Ribe Group

new group

History. Non-fossiliferous sand and gravel encountered below 125.6 m in a borehole at Ribe 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. L.B. Rasmussen (1961) suggested that a succession of quartz gravel and sand with some lignite between 255.7 and 144.5 m in the Arnum-1 borehole should be referred to the Ribe Formation. He further indicated that the fluvio-deltaic, brown-coal-bearing succession around Silkeborg and Skanderborg may be correlative with the Ribe Formation. In this stratigraphic revision, however, the fluvio-deltaic deposits at Silkeborg are referred to the Vejle Fjord and Billund Formations.

The Ribe Formation was included in the stratigraphic chart of L.B. Rasmussen (1961) where it was suggested to encompass 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 (E.S. Rasmussen 2004b; Dybkjær 2004a; Rasmussen & Dybkjær 2005; E.S. Rasmussen *et al.* 2006; Dybkjær & Piasecki 2010). These studies have revealed that the stratigraphy of the Lower Miocene deposits is more complicated than formerly believed. The fluvio-deltaic sediments that are so characteristic of the Lower Miocene – lower Middle Miocene succession are thus 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 lithostratigraphy of Schleswig-Holstein, northern Germany (Rasser *et al.* 2008; Knox *et al.* 2010). 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 (K. Gürs, personal communication 2006; Rasser *et al.* 2008; Knox *et al.* 2010).

The Ribe Group correlates with the upper part of the Hordaland Group as applied in the North Sea region,

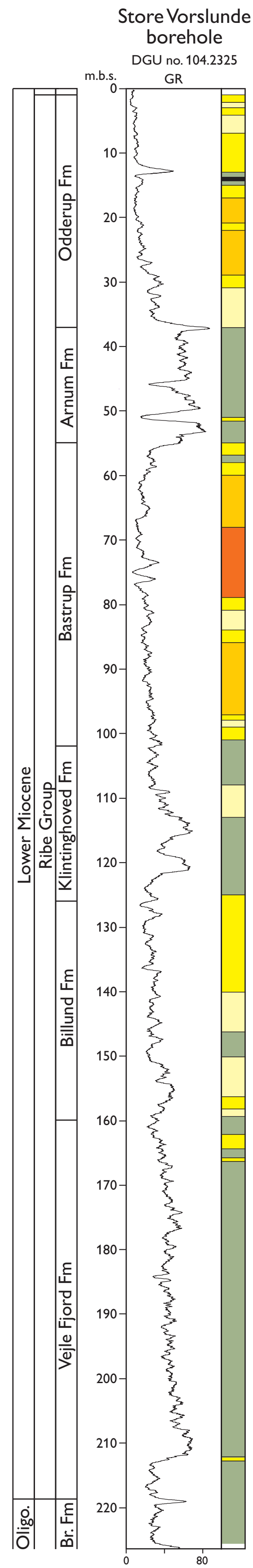


Fig. 17. The full development of the Ribe Group is illustrated by the interval from 219 to 1 m in the Store Vorslunde borehole, north-east of Vejle; for legend, see Fig. 8, p. 17. **Br.**: Brande. **Oligo.**: Oligocene.

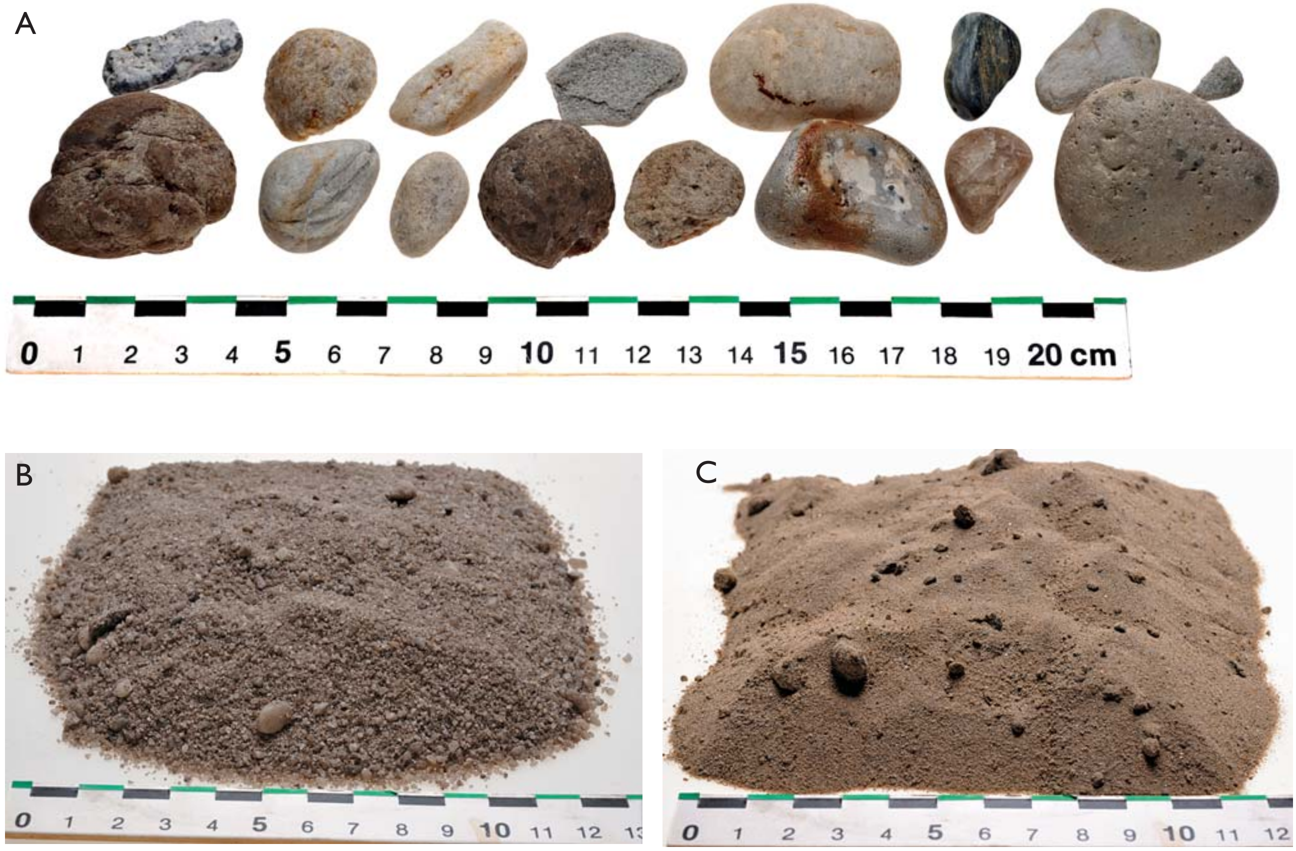


Fig. 18. Quartz-rich sand and pebbles from the Miocene fluvio-deltaic deposits; photographs courtesy of P. Warna-Moors. **A**: Pebbles of quartz, quartzite and chert; these are commonly found near sequence boundaries, associated with transgressive lags or within fluvial channels. Note that the clasts are up to 3 cm in diameter. **B**: Granules and coarse-grained sand of the Billund Formation. **C**: Fine- and medium-grained sand of the Billund Formation.

including offshore Denmark in the Norwegian–Danish Basin (Deegan & Scull 1977; Hardt *et al.* 1989; Schiøler *et al.* 2007).

Name. After the town of Ribe (Fig. 1).

Type area. The type area of the Ribe Group is central and east Jylland. In the gravel pit at Voervadsbro in central Jylland (Fig. 1), both marine sand and fluvial sand and gravel of the Ribe Group are exposed. In the Store Vorslunde borehole (Fig. 17; DGU no. 104.2325) a complete section through the group is represented in the interval from 219 to 1 m (220–1 m MD). The group crops out 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 and Abildå in central Jylland and at Gyldendal, Søndbjerg, Lyby, Skyum Bjerge, Skanderup and Lodbjerg in the Limfjorden area.

Thickness. The group is 218 m thick in the Store Vorslunde 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, located in the Tønder Graben, more than 200 m has been penetrated without reaching the lower boundary of the group (Plate 1). Reduced thicknesses are seen in the eastern part of Jylland, partly due to erosion during the Pleistocene.

Lithology. The group consists of three cycles of alternating mud-rich and sand-rich units with some intercalation of coal beds, especially in the upper cycle (Odderup Formation); each cycle, 50 to 100 m thick, represents a coarsening-upward cycle. The sands are typically medium- to coarse-grained, quartz-rich with a variable mica content. Various types of cross-bedding, including tabular, trough, hummocky and swaley cross-stratification, characterise the sand-rich units. The sand grains are normally sub- to well-rounded. Well-rounded pebbles of quartz, quartzite and

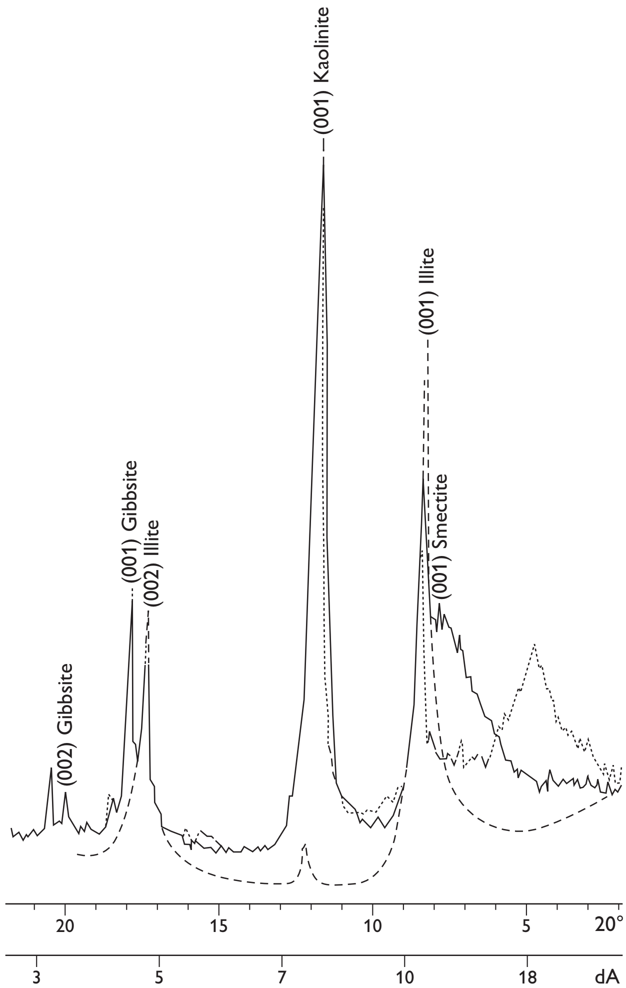


Fig. 19. X-ray diffractogram of the clay fraction from muds of the Vejle Fjord Formation (Ribe Group). Note that gibbsite is present indicating that the source area was heavily weathered. Full line = untreated samples, dotted line = glycolated samples and dashed line = samples heated to 500°C. Modified from E.S. Rasmussen (1995). **dA**: lattice separation (in angstrom).

chert up to 4 cm in size (Fig. 18) commonly occur in the upper part of the units near sequence boundaries (in transgressive lags or fluvial channels). Fossils occur only sporadically in the sand-rich units.

The micaceous, mud-rich portions of the group are typically homogeneous, with some intercalation of laminated mud intervals as well as discrete sand layers. The sand layers are commonly hummocky cross-stratified or represent tidal rhythmites. The clay mineral association is dominated by illite, kaolinite and gibbsite (Fig. 19); pyrite is a very common authigenic mineral.

The coal beds are found associated with cross-stratified fluvial sands and muds, and also cap shoreface/beach sands and lagoonal muds. The coal beds are limited to the Norwegian–Danish Basin where they typically reach thicknesses of 2–3 m; the thickest succession has been recorded in the Fasterholt area, where there is a cumulative thickness of about 9 m of coal. Lithological details of the respective formations of the Ribe Group are given below under the individual formation descriptions.

Log characteristics. The typical log pattern shows three cycles of decreasing-upward gamma-ray values (Fig. 17). The gamma-ray log is generally characterised by a serrated pattern, but distinct gamma-ray spikes are common in the lower part of each cycle; in 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, decreasing gamma-ray values are commonly observed in the upper part of each cycle. For more detailed descriptions, see the individual units below.

Fossils. Molluscs occur abundantly in the marine and near-shore deposits and plant fossils are locally abundant in the terrestrial deposits. More detailed descriptions of the fauna/flora are given below in the definitions of the formations and members.

Depositional environment. The Ribe Group was deposited by delta systems prograding from the north and north-east towards the south and south-west. Deposition of the first cycle (Billund Formation) was strongly controlled by the topography formed during Early Miocene inversion tectonism (Rasmussen & Dybkjær 2005; Hansen & Rasmussen 2008; E.S. Rasmussen 2009a). During the deposition of this cycle, the so-called Ringkøbing and Brande lobes were focussed particularly within 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 shore-parallel transport of sand that was delivered from the river mouths of the delta systems (Rasmussen & Dybkjær 2005; Hansen & Rasmusen 2008). Fluvial sands interpreted as braided river system deposits (Hansen 1985; Jesse 1995; E.S. Rasmussen *et al.* 2006) dominate in the northern part.

The second cycle (Bastrup Formation) shows a more evenly distributed progradational pattern across Jylland. Due to the lack of outcrops of this part of the Miocene succession, detailed sedimentology has not been carried out. Judging from borehole data, there are no indications of widespread spit and barrier complexes. As for the first cycle, fluvial systems dominate the upper part of the succession. Log and seismic data (E.S. Rasmussen *et al.* 2007; E.S. Rasmussen 2009b) indicate that a meandering fluvial system was widespread, although local or periodic 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 commonly sharp, being defined where greenish to brownish, glaucony-rich clay and silt is overlain by dark brown, organic-rich mud. Over much of Jylland, the boundary is also marked by a change in the degree of consolidation, from the well-consolidated sediments of the Oligocene Brejning and Branden Formations to poorly consolidated Ribe Group sediments. The boundary may be marked by a gravel lag or sand bed. Due to intense bioturbation, the boundary may be locally blurred. In central east Jylland, the boundary is characterised by a marked change from the sand deposits of the Øksenrade Member to dark brown clayey silt of the Vejle Fjord Formation of the Ribe Group. The upper boundary is sharp, being marked by a thin gravel layer that separates the white, fine-grained sand of the uppermost Ribe Group (Odderup Formation) from the dark brown mud of the succeeding Måde Group. This is reflected by a prominent shift on the gamma-ray log towards high gamma-ray values.

Distribution. The Ribe Group is present over most of Jylland. The northern and eastern limits of the group closely follow the lower boundary of the Miocene deposits (Fig. 4)

Geological age. The Ribe Group is of Aquitanian – early Langhian (Early Miocene – earliest Middle Miocene) age.

Subdivision. The Ribe Group is divided into six formations: the Aquitanian Vejle Fjord and Billund Formations, the uppermost Aquitanian – lower Burdigalian Klintinghoved and Bastrup Formations and the upper Burdigalian – lower Langhian Arnum and Odderup Formations (Fig. 7).

Vejle Fjord Formation

redefined formation

General. The marine, clay-dominated Vejle Fjord Formation interdigitates north-eastwards with the fluvio-deltaic, sand-rich Billund Formation. These two formations thus alternate up-section in some boreholes (e.g. Plates 2–8).

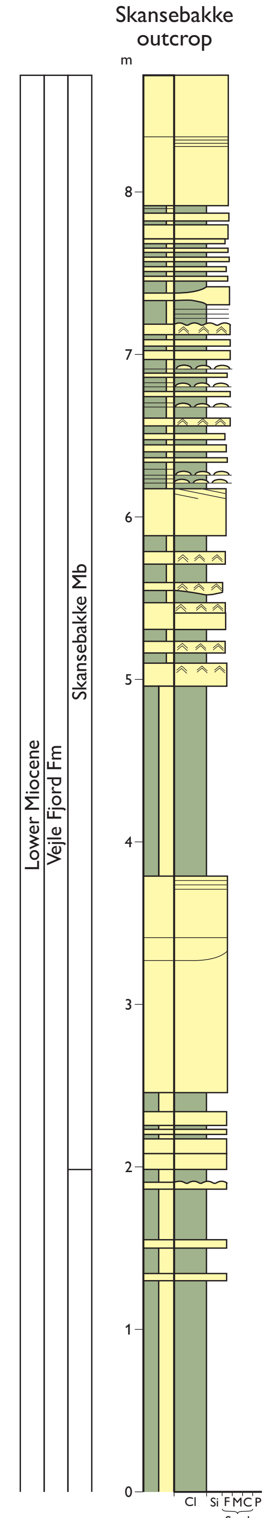


Fig. 20. Type section of the Vejle Fjord Formation and the Skansebakke Member at Skansebakke, Brejning; for legend, see Fig. 8, p. 17.

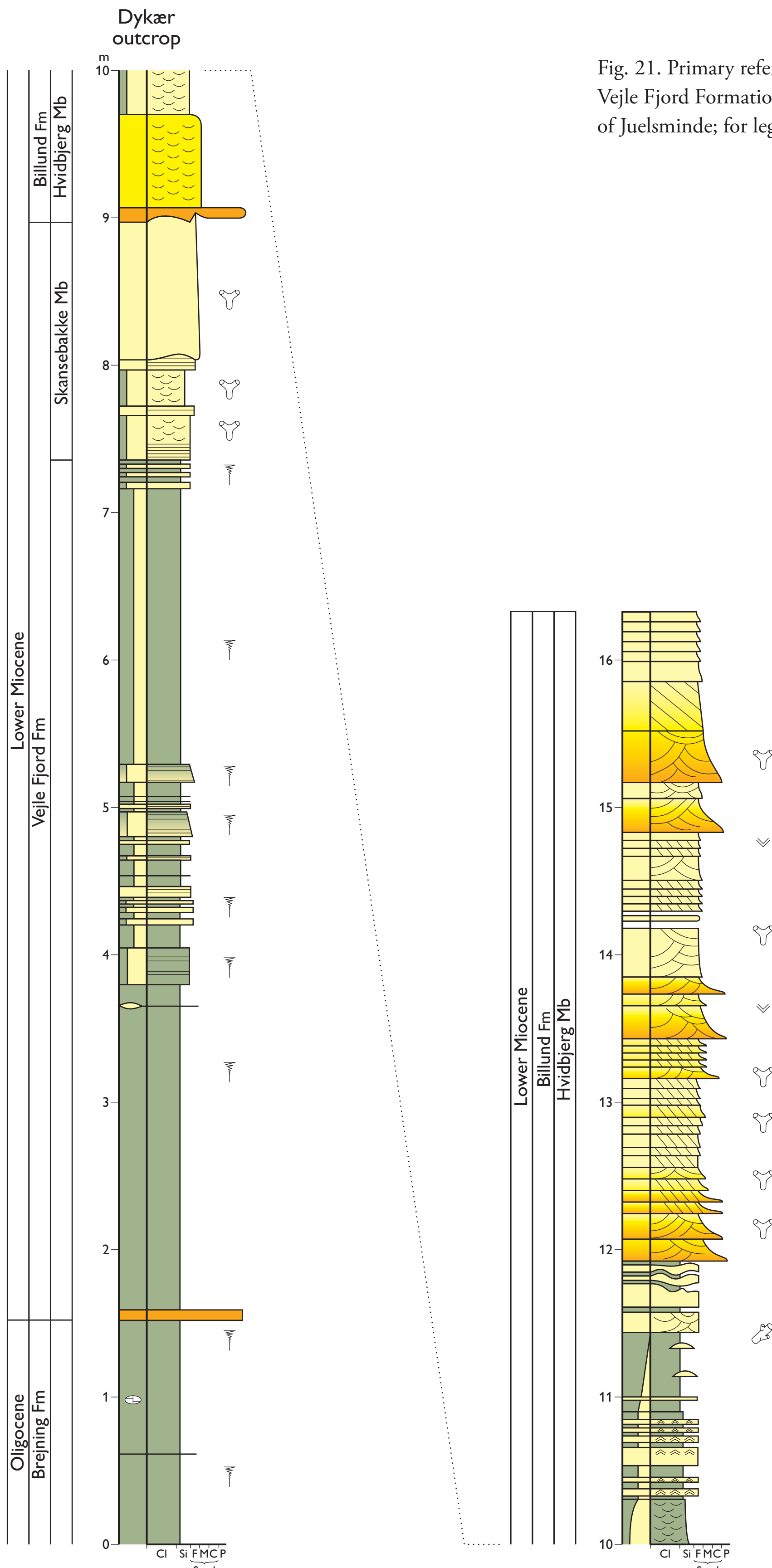


Fig. 21. Primary reference section of the Vejle Fjord Formation at Dykær, south-west of Juelsminde; for legend, see Fig. 8, p. 17.

History. The Vejle Fjord Formation was defined by Larsen & Dinesen (1959). The formation was originally defined as the succession from the base of the Brejning Clay Member to the top of the Vejle Fjord Sand Member. For stratigraphic and practical reasons, the Brejning Clay Member is herein removed from the Vejle Fjord Formation and elevated to the status of formation (see above); redefinition of the Vejle Fjord Formation is therefore necessary. Revision is also needed because of the large amount of data acquired during the last decade, which has shed new light on the depositional system (Dybkjær & Rasmussen 2000; Rasmussen & Dybkjær 2005). Sediments referred by Christensen & Ulleberg (1973) to the upper Sofienlund Formation are assigned here to the Vejle Fjord Formation; the Sofienlund Formation is abandoned.

Name. After Vejle Fjord in east Jylland (Fig. 1).

Type and reference sections. The type section is the Skansebakke outcrop at Brejning 55°40′19.74′′N, 9°41′33.84′′E; Figs 1, 20). The outcrop reference section is defined at Dykær near Juelsminde (Figs 1, 21). Other exposures in the Vejle Fjord area are Brejning Hoved, Sanatoriet, Fakkegrav and Jensgård. It is further exposed at Hindsgavl near Middelfart, and the formation crops out at Skyum Bjerge, Lyby, Mogenstrup and Skanderup (Mors) in the Limfjorden area (Fig. 1). The secondary reference section is the Store Vorslunde borehole (DGU no. 104.2325) (Fig. 22), in the interval from 219 to 160 m (220–161 m MD).

Thickness. The formation is *c.* 20 m thick at the type locality though neither the base nor the top are seen; the formation is about 18 m thick in the nearby Andkær borehole (see Plate 1). In the western part of Jylland, it may reach a thickness of up to *c.* 100 m, as exemplified by the Holstebro borehole (Plate 4).

Lithology. The Vejle Fjord Formation consists mainly of dark brown clayey silt (Fig. 23). In some areas, it is dominated by laminated, greenish-grey sand and dark brown, clayey silt. Sand stringers up to a few centimetres thick may occur. Locally, the formation is composed of wave-influenced heterolithic mud and sand showing hummocky cross-stratification (Figs 24, 25); the heterolithic succession is commonly characterised by double clay layers and climbing ripples. Soft-sediment deformation structures occur locally. Trace fossils occur in places in the Vejle Fjord Formation.

Log characteristics. The formation is characterised by intermediate gamma-ray values (Fig. 22). The log pattern is serrated and shows both decreasing- and increasing-upward trends throughout the succession.

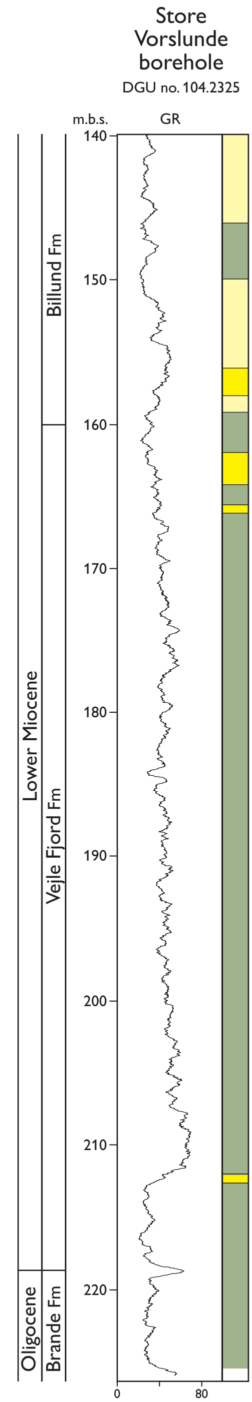


Fig. 22. Secondary reference section of the Vejle Fjord Formation: the interval from 219 to 160 m in the Store Vorslunde borehole, north-east of Vejle; for legend, see Fig. 8, p. 17.

Fossils. The Vejle Fjord Formation contains an impoverished mollusc fauna (Ravn 1907; Eriksen 1937; Schnetler &

Fig. 23. Type section of the Vejle Fjord Formation at Skansebakke, Brejning; spade for scale (*c.* 1.3 m long).

Beyer 1987, 1990). The foraminifer fauna (Larsen & Dinesen 1959; Laursen & Kristoffersen 1999) and the dinocyst flora (Dybkjær 2004 a, b; Rasmussen & Dybkjær 2005) are similarly impoverished within this formation, although the abundance of dinocysts is locally very high, albeit restricted to a few species.

Depositional environment. The Vejle Fjord Formation was deposited in a brackish to fully marine depositional environment. Brackish-water conditions predominated within the Norwegian–Danish Basin in the early phase of deposition as a consequence of the elevated Ringkøbing–Fyn High (Rasmussen & Dybkjær 2005; E.S. Rasmussen 2009a). As sea level rose during the Early Miocene, fully marine conditions were re-established and the water 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 developments of the formation are associated with inter-lobe depositional environments.

Boundaries. The lower boundary is typically sharp, being characterised by a change from greenish dark brown, glaucony-rich, clayey silt to dark brown, clayey silt. A change in the degree of consolidation is observed at the boundary over much of Jylland, relatively loose sediments of the Vejle Fjord Formation overlying well-consolidated sediments of the Brejning Formation. A gravel layer is commonly found at the lower boundary. At the type locality, the lower boundary is marked by a distinct decrease in the content of glaucony (Larsen & Dinesen 1959); the scattered glaucony grains found in the Vejle Fjord Formation are reworked (E.S. Rasmussen 1987). In central east Jylland, the boundary is commonly characterised by a marked change from the sand deposits of the Øksenrade Member (upper Brejning Formation) to dark brown, clayey silt of the Vejle Fjord Formation. Recognition of the lower boundary of the formation in subsurface data is based on both lithological and petrophysical data. The gamma-ray response at the boundary is variable. Where the upper Brejning Formation is mud-rich, as in the reference section for the formation (Fig. 8), gamma-ray values fall at the boundary to intermediate levels. In contrast, where the upper Brejning Formation is sand-rich (e.g. Fig. 14), or where the Vejle Fjord Formation overlies deltaic sands referred to the Billund Formation (e.g. Stakroge and Assing Mølleby boreholes, Plate 3), the

Fig. 24. Hummocky cross-stratified sand in the upper part of the Vejle Fjord Formation at Jensgård, east of Horsens (Fig. 1); the dipping, weakly deformed attitude of these strata is due to glaciotectonics.

Fig 25. Hummocky cross-stratified sand with burrows (*Scolicia* isp.) from the Vejle Fjord Formation at Skyum (Fig. 1). 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 the thicker storm sand layers were preserved. Knife blade for scale.

lower boundary is defined by an abrupt increase in gamma-ray values. Although in a number of wells the boundary can be difficult to position based on log data alone, lithological evidence (e.g. the presence of a gravel layer, glaucony content, clay colour and consolidation) can aid identification (e.g. Resen and Mausvig boreholes, Plate 5).

The upper boundary is typically defined where clayey, organic-rich silty sediments of the Vejle Fjord Formation are succeeded by sand-rich deposits (> 75% sand) with a minimum thickness of 5 m; the overlying sands are referred either to the Billund Formation or to the Kolding Fjord Member of the Klintinghoved Formation (e.g. Plate 6). On the gamma-ray log, this boundary may show a marked decrease in gamma-ray readings where overlain by a discrete sand unit, or a gradual but steady decrease in gamma-ray readings reflecting a transitional, interbedded, sand-rich unit at the base of the overlying formation. Where the Billund Formation is absent in south and west Jylland, the Vejle Fjord Formation is succeeded by the clay-rich Klintinghoved Formation, and the boundary can be difficult to locate in detail. In the Rødding and Føvling boreholes (Plate 8), for example, the two formations are lithologically very similar although the clayey silts of the Vejle Fjord Formation may be slightly more consolidated. The boundary can typically be picked on the gamma-ray log, however, at a minor or moderate upward increase in values, commonly capping a weak coarsening-upward succession (decreasing-upward gamma-ray values).

Distribution. The formation is present over much of Jylland with the exception of the southern and westernmost parts (Fig. 10B). The northern and eastern limit closely follows the overall outcrop pattern of the Miocene deposits (Fig. 4).

Biostratigraphy. The *Chiropteridium galea* and the *Homotryblium* spp. Dinocyst Zones of Dybkjær & Piasecki (2010) are recorded in the Vejle Fjord Formation.

Geological age. The Vejle Fjord Formation is of Aquitanian (earliest Early Miocene) age.

Subdivision. The Vejle Fjord Formation includes the Skansebakke Member.

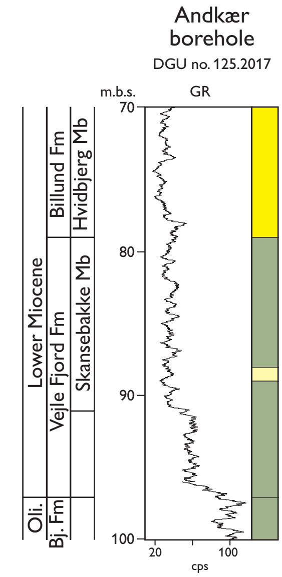


Fig. 26. The reference section of the Skansebakke Member is the interval from 91.10 to 79 m in the Andkær borehole. Note that the sand-rich nature of the interval indicated by the gamma-ray log is not reflected by the lithological sample data; for legend, see Fig. 8, p. 17. **Bj.**: Brejning. **Oli.**: Oligocene.

Skansebakke Member

revised member

History. Sediments referred here to the Skansebakke Member were formerly assigned to the Vejle Fjord Sand Member by Larsen & Dinesen (1959); the member is renamed here in accordance with modern lithostratigraphic guidelines.

Name. After the outcrop of the type section at Skansebakke, Brejning, on the south coast of Vejle Fjord.

Type and reference sections. The type section is the outcrop at Skansebakke (55°40´19.74´´N, 9°41´33.84´´E; Fig. 1). It is also exposed at Brejning Hoved, Sanatoriet, Fakkegrav and Dykær. The reference section is the interval from 91.10 to 79 m (92–79 m MD) in the Andkær borehole (DGU no. 125.2017; Fig. 26).

Thickness. At the type locality, the member is *c.* 7 m thick (top not seen); the member is *c.* 12 m thick at Brejning Hoved and 7 m thick at Sanatoriet.

Lithology. The Skansebakke Member consists of alternating layers of fine-grained, well-sorted, yellowish sand and brownish clay (Fig. 27). The sand beds are sharp-based and homogenous to evenly laminated. The sand beds are commonly capped by wave- and current-ripples. The trace fossils *Arenicolites* isp. and *Macaronichnus* isp. are common, and *Ophiomorpha* isp. is sporadically distributed (Friis *et al.* 1998). The pyrite content is relatively high compared to the overlying Billund Formation, resulting in the yellowish colour in exposed sections (M. Olivarius, personal communication 2010).

Log characteristics. The member is characterised by low gamma-ray readings with a serrated pattern (Fig. 26), reflecting the alternation of sand and mud beds.

Fossils. The Skansebakke Member contains an impoverished mollusc fauna (Ravn 1907; Eriksen 1937). The foraminifer fauna (Larsen & Dinesen 1959) and the dinocyst flora (Dybkjær 2004 a, b; Rasmussen & Dybkjær 2005) are also 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 at the base of the first significant sand layer separating dark brown, clayey silt from a succession dominated by interbedded yellowish fine-grained sand and dark brown to brown, silty clay. On the gamma-ray log, the lower boundary is placed at a minor, but distinct decrease in gamma-ray readings. The upper boundary is defined by the distinct change from yellowish, fine-grained sand to white, fine- to medium-grained

Fig. 27. Alternating fine-grained sand and clay of the Skansebakke Member at Skansebakke. 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 (*c.* 1.3 m long).

sand of the Hvidbjerg Member (Billund Formation). This boundary is only documented in the Andkær borehole where the gamma-ray log changes from serrated, low–intermediate gamma-ray readings of the Skansebakke Member to more consistently low gamma-ray values of the Hvidbjerg Member.

Distribution. The Skansebakke Member is restricted to central east Jylland and is exposed along the coast of Vejle Fjord (Fig. 10B). In the subsurface, this member is only recognised in the Andkær borehole.

Biostratigraphy. The *Chiropteridium galea* and the *Homotryblium* spp. Dinocyst Zones of Dybkjær & Piasecki (2010) are recorded in the Skansebakke Member.

Geological age. The Skansebakke Member is of Aquitanian (earliest Early Miocene) age.

Billund Formation

new formation

Name. After the town of Billund (Fig. 1).

Type and reference sections. The type section of the Billund Formation is the interval from 235 m to 184 m (235–185 m MD) in the Billund borehole (DGU no. 114.1857, 55°43´08.53´´N, 9°08´33.98´´E; Fig. 28). The reference section is the interval from 160 to 126 m (161–128 m MD) in the Store Vorslunde borehole (DGU no. 104.2325; Fig. 28).

Thickness. In the type section, the formation is 51 m thick; the maximum thickness of 77 m has been found in the Hammerum borehole (Plate 6).

Lithology. The Billund Formation is primarily known from the subsurface but is exposed at a number of localities. In the Lillebælt area, the formation is exposed at Børup, Galsklint, Hindsgavl, Røjle and Rønshoved and in the Vejle Fjord region at Dykær, Fakkegrav and Hvidbjerg. In central Jylland, the formation can be observed at Addit, Salten and Voervadsbro, and at Søndbjerg and Lyby in northern Jylland. It is composed of fine- to coarse-grained sand with some gravel or pebble-rich beds (Fig. 29). The formation consists of almost pure quartz sand and includes clasts of quartzitic sandstone with subordinate mica and heavy minerals. Clasts of well-rounded chert occur locally. Pebbly horisons are common in the upper part and at the base of fluvial channels; clasts up to 4 cm occur in erosional scours within steep clinoform units. The formation is characterised by both coarsening-upward and fining-upward depositional patterns. Fine-grained sand units which are commonly hummocky cross-stratified, occur in the lower part of the formation and in eastern sections. The upper part is commonly dominated by swaley cross-stratified sand or sharp-based sand with a homogeneous or laminated lower part capped by wave ripples. The trace fossils *Ophiomorpha* isp. and *Skolithos* isp. are common (Fig. 29; Friis *et al.* 1998; Rasmussen & Dybkjær 2005).

In the northern area, the formation is dominantly composed of cross-bedded sand with a range of set thicknesses. Soft sediment deformation structures are commonly seen. Some sections show an interval of interbedded, fine-grained, wave-rippled sands, muds and coals, sandwiched between two sand bodies with an overall sheet geometry. Root horizons and tree stumps are locally present (Weibel 1996; E.S. Rasmussen *et al.* 2007). In the eastern area, where the formation crops out, 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 (Fig. 30). The interbedded muds and heteroliths are dark brown in the northern part due to a high content of organic matter. In the southern area, the mud is light brown and typically thinner bedded, occurring interbedded with storm sand beds.

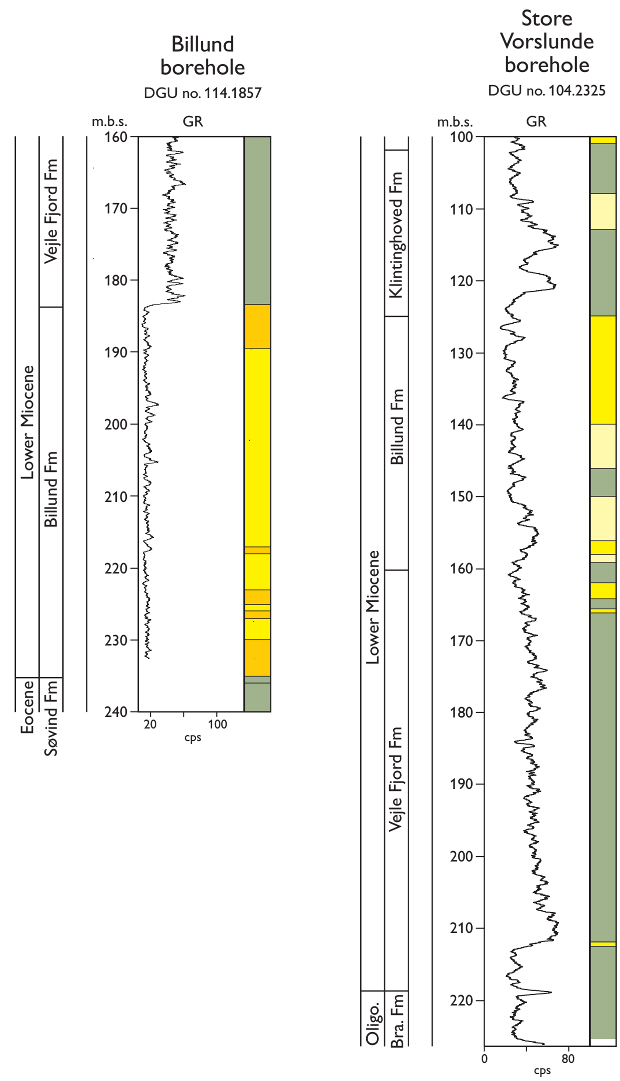


Fig. 28. Type and reference sections of the Billund Formation. The type section is the interval from 235 to 184 m in the Billund borehole and the reference section is the interval from 160 to 126 m in the Store Vorslunde borehole; for legend, see Fig. 8, p. 17. **Bra.**: Brande. **Olig.**: Oligocene.

Log characteristics. The formation is generally characterised by low gamma-ray values. In some boreholes, the lower part is characterised by a serrated lower part with gener-

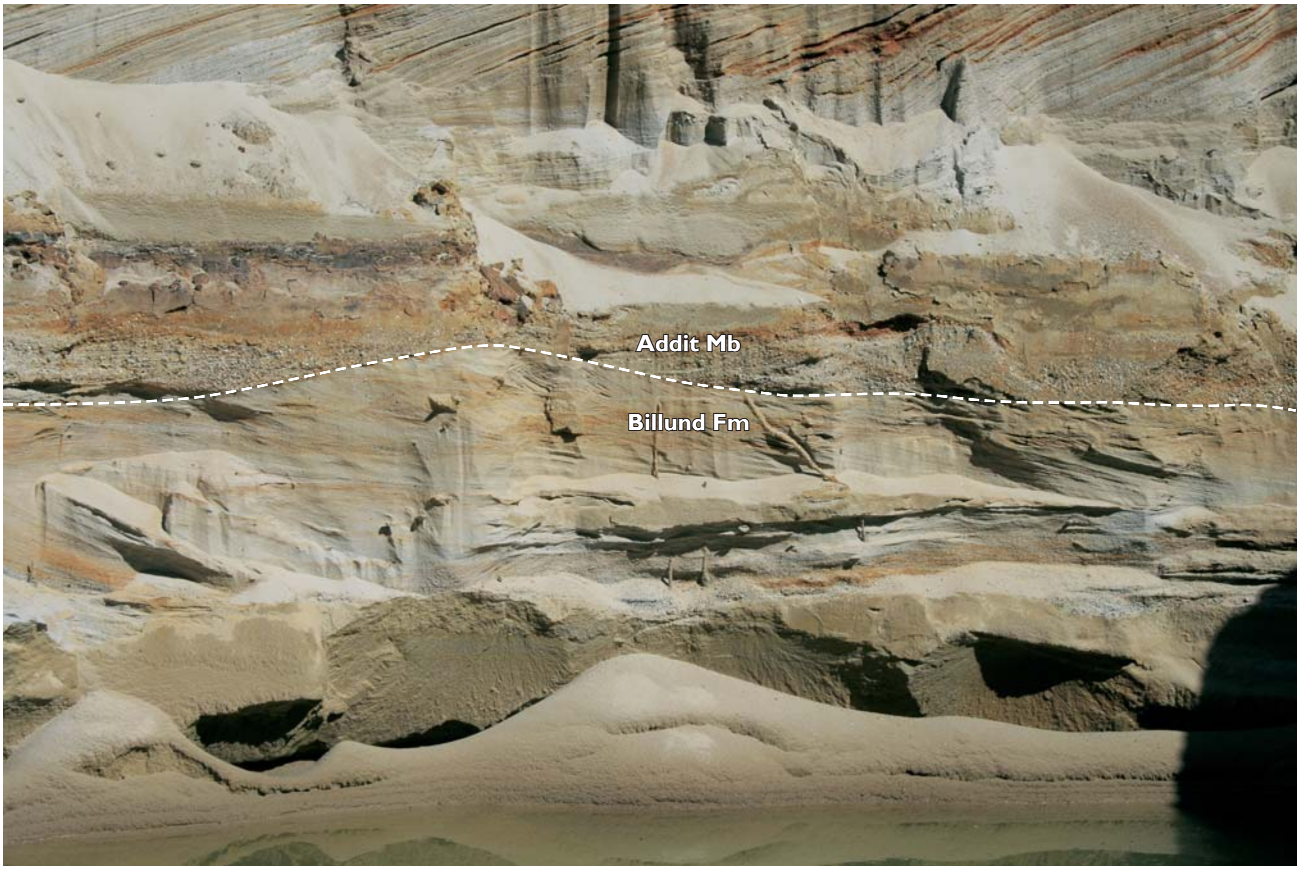


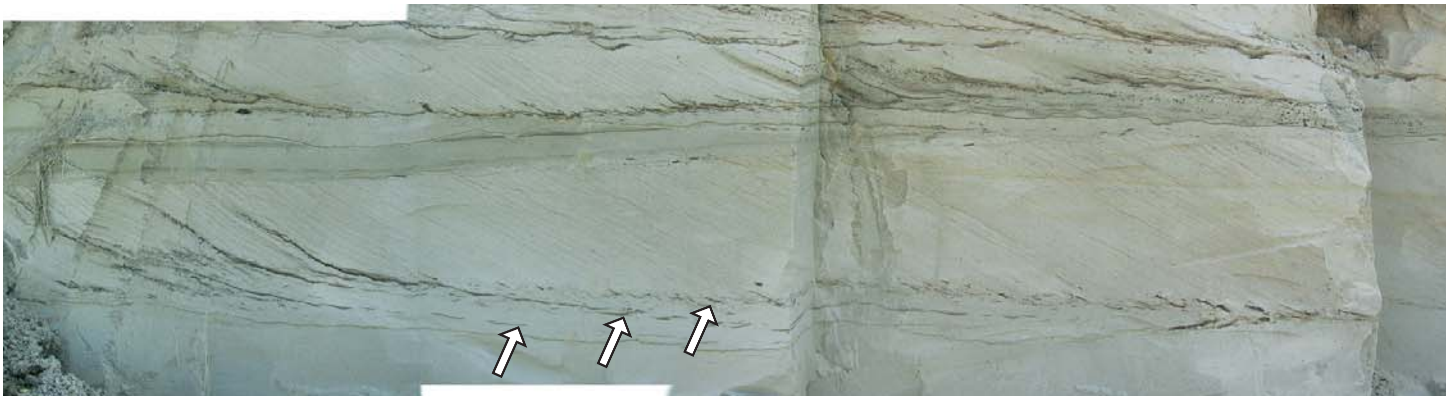
Fig. 29. Marine sand and fluvial gravel and sand of the Billund Formation exposed at Voervadsbro. Note the *Skolithos* burrows (centre) indicating a marine depositional environment. The lower boundary of the fluvial deposits (Addit Member) is at the base of the gravel layer (dashed line). The illustrated section is 2 m high.

ally higher gamma-ray values (e.g. Hammerum borehole, Plate 6). In the type borehole, the Billund Formation shows consistently low gamma-ray readings (Fig. 28).

Fossils. The Billund Formation contains fossil wood (Weibel 1996), leaves and seeds (Ravn 1907) but also marine molluscs (e.g. in the 'Brøndum Blokke'; Friis 1995). Foraminifers and dinocysts are present locally (Laursen & Kristoffersen 1999; E.S. Rasmussen *et al.* 2006).

Depositional environment. The Billund Formation was deposited as a delta system prograding from the north and north-east towards the south and south-east. The well-constrained palaeogeographical setting is based on high-resolution seismic data and facies distribution (Rasmussen & Dybkjær 2005; Hansen & Rasmussen 2008). Progradation took place in association with an Early Miocene inversion phase (E.S. Rasmussen 2009a), and the distribution of the delta lobes was consequently strongly controlled by the antecedent topography. Two major lobes, the Ringkøbing and Brande lobes, were mapped by Hansen & Rasmussen (2008). The Billund delta complex was deposited as wave-dominated deltas (Rasmussen & Dybkjær 2005; Hansen & Rasmussen 2008; E.S. Rasmussen 2009b). The south-eastward longshore currents that prevailed during the Early Miocene resulted in deposition of spit and barrier complexes south-east of the main delta lobes (Hvidbjerg Member). The most coarse-grained part was deposited in steeply dipping clinoformal packages deposited during falling sea-level (Hansen & Rasmussen 2008; E.S. Rasmussen 2009b) and within incised valleys (Addit Member).

Boundaries. The lower boundary is defined by a change from clayey, organic-rich silty sediments of the Vejle Fjord Formation to sand-rich deposits; as noted earlier, recognition of the Billund Formation requires a minimum sand thickness of 5 m and a sand–mud ratio of over 75%. Locally, for example in the type section at Billund, sand referred to the Billund Formation overlies the Eocene Søvind Marl; in such sections, the base of the formation is a significant



hiatal surface. On the gamma-ray log, the lower boundary is identified by a marked decrease in gamma-ray readings. In some sections (e.g. Store Vorslunde, Fasterholt boreholes, Plate 2), the shift from mud- to sand-rich deposits is gradational and reflected by a gradual but steady decrease in gamma-ray readings; the boundary is placed according to the criteria described above.

The upper boundary is placed at the change from sand-rich deposits of the Billund Formation to the predominantly dark brown, silty clays of the Klintinghoved Formation or the Vejle Fjord Formation. At outcrop, the boundary is often erosive and overlain by a gravel lag or sand layer showing a fining-upward trend; the base of the gravel lag or sand layer forms the upper boundary. On the gamma-ray log, the upper boundary shows a variety of motifs. In boreholes where the sandy Billund Formation is succeeded by mud-dominated facies of the Klintinghoved Formation, the boundary is defined at an abrupt increase in values. Where the lower Klintinghoved Formation includes gravel and sand layers succeeded by mud-rich facies (e.g. Egtved borehole, Plate 7), the boundary is placed at the base of a prominent shift to lower gamma-ray values that is succeeded by a general upward increase in values. Where gamma-ray readings are strongly serrated, the boundary is placed at the base of the most coarse-grained sand or gravel layer found in the lithological descriptions.

Distribution. The Billund Formation is distributed in central Jylland (Fig. 10C). Although beyond the formal boundaries of the formation, a sand-rich succession reported from the subsurface of the North Sea may represent the westernmost lobe of the Billund delta complex (Hansen & Rasmussen 2008).

Biostratigraphy. The *Chiropteridium galea* and the *Homotryblium* spp. Dinocyst Zones of Dybkjær & Piasecki (2010) are recorded in the Billund Formation.

Geological age. The Billund Formation is of Aquitanian (earliest Early Miocene) age.

Subdivision. The Billund Formation includes two members: the Hvidbjerg Member and the Addit Member.

Hvidbjerg Member

new member

General. The new Hvidbjerg Member represents a particular facies variant of the Billund Formation, dominated by spit deposits. The diagnostic features are only convincingly recognised at outcrop; the member is thus only recognised in the Vejle Fjord area in outcrops and closely adjacent boreholes. The member also crops out at Søndbjerg and Lyby in the Limfjorden area (Fig. 1).

History. The succession of white sands at Hvidbjerg Strand was studied by Larsen & Dinesen (1959); these authors refrained from including the 'Hvidbjerg Sand' in the Vejle Fjord Formation due to contrasting heavy mineral suites in these two units.

Name. After the outcrop at Hvidbjerg Strand on the south coast of Vejle Fjord (Fig. 1).

Type and reference sections. The type section of the Hvidbjerg Member is the coastal exposure at Hvidbjerg Strand on the south coast of Vejle Fjord (55°38´24.58´´N, 9°44´39.22´´E; Figs 31, 33). Other exposures are at Sanatoriet, Fakkegrav and Dykær in the Vejle Fjord area, at Pjedsted north-west of Fredericia and at Hindsgavl, Galsklint, Børup and Rønshoved in the Lillebælt area. The sand crops out at two localities in the Limfjorden area, at Søndbjerg and Lyby. The reference section is the interval

Fig. 30. Tidal bundles in the Hvidbjerg Member exposed at Pjedsted, north-west of Fredericia (Fig. 1). The cross-bedding dips towards the south-west and thus reflects ebb current flow. Note the clay drapes and preserved bottom sets (arrows) recording sedimentation during neap tides. The cross-bedded section thus represents a neap–spring–neap cycle (i.e. *c.* one and a half months). The section is 1.5 m high. Photograph courtesy of Ole Rønø Clausen.

from 79 to 58 m (79–58 m MD) in the Andkær borehole (DGU no. 125.2017; Fig. 32).

Thickness. The member is 28 m thick in the type section at Hvidbjerg (Fig. 31). In the outcrops of the Lillebælt area, it can attain 13 m but is rarely thicker than 6 m. In the subsurface, the member is recognised in the Andkær borehole (reference section, 21 m thick) and the Lillebælt borehole (*c.* 11 m).

Lithology. The Hvidbjerg Member consists of white, fine- to medium-grained sand with a few pebble layers (Fig. 33). The sand beds are dominated by sharp-based, structureless to evenly laminated sand capped by wave ripples. Hummocky and swaley cross-stratification are common in the southern area, near Lillebælt (Fig. 34). Trough and tabular cross-stratified sand beds occur locally as well as tidal bundles. The cross-bedding indicates bipolar current directions towards the north-east and south-west. Thin, light brown clay layers are common in the southern part. North of Hvidbjerg, a dark brown, mud-dominated unit up to 3 m thick is recognised, locally capped by wood debris. The trace fossils *Ophiomopha* isp. and *Skolithos* isp. occur locally. The Hvidbjerg Member differs from the remainder of the Billund Formation in relation to its better sorting and its dominantly aggradational stacking pattern (e.g. Rasmussen & Dybkjær 2005).

Log characteristics. The member is characterised by low gamma-ray readings (Fig. 32). High gamma-ray readings may be recorded where clay-rich, lagoonal deposits occur.

Fossils. A relatively rich dinocyst assemblage occurs in the Hvidbjerg Member (Dybkjær 2004a; Rasmussen & Dybkjær 2005).

Depositional environment. Deposition took place in a storm-dominated shoreface environment associated with spit development, south-east of the main Billund delta lobes. The core of a spit system crops out at Hvidbjerg. North of Hvidbjerg, shoreface sands alternate with mud-rich lagoonal deposits (Fig. 21). Tidal inlet deposits are observed at Dykær and Pjedsted where flood- and ebb-dominated systems, respectively, are recorded (Fig. 30).

Boundaries. The member overlies the Vejle Fjord Formation; the lower boundary is marked by a change from black, organic-rich, clayey silt to white sand. At Hvidbjerg, the lower boundary is erosional (Fig. 31). Where the member is superimposed on the Skansebakke Member of the Vejle Fjord Formation, the lower boundary is identified by a change from yellowish sands of the Skansebakke Member to white sands of the Hvidbjerg Member. On the gamma-ray log, the boundary is characterised by a distinct shift towards low gamma-ray readings.

The upper boundary is placed at the change from sand-rich deposits of the Hvidbjerg Member to the predominantly dark brown, silty clay of the Klintinghoved Formation. The boundary is often erosional and overlain by a gravel lag or sand layer showing a fining-upward trend; the gravel lag commonly contains of clasts up to 4 cm in diameter. The base of the gravel lag forms the upper boundary of the member. The gamma-ray readings may be characterised by an abrupt increase followed by a gradual decrease in values or a marked decrease in gamma-ray readings suc-

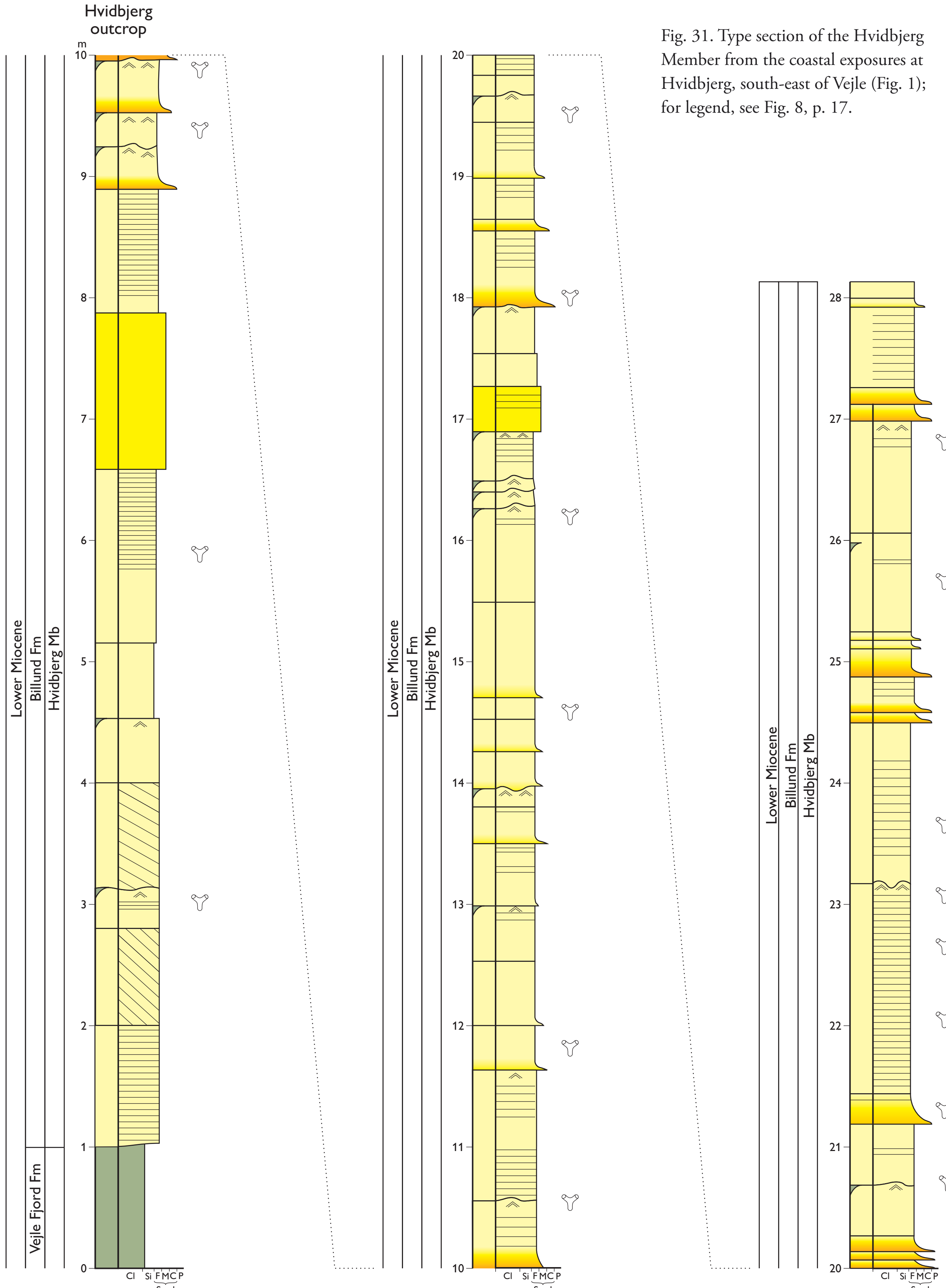


Fig. 31. Type section of the Hvidbjerg Member from the coastal exposures at Hvidbjerg, south-east of Vejle (Fig. 1); for legend, see Fig. 8, p. 17.

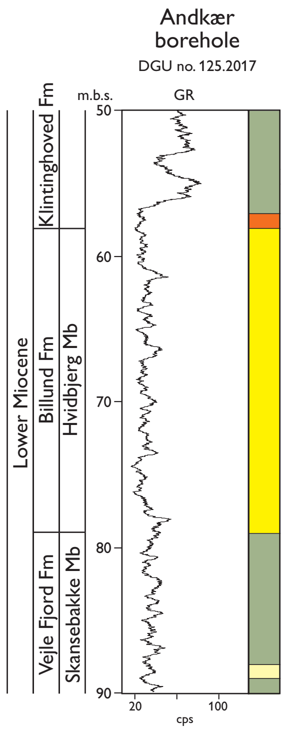


Fig. 32. Reference section of the Hvidbjerg Member in the Andkær borehole (79–58 m); for legend, see Fig. 8, p. 17.

ceeded by a gradual increase (e.g. Andkær borehole, Fig. 32); the boundary is placed at the lowest gamma-ray response.

Distribution. The Hvidbjerg Member is present in east Jylland and has also been found at Søndbjerg in northwest Jylland (Fig. 10C).

Biostratigraphy. The *Chiropteridium galea* and the *Homotryblium* spp. Dinocyst Zones of Dybkjær & Piasecki (2010) are recorded in the Hvidbjerg Member.

Geological age. The Hvidbjerg Member is of Aquitanian (earliest Early Miocene) age.

Fig. 33. The *c.* 27 m of white sand exposed at Hvidbjerg represents deposition on a spit system east of the main delta lobe of the Billund Formation. Note the stratification defined by the most bioturbated parts of the succession; photograph illustrates the upper levels of the Hvidbjerg Member shown in Fig. 31.

Fig. 34. Hummocky cross-stratified sand of the Billund Formation (Hvidbjerg Member) overlying interbedded, hummocky cross-stratified sands and clays of the Vejle Fjord Formation; Hindsgavl, near Middlefart (Fig. 1).

Addit Member

new member

History. Sand-rich fluvial and coal-bearing deposits in the Silkeborg area were first studied by Hartz (1909). He correlated the succession with Lower Miocene coal-bearing deposits in Schleswig-Holstein. L.B. Rasmussen (1961) indicated that the fluvio-deltaic sediments of the Silkeborg–Skanderborg area could be of similar age to the Ribe Formation as defined from the Arnum-1 well in southern Jylland. Studies of the succession in gravel pits south of Silkeborg were carried out during the 1970s and 1980s, 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, although Friis (1995) was aware of the problems inherent in this correlation. Re-investigation of the Salten inland cliff and the gravel pits at Addit and Voervadsbro, including biostratigraphic analysis based on dinocysts, revealed that the succession is Early Miocene in age and should be correlated with the Vejle Fjord Formation – Billund Formation depositional phase (E.S.Rasmussen *et al.* 2006).

Name. After the village of Addit, south-south-west of Århus (Fig. 1).

Type and reference sections. The type section of the Addit Member is defined as the Dansand gravel pit at Addit (56°02´26.33´´N, 9°37´59.62´´E; Fig. 35). The member is also exposed in the Voervadsbro gravel pit which forms the primary reference section (Fig. 36), and in the inland cliff at Salten. The secondary reference section is the interval from 117 to 55 m (119–55 m MD) in the Addit Mark borehole (DGU no. 97.928; Fig. 37).

Thickness. In the type section, the Addit Member is over 33 m thick; neither top nor base are seen. In the Addit borehole nearby (Fig. 1), the member is 50 m thick (Plate 6) and 62 m was penetrated in the borehole at Addit Mark (Fig. 37; Plate 6). Where well developed in central and north-east Jylland, the member is typically 20–50 m thick (see Plates 1, 2, 5, 6).

Lithology. The succession is typically composed of two sand- and gravel-rich units separated by fine-grained, sandy and clayey sediments, commonly with intercalated coal layers (Figs 35, 36, 38; Plates 1, 6), though the middle heterogeneous unit may be absent or poorly developed. The sands consist almost solely of quartz and quartzitic sandstone lithic grains, with minor content of mica and heavy minerals; clasts of well-rounded chert may occur. The two sand-rich units are characterised by fining-upward trends and possess 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 (Figs 35, 36, 39). Upwards, these sand-rich units are 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 structures. The coal-bearing, fine-grained sand and clay layer, sandwiched between the coarser units, consists of cross-bedded sand and alternating thin, rippled, fine-grained sand and clay layers. Bioturbation is observed rarely. Wood fragments are abun-

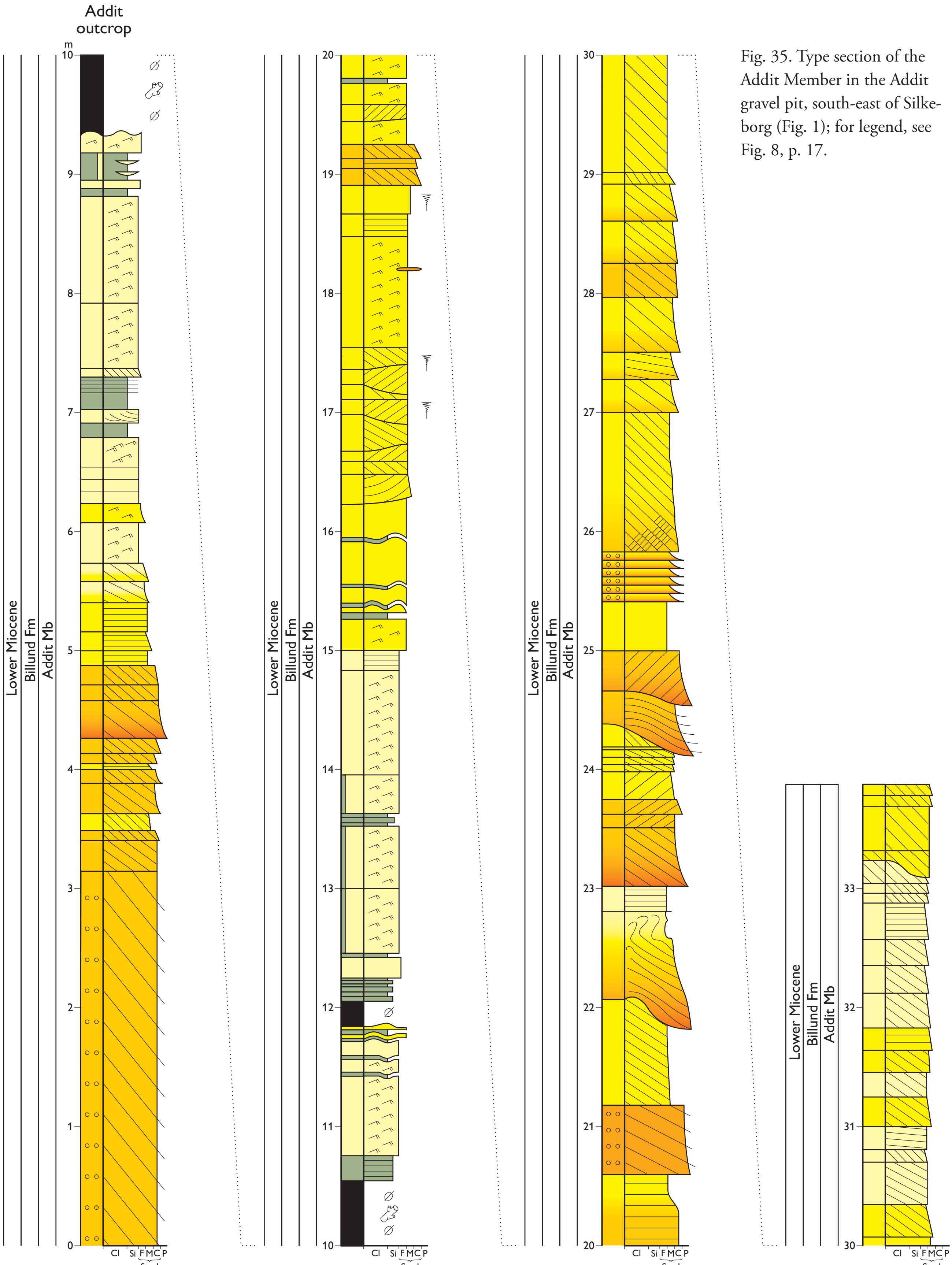


Fig. 35. Type section of the Addit Member in the Addit gravel pit, south-east of Silkeborg (Fig. 1); for legend, see Fig. 8, p. 17.

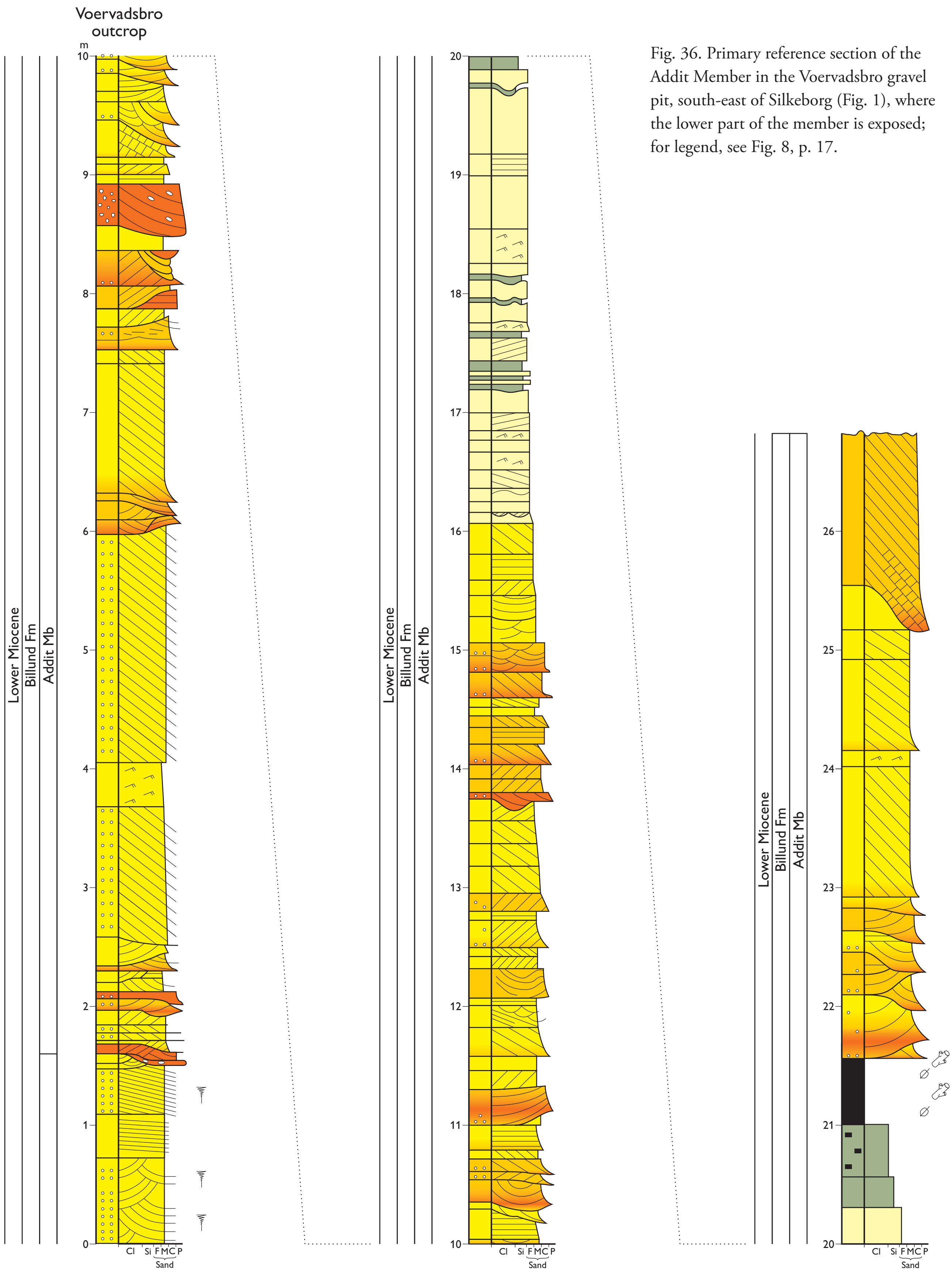


Fig. 36. Primary reference section of the Addit Member in the Voervadsbro gravel pit, south-east of Silkeborg (Fig. 1), where the lower part of the member is exposed; for legend, see Fig. 8, p. 17.

dant at certain horizons and petrified wood is common at Voervadsbro (Weibel 1996).

Log characteristics. The member is characterised by low gamma-ray readings, especially in the lower part (Fig. 37). The sand-rich part is commonly characterised by a slight upward increase in gamma-ray values. A moderate–high gamma-ray response commonly characterises the middle part of the member, reflecting the clay-rich and coal-bearing deposits at this level.

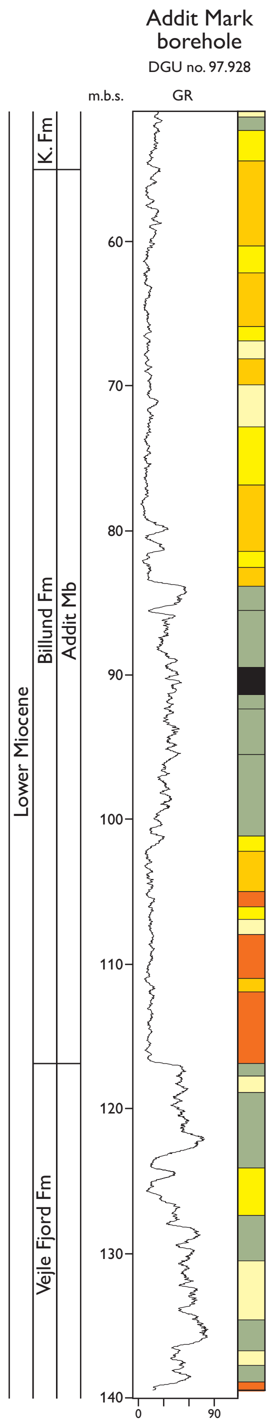


Fig. 37. Secondary reference section of the Addit Member in the Addit Mark borehole (117–55 m); for legend, see Fig. 8, p. 17. **K.**: Klintinghoved.

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

Depositional environment. The lower sands of the member were deposited as migrating three-dimensional dunes (main channel) and migrating unit and compound bars in a braided fluvial system (Hansen 1985; Hansen 1995; E.S. Rasmussen *et al.* 2006). The upper part of the member was deposited as migrating two-dimensional dunes; sedimentary structures such as cross-bedded sand beds with preserved bottomsets and normally graded foresets indicate 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 middle part of the member was deposited in a flood plain and lake environment that was occasionally flooded by the sea as indicated by the rare presence of dinocysts and *Ophiomorpha* trace fossils.

Boundaries. Where the Addit Member directly overlies the Vejle Fjord Formation, the lower boundary is marked by an abrupt change from dark brown, silty clay or clayey silt to grey, coarse-grained sand and gravel (Fig. 37; Plates 1, 2, 6). Where the Addit Member overlies the Hvidbjerg Member, the boundary is marked by an erosional boundary where white, fine- to medium-grained sand is overlain by gravel (Fig. 29). On the gamma-ray log, the lower boundary is shown as a prominent shift on the gamma-ray log where the Addit Member overlies the Vejle Fjord Formation. Where the member overlies the Hvidbjerg Member, the lower boundary is placed at the change of gamma-ray reading from a gradual upward decrease in gamma-ray readings to consistently low or decreasing-upward gamma-ray readings.

The upper boundary is placed at the change from sand-rich deposits of the Addit Member to predominantly dark brown, silty clays of the Klintinghoved Formation. The boundary may be erosional, being overlain by a gravel lag or sand layer showing a fining-upward trend; the gravel lag commonly contains clasts up to 4 cm in diameter. The base of the gravel lag or sand layer forms the upper boundary of the member. The gamma-ray log is commonly characterised by an abrupt increase in gamma-ray values (e.g.

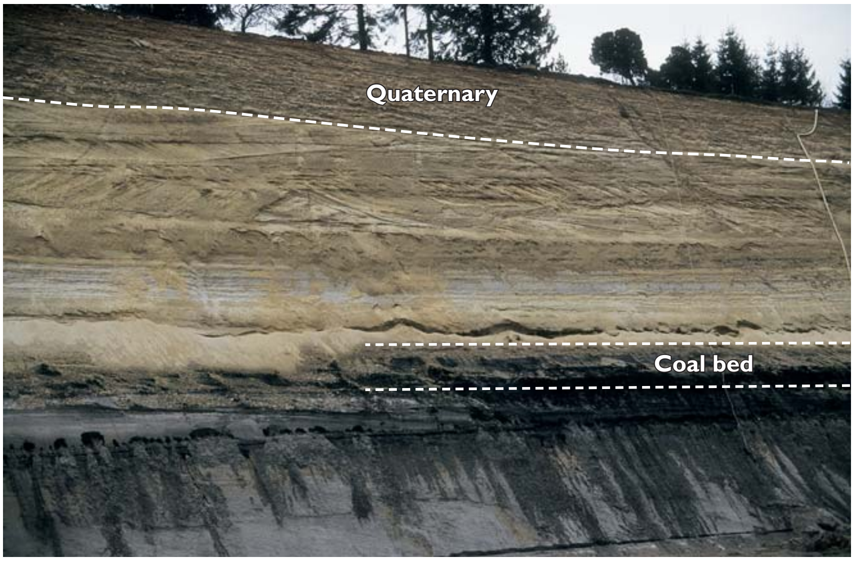


Fig. 38. Addit Member at the Addit gravel pit showing the two fining-upward sand- and gravel-rich units and the intercalated coal unit. The height of the section is 40 m.

Resen, Plate 5; Isenvad, Plate 6). Locally, a decrease in gamma-ray readings is succeeded by a gradual increase in gamma-ray values (e.g. Hammerum, Sunds, Plate 2). Here the boundary is placed at the lowest gamma-ray readings.

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 elongate zone striking from Resen (south-west of Viborg) to the area between Herning and Ikast (Figs 1, 10C).

Biostratigraphy. The *Homotryblium* spp. Dinocyst Zone of Dybkjær & Piasecki (2010) is recorded in the Addit Member.

Geological age. The Addit Member is of Aquitanian (earliest Early Miocene) age.

Fig. 39. Cross-bedded sand and gravel of the Addit Member in the Addit gravel pit deposited as a mid-channel bar in a braided fluvial system. The height of the section is 3 m.

Klintinghoved Formation

redefined formation

General. The marine clay-rich deposits of the Klintinghoved Formation interdigitate towards the north-east with the more proximal sand-rich deltaic sediments of the Bastrup Formation. These formations thus alternate up-section in certain boreholes (e.g. Plates 1, 2, 6).

History. The mollusc fauna of marine clay-rich deposits at Klintinghoved was described by Sorgenfrei (1940). The deposits were defined as the Klintinghoved Formation in a later publication (Sorgenfrei 1958). The Klintinghoved Formation was included in the stratigraphy of L.B. Rasmussen (1961).

Name. After Klintinghoved cliff, Flensborg Fjord (Figs 1, 42).

Type and reference sections. Following Sorgenfrei (1958), the type section is the outcrop at Klintinghoved cliff (54°53´23.15´´N, 9°49´43.62´´E; Figs 40, 42). The reference section is designated in the cored Sdr. Vium borehole (DGU no. 102.948; 54°53´23.18´´N, 9°49´43.94´´E) from 288 to 132 m (Figs 40, 41).

Thickness. At Klintinghoved, the exposed section is 3.5 m thick; neither base nor top of the formation is seen. In the subsurface, the formation is 10–50 m thick in central Jylland, thickening to over 125 m in the west and southwest (e.g. Sdr. Vium, Fig. 40).

Lithology. The formation consists of dark brown, silty clay with subordinate intercalated sand beds (Figs 43, 44). The sand beds are sharp based and homogenous to finely laminated; double clay layers are recognised locally. In the cored borehole at Sdr. Vium, the formation is dominated by dark brown mud with intercalated sand beds (Figs 40, 41, 45). The sand beds typically show sharp lower boundaries, and are commonly structureless in the lower part passing upward into laminated sand.

Log characteristics. The formation is characterised by moderate to high gamma-ray values (Fig. 40). The log pattern is highly serrated, reflecting interbedded muds and sands at various levels, and shows a general decrease in gamma-ray response upwards.

Fossils. The Klintinghoved Formation contains a rich mollusc fauna (Sorgenfrei 1958). Shark teeth also occur and marine microfossils such as foraminifers (Laursen & Kristoffersen 1999) and dinocysts (Dybkjær & Rasmussen 2000; Dybkjær 2004a; Rasmussen & Dybkjær 2005) are abundant and diverse.

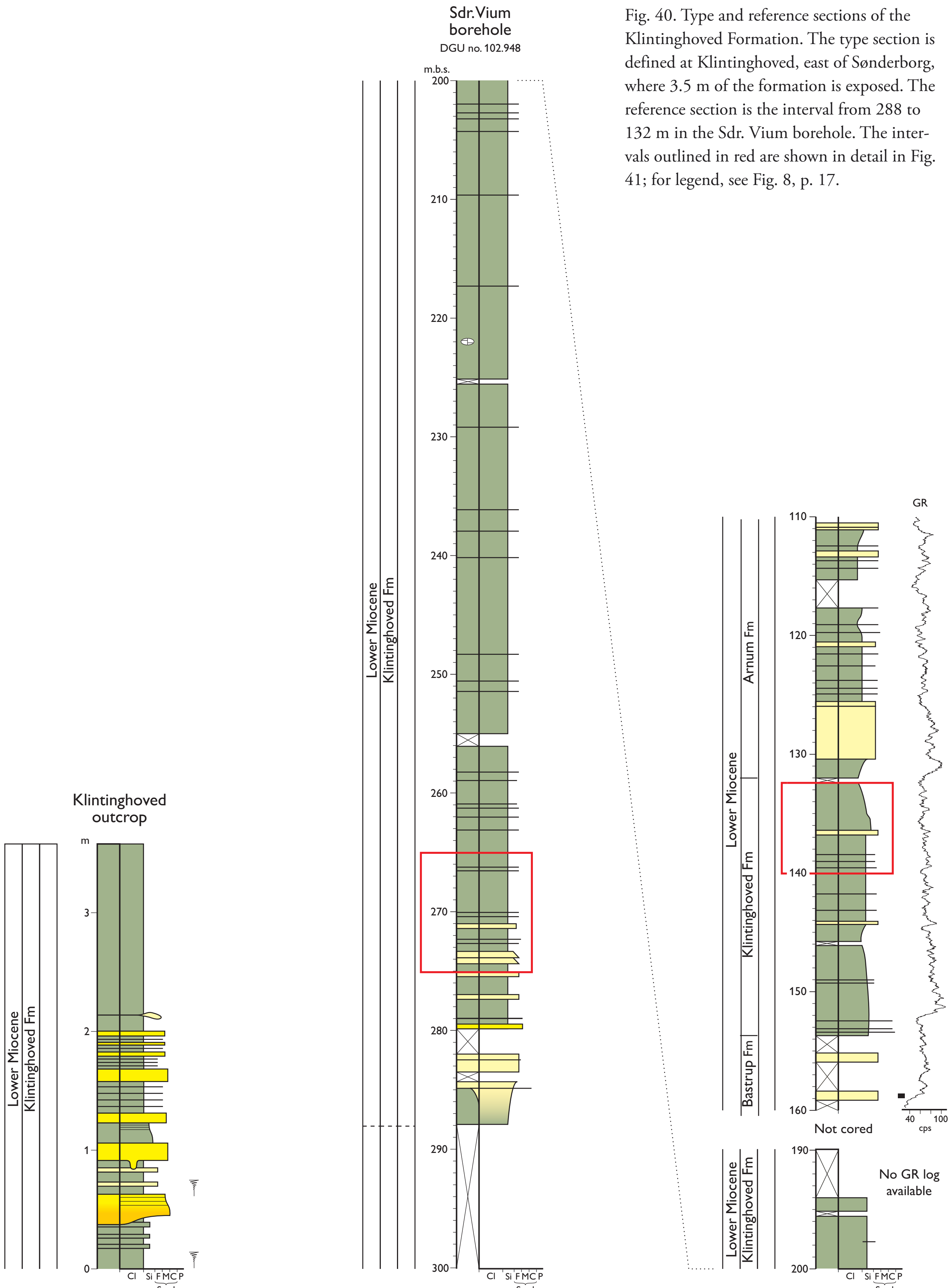


Fig. 40. Type and reference sections of the Klintinghoved Formation. The type section is defined at Klintinghoved, east of Sønderborg, where 3.5 m of the formation is exposed. The reference section is the interval from 288 to 132 m in the Sdr. Vium borehole. The intervals outlined in red are shown in detail in Fig. 41; for legend, see Fig. 8, p. 17.

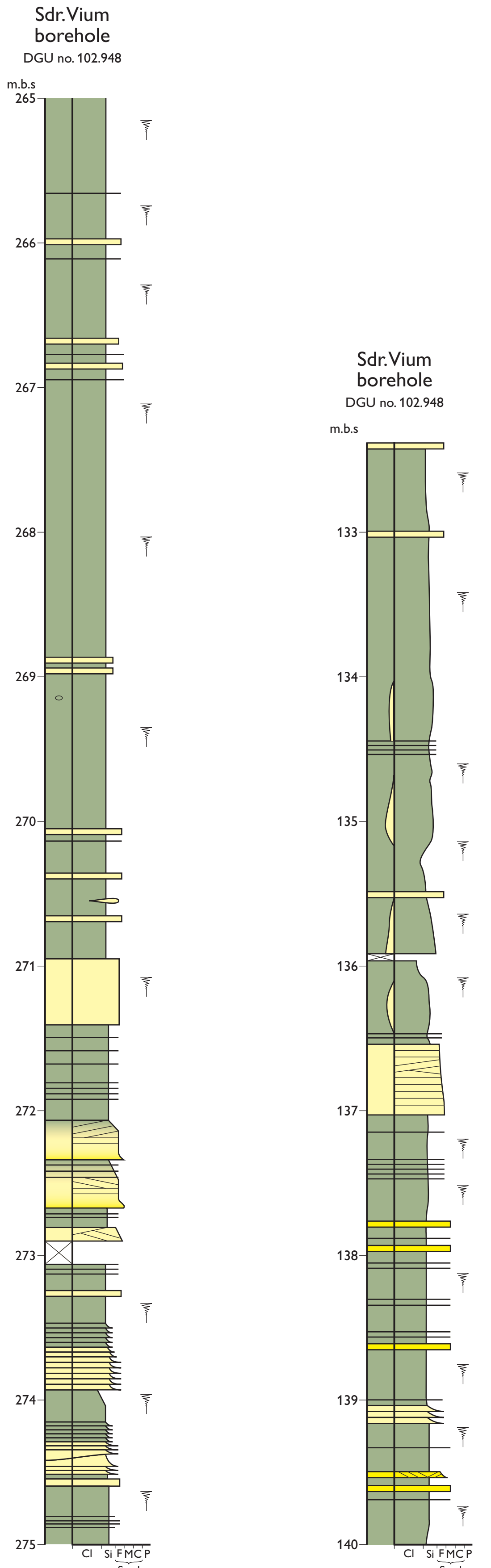


Fig. 41. Detailed sedimentological logs of representative intervals of the Klintinghoved Formation in the reference section (for location, see Fig. 40; for legend, see Fig. 8 on page 17).

Depositional environment. The Klintinghoved Formation was deposited in shelf, delta slope and lower shoreface environments. 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 strongly influenced by storms and tidal processes.

Boundaries. The lower boundary is, in the northern part, characterised by a change from sand-rich deposits of the Billund Formation to the predominantly dark brown, silty clay of the Klintinghoved Formation (e.g. Store Vorslunde, Fasterholt, Sunds and Resen boreholes, Plate 2). In the southern part where the Klintinghoved Formation overlies the Vejle Fjord Formation, the boundary is not marked by significant changes in lithology, although the Vejle Fjord Formation tends to be slightly more consolidated. On the gamma-ray log, a weak to marked shift to higher gamma-ray values defines the boundary, especially where the Klintinghoved Formation overlies the Billund Formation (e.g. Rødding, Almstok, Store Vorslunde, Fasterholt, Sunds and Resen boreholes, Plate 2). At outcrop, the lower boundary is often erosional and overlain by a gravel lag, as seen at Rønshoved and Børup (Rasmussen & Dybkjær 2005); the gravel lag commonly contains clasts up to 4 cm in diameter.

The upper boundary is either sharp, exemplified by the Bastrup borehole (Fig. 52; Plate 8), or gradational as in the Almstok borehole (Fig. 52; Plate 2). In the Bastrup borehole, the upper 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 a change from alternating beds of sand and mud to a clean sand unit at least 5 m thick and comprising at least 75% sand. On the gamma-ray log, the

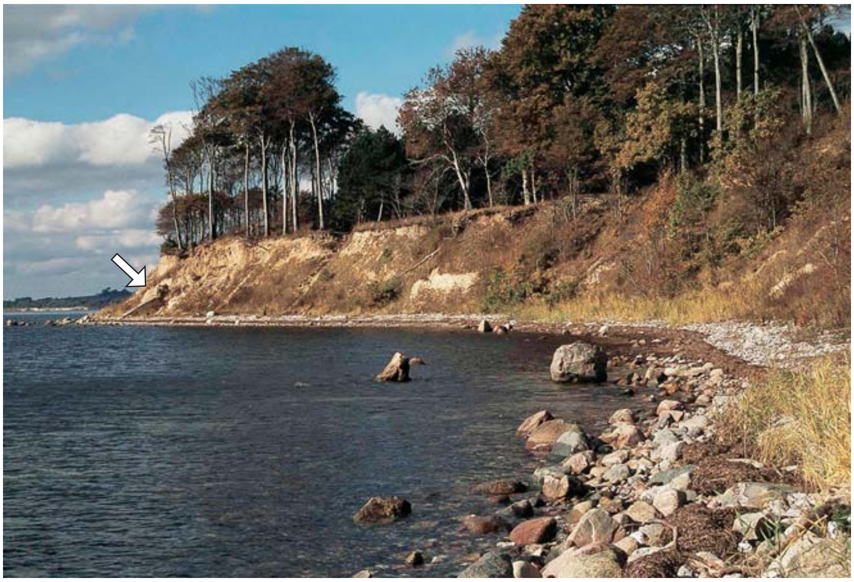


Fig. 42. The Klintinghoved cliff, viewed from the east (cliff is *c.* 10 m high). The location of the type section of the Klintinghoved Formation is arrowed.

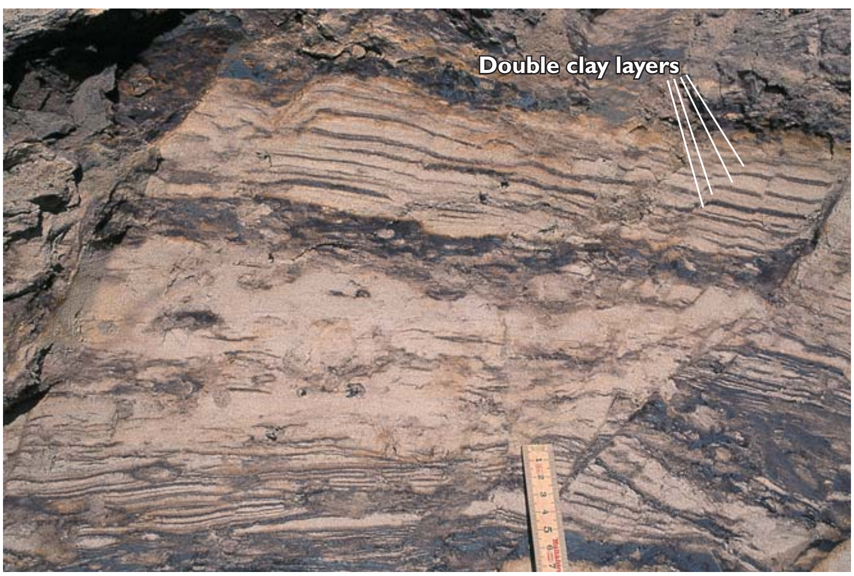


Fig. 43. Alternating clay and bioturbated and laminated sand of the Klintinghoved Formation at the type locality. Note the double clay layers in the sand indicating tidal influence on deposition.

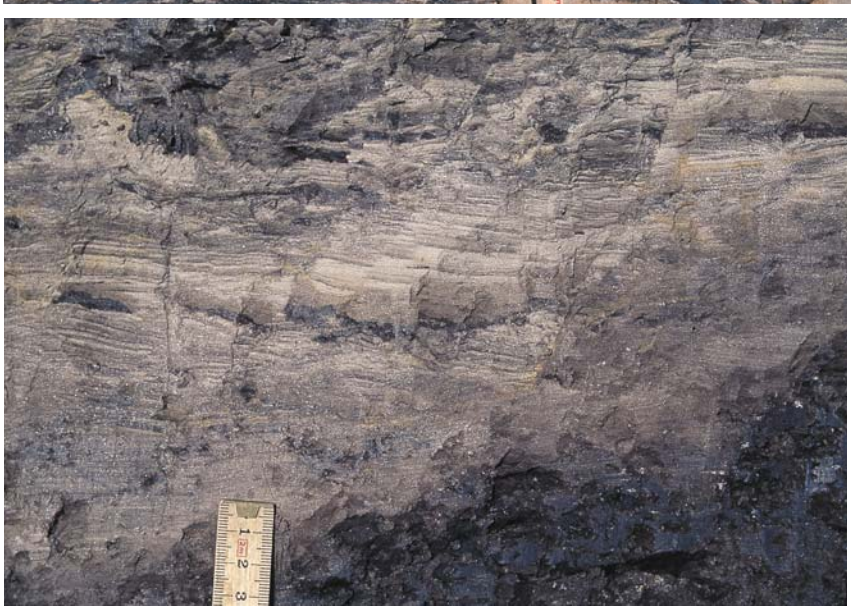


Fig. 44. Interlaminated, dark brown clayey silt and thin, fine-grained sand of the Klintinghoved Formation at the type locality.

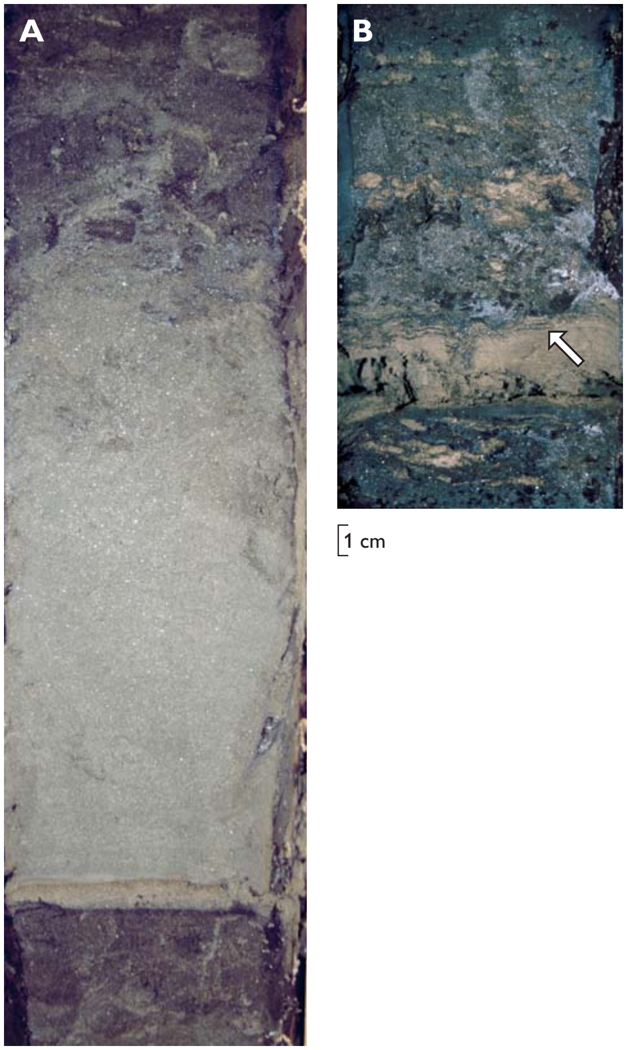


Fig. 45. Core sections from the Sdr. Vium borehole, illustrating interbedded, dark brown silty clays and sharp-based sands of the Klintinghoved Formation. **A**: 272.70 m (base of illustrated section); **B**: 250.45 m (base). The sand beds are normally graded and homogenous to weakly laminated in the lower part. Note the double clay layers (B, arrow) indicating tidal influence on sedimentation.

boundary is generally characterised by a minor decrease in gamma-ray values followed by a consistent decrease in values upwards, as seen in the Almstok borehole (Fig. 52; Plate 2) and in the Holstebro and Klosterhede boreholes (Plate 4). In the Bastrup borehole, the upper boundary is characterised by a distinct decrease in gamma-ray values. In western Jylland where Klintinghoