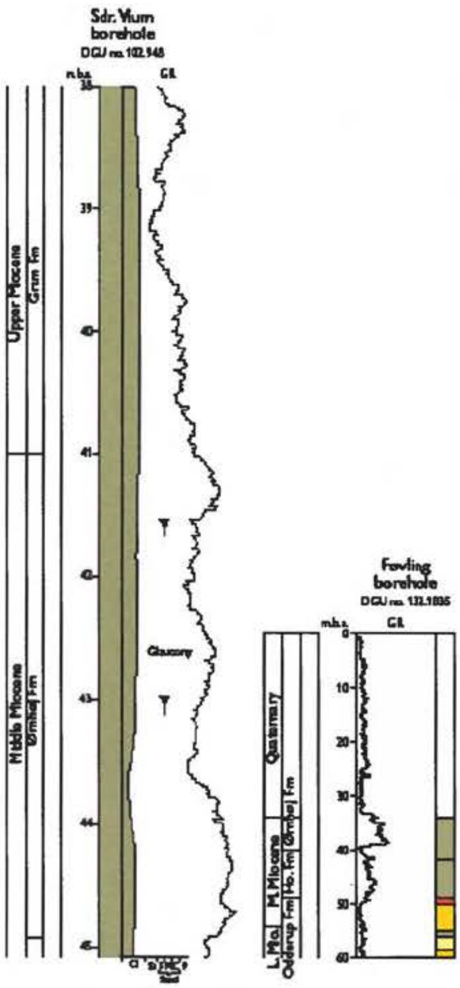

Fig. 54. The type and reference section for the Ømhøj Formation. The type section is the interval from 41–44.80 m in the cored Sdr. Vium borehole (DGU no. 102.948). The reference section is the interval from 34–40 m in the Føvling borehole (DGU no. 132.1835).

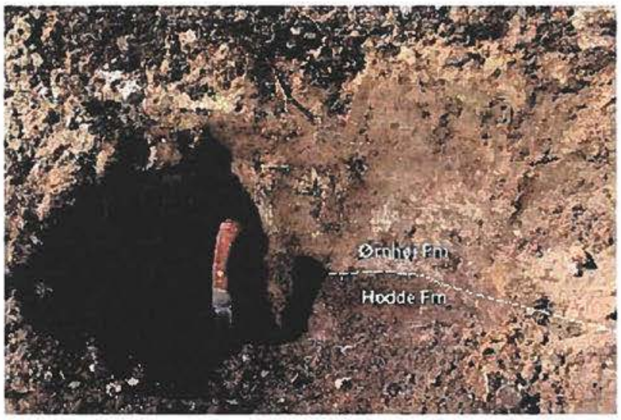

Fig. 55. The Ørnhøj Formation at Lille Spåbæk, Ørnhøj. The lower boundary towards the Hodde Formation is seen in the lower part of the section. Knife for scale, c. 20 cm long.

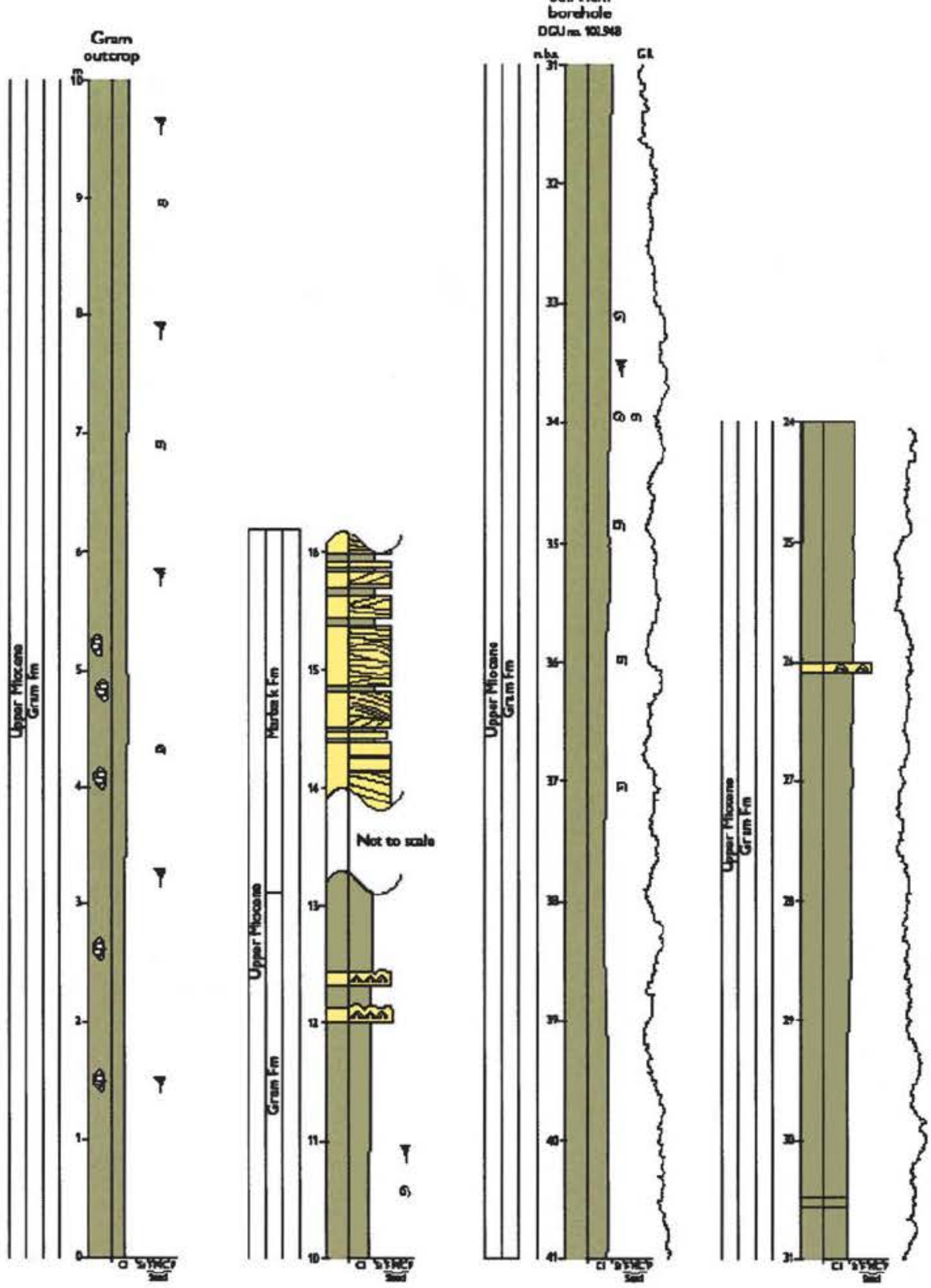

Fig. 56. *Type and reference section for the Gram Formation. The type section is at Gram Clay pit near Gram. Here 13.1 m of the formation is exposed. The reference section is the interval from 24–41 m in the cored Sdr. Vium borehole (DGU no. 102.948).*

Fig. 57. Fine-grained, partly biotubated sand intercalated in the upper part of the Gram Formation. The sand beds are commonly wave-rippled. The section is 0.30 m high

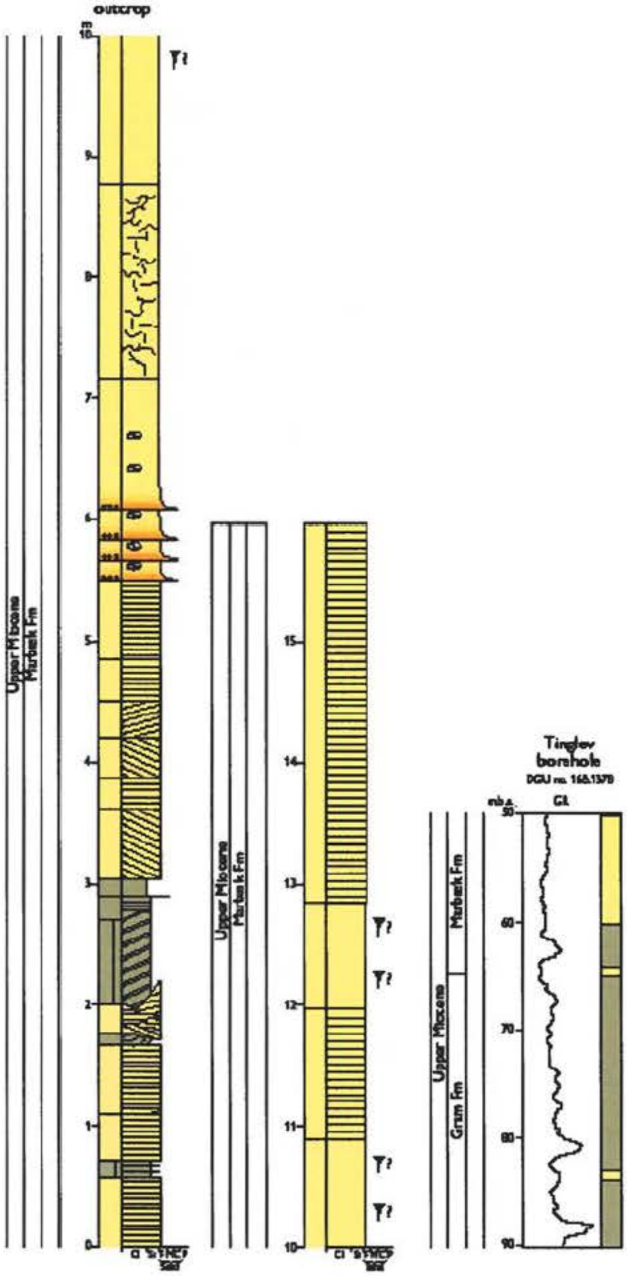

Fig. 58. Type and reference section for the Marbæk Formation. The type section is at the coastal clif at Marbæk northwest of Esbjerg. Here 15 m of the formation are exposed. The reference section is the interval from 50–65 m in the Tinglev borehole (DGU no. 168.1378).

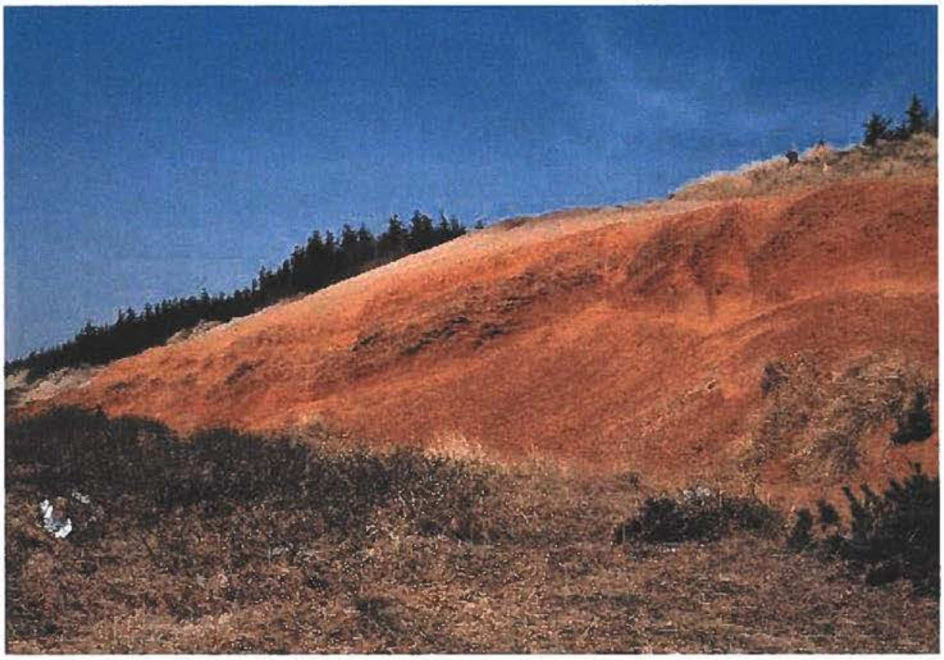

Fig. 59. Oblique view of the Marbæk Formation at Marbæk, northwest of Esbjerg. Two persons in the upper right for scale.

Fig. 60. *Hummocky cross-stratified sand of the Marbæk Formation. The section on the photo is 50 cm high.*

Fig. 61. Glacial disturbed sand of the Marbæk Formation, but homogenous sand and wave-rippled sand typical for upper shoreface deposits can be seen. The section is 0.4 m high.

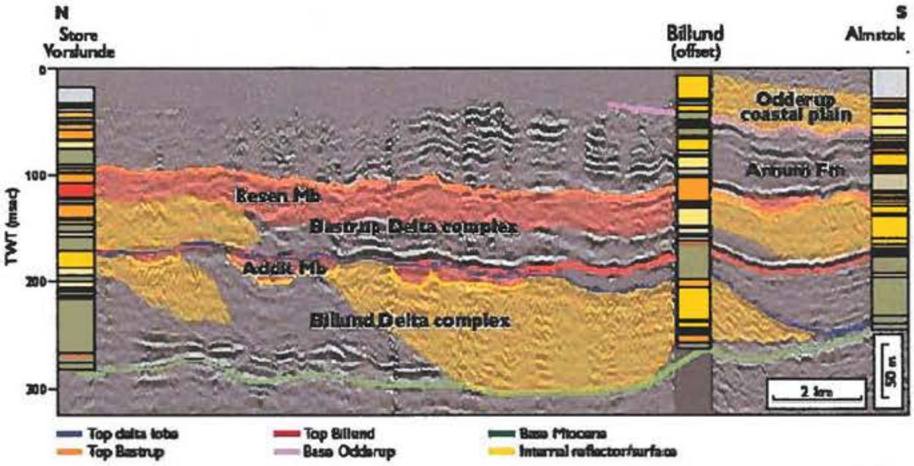

Fig. 62. N–S trending seismic section tying the Store Vorslunde, Billund and Almstok boreholes. Delta lobes characterised by oblique-parallel reflection pattern is indicated in yellow. This pattern correlates to sand-rich delta lobe deposits. Note the alternation of these sand-rich delta deposits and more clay-rich inter delta deposits which is so characteristic for the Vejle Fjord–Billund Formations and the Klintinghoved–Bastrup Formations. The upper part of section is dominated by a parallel to subparallel reflection pattern which is characteristic for the Arnum–Odderup Formation and indicate a change in sedimentation pattern of these formations.

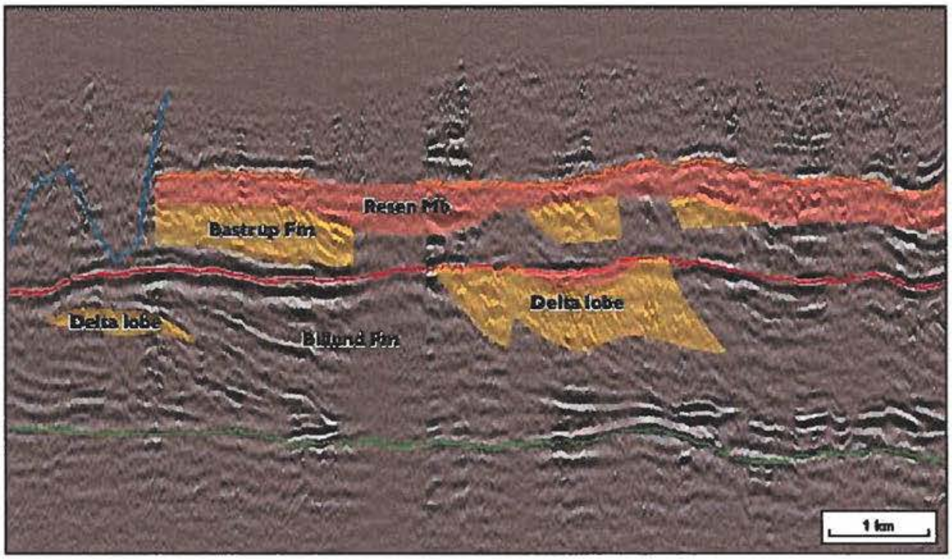

Fig. 63. *Seismic section close up at Store Vorslunde area where the sand-rich part of the deltas are indicated in yellow. Sand-rich fluvial deposits of the Addit and Resen Members are shown in red respectively.*

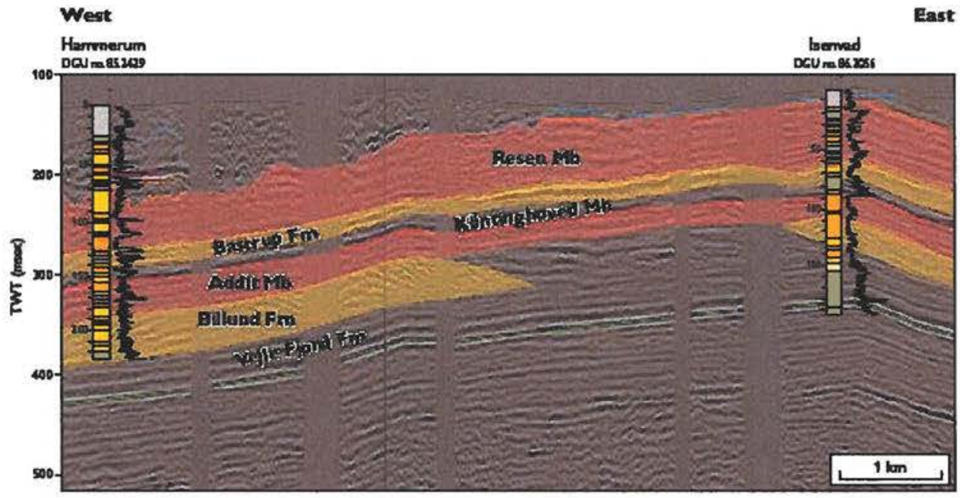

Fig. 64. *E–W striking Seismic section at Ikast. The section shows a cross-section of the Billund and Bastrup delta system as indicated by dipping reflectors both towards the west and east. In this area the fluvial systems of the Addit and Resen Members, shown in red, are particularly well developed.*

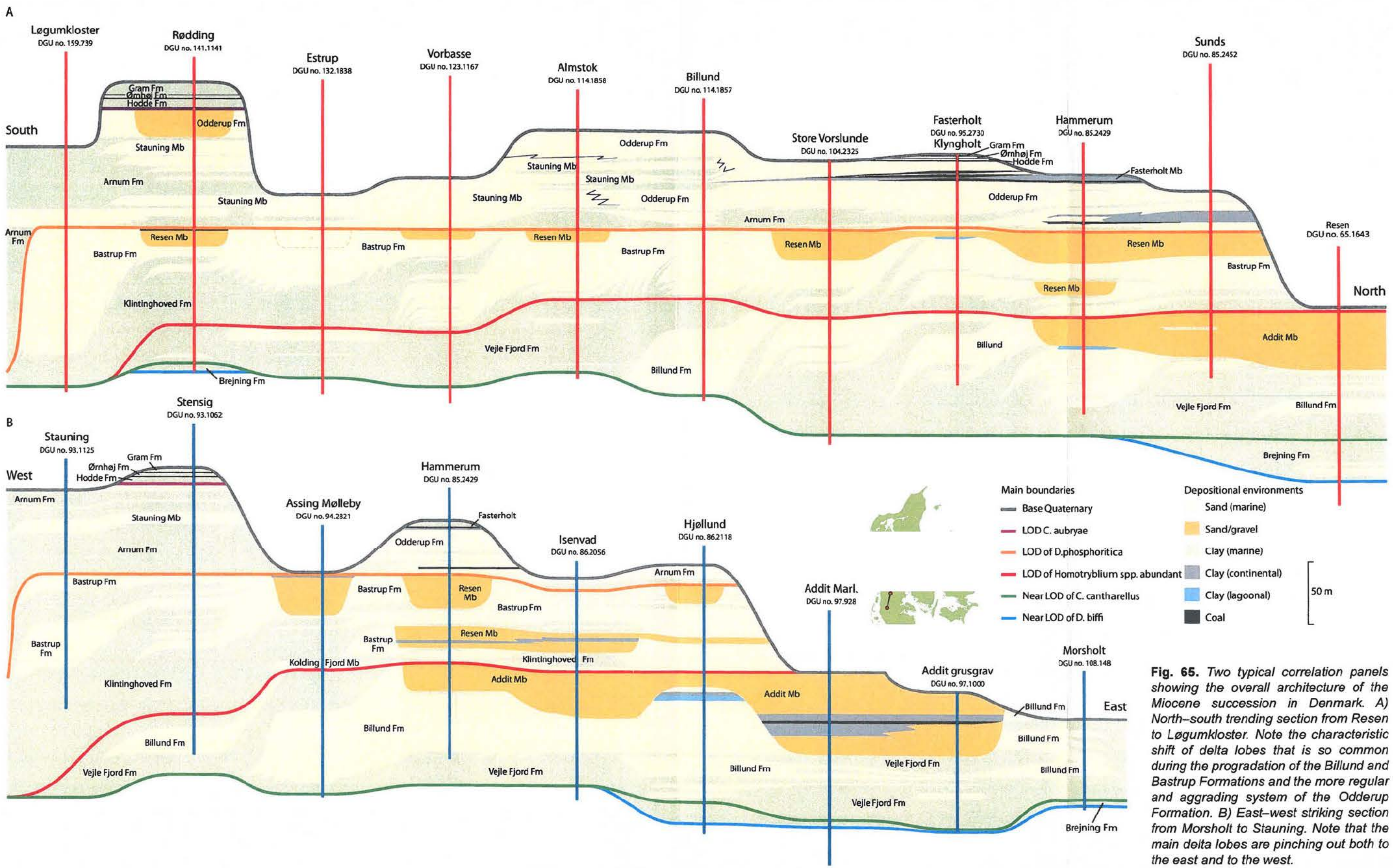

Fig. 65. *Two typical correlation panels showing the overall architecture of the Miocene succession in Denmark. A) North–south trending section from Resen to Løgumkloster. Note the characteristic shift of delta lobes that is so common during the progradation of the Billund and Bastrup Formations and the more regular and aggrading system of the Odderup Formation. B) East–west striking section from Morsholt to Stauning. Note that the main delta lobes are pinching out both to the east and to the west.*

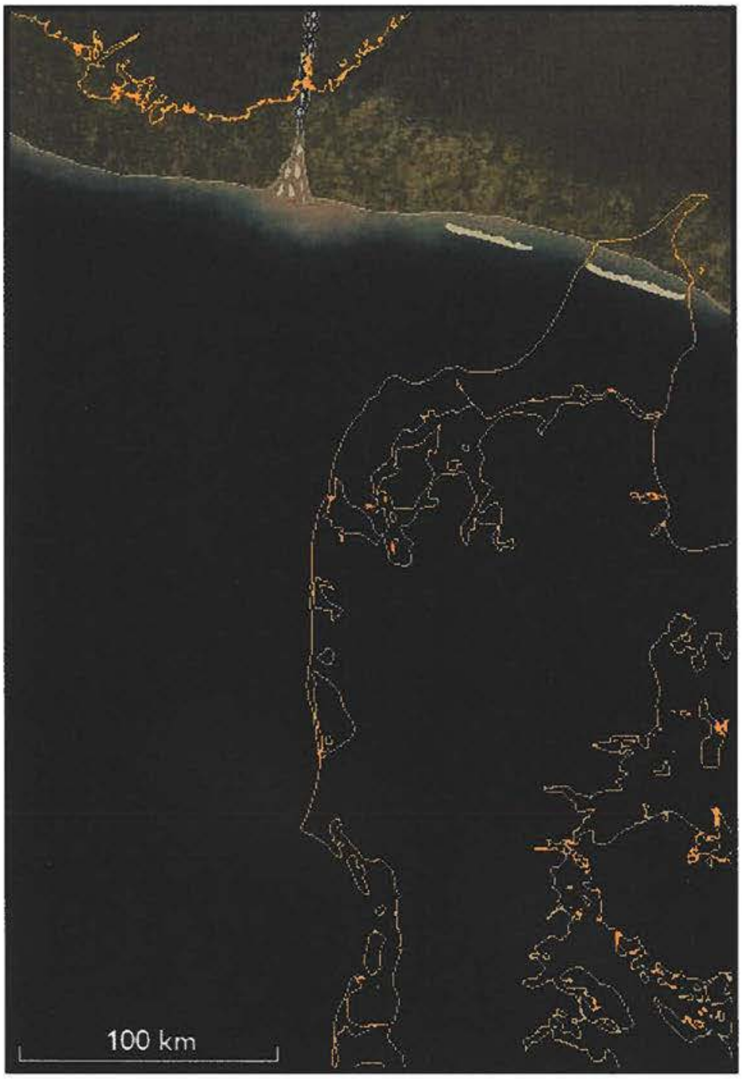

Fig. 66. Palaeogeographic reconstruction of the latest Late Oligocene Brejning Formation. The exact location of the shoreline is uncertain, but most of Jylland was marine at that time. Water depth in northern Jylland was over 200 m and formation of glaucony dominates indicating a certain distance to the shoreline.

Fig. 67. *Palaeogeographic reconstruction of earliest Early Miocene (ealiest Aquitanian) Vejle Fjord Formation. Due to Early Miocene inversion reactivation of the Ringkøbing–Fyn High and salt structured a barrier between the eastern part of the Norwegian–Danish Basin and the North Sea Basin was formed. This resulted in brackish water environment northeast of the the Ringkøbing–Fyn High. Note that small spit systems developed east of these structures. The degradation of these spit systems during the Early Miocene transgression resulted in the formation of the Skansebakke Member.*

Fig. 68. *Palaeogeographic reconstruction of Early Miocene (Aquitanian) Billund and Vejle Fjord Formations. The sea level continued to rise during this phase and flooded the Ringkøbing–Fyn High. However, due to high sediment supply to the basin, the shoreline prograded southward. This favoured the formation of spit/barrier complexes southeast of the main delta lobes which consistute the Hvidbjerg Member of the The Billund Formation. The river system during the Early Miocene was dominantly braided rivers.*

Fig. 69. *Palaeogeographic reconstruction of of Early Miocene (late Aquitanian) Billund Formation. During this period the relative sea-level fall and progradation of the shoreline is reflected by amalgamation of beach ridges along the coast. Distinct incision and formation of broad valleys commenced at the same time.*

Fig. 70. *Palaeogeographic reconstruction of Early Miocene (early Burdigalian) Klinthoved Formation and Kolding Fjord Member. A global climatic warming resulted in a relative rise in sea level. The shoreline was characterised by eatuaries and associated barrier complexes and the formation of braided fluvial deposits occurred within incised valleys.*

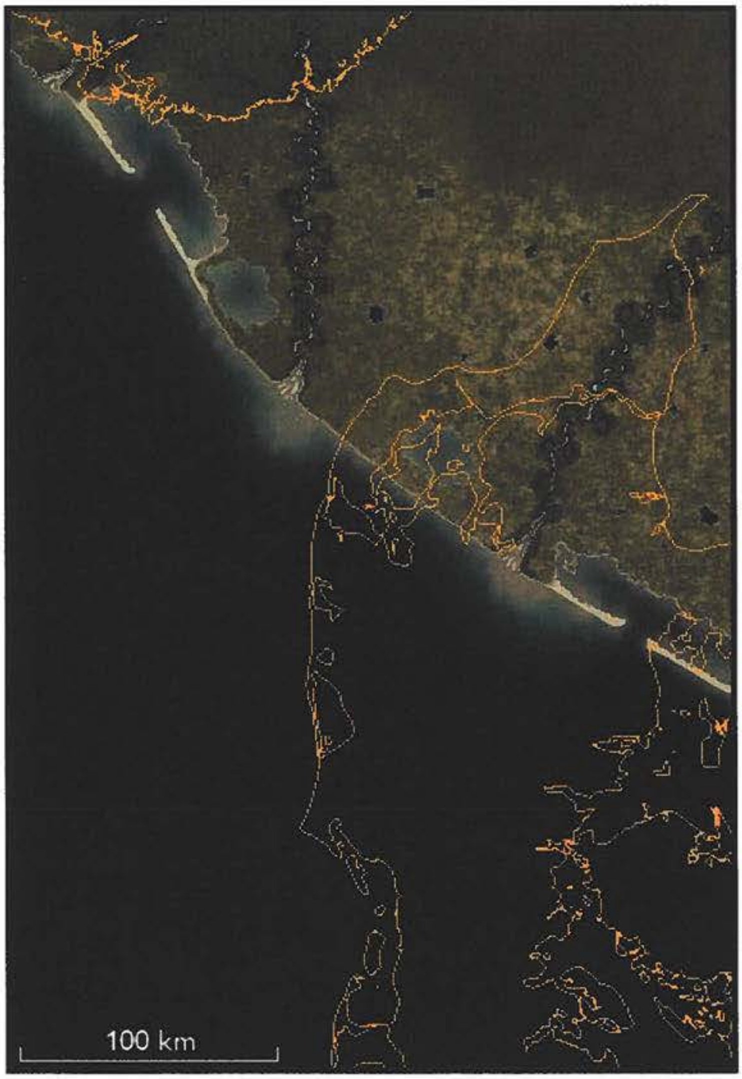

Fig. 71. Palaeogeographic reconstruction of Early Miocene (early Burdigalian) Klinting-hoved Formation. During the most widespread flooding in the early Burdigalian most of western and central Jylland was covered by the sea and the deposition of the Klinting-hoved Formation took place here.

Fig. 72. Palaeogeographic reconstruction of the Early Miocene (early Burdigalian) Bastrup Formation. The progradation occurred during rising relative sea level which formed optimal conditions for a shoreline dominated by lagoons and barrier islands. The fluvial system was dominated by meandering river systems.

Fig. 73. Palaeogeographic reconstruction of the Early Miocene (Burdigalian) Bastrup Formation. During this period the relative sea level fall and the prograding shoreline was characterised by amalgamation of beach ridges parallel to the coast. Distinct incision on land and formation of broad valleys commenced at the same time.

Fig. 74. Palaeogeographic reconstruction of the Early Miocene (Burdigalian) Bastrup Formation. During this part of the Miocene most parts of Jylland was land. The progradation took place during rising sea level.

Fig. 75. Palaeogeographic reconstruction of the late Early Miocene (late Burdigalian) Arnum Formation. The shoreline was located across the northern part of Jylland.

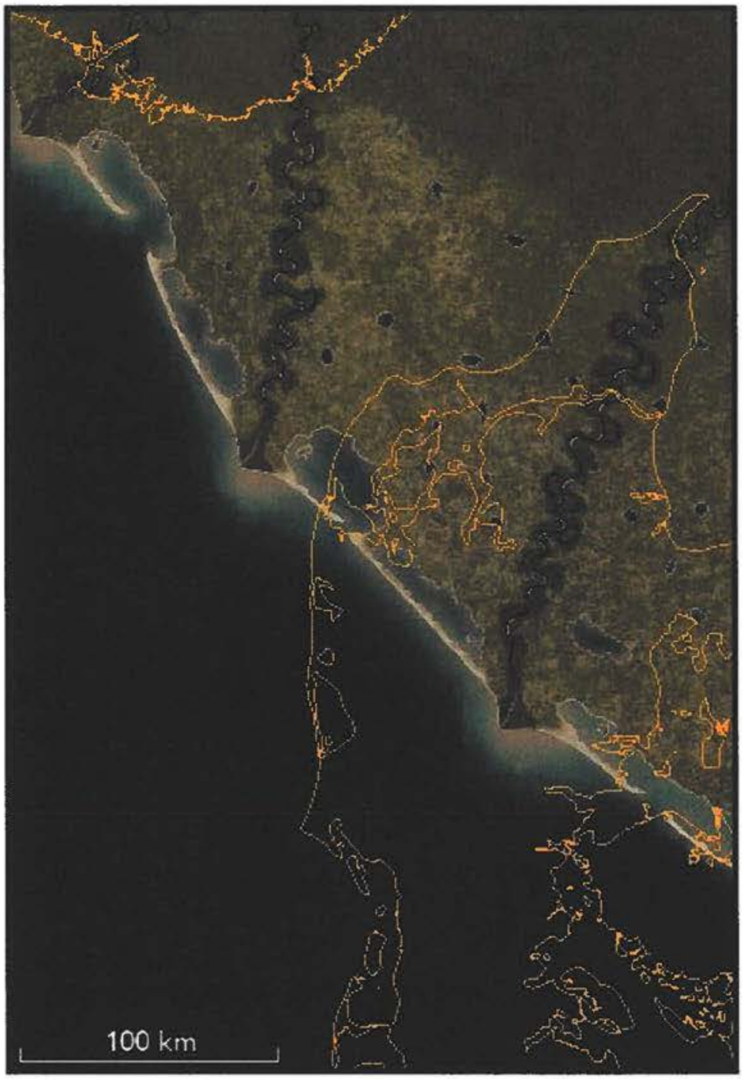

Fig. 76. Palaeogeographic reconstruction of the late Early Miocene (late Burdigalian) Odderup Formation. During this time period the climate became subtropical and the global sea level rose. High sediment supply, however, forced the shoreline to prograde. These condition favoured formation of lagoons and swamp lakes which were optimal for the formation of coal-rich deposits.

Fig. 77. Palaeogeographic reconstruction of the early Middle Miocene (early Langhian) Odderup Formation. During the maximum regression of the shoreline most of Jylland was land only the south western part was covered by the sea. Lagoonal–swamp conditions prevailed north of the Ringkøbing–Fyn High probably favoured by increased subsidence in this area.

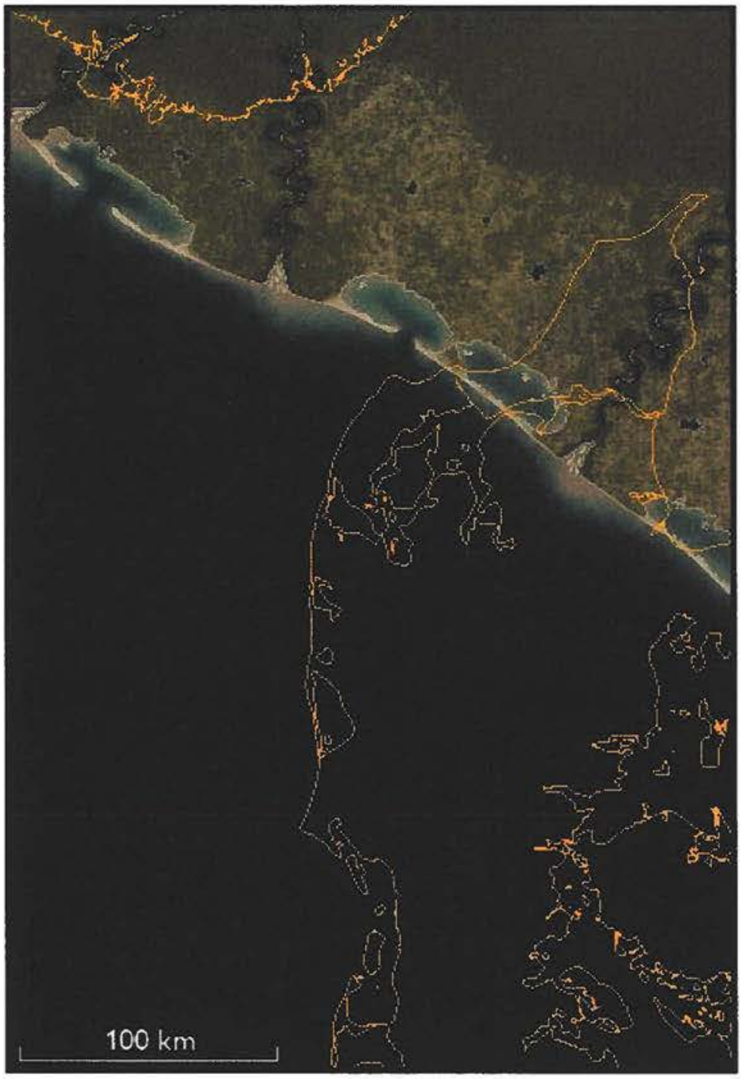

Fig. 78. *Palaeogeographic reconstruction of Middle Miocene (Serravallian) Ømhøj Formation. Despite a climatic deterioration in the Middle Miocene most of Jylland was flooded and the shoreline was located in the northern part of Jylland. Due to a very low sedimentation rate optimal conditions excisted for the formation of glaucony.*

Fig. 79. Palaeogeographic reconstruction of Late Miocene (Tortonian) Gram Formation. In the latest part of the Miocene distinct uplift of Scandinavian and the Alpine mountains resulted in extreme high sediment supply into the North Sea Basin. This resulted in marked progradation from both the north and south.

Fig. 80. *Palaeogeographic reconstruction of Late Miocene (Tortonian) Marbæk Formation. The marked progradation of the shoreline during the Late Miocne resulted in subaerial conditions in most parts of Jylland and deposition of shoreface deposits in the extreme western part of Jylland. At the end of the Miocene the shoreline was located ca. 250 west of the present day west coast.*

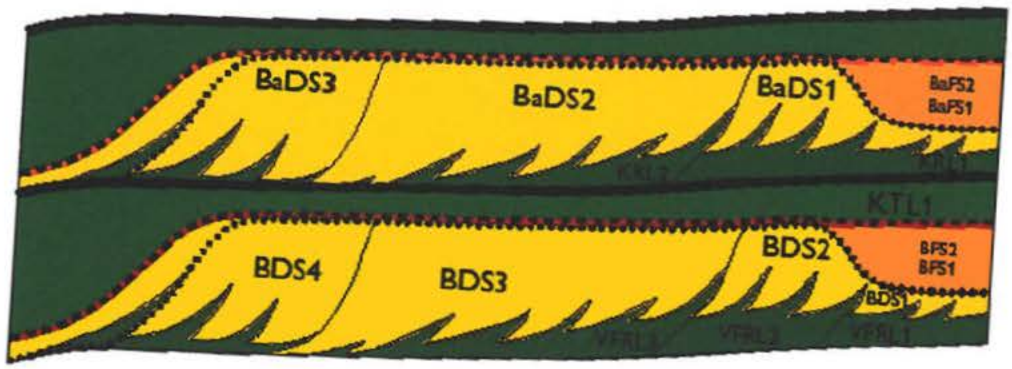
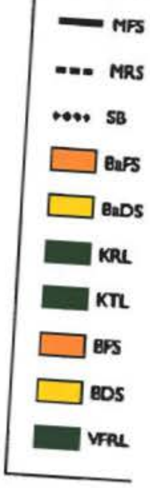

Fig. 81. Principskitse for opbygningen af lithologiske enheder.

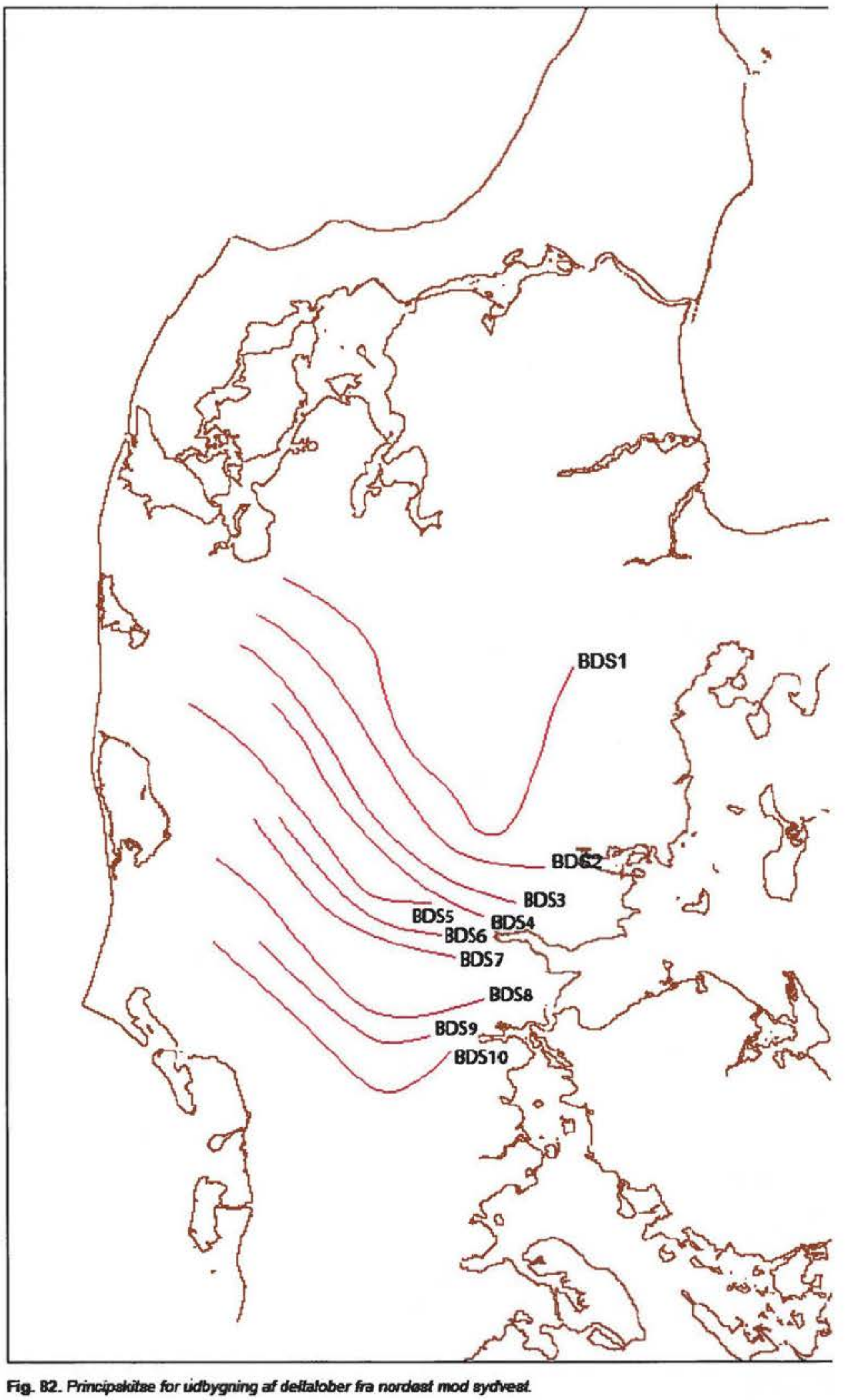

Fig. 82. *Principskitse for udbygning af deltalober fra nordøst mod sydvest.*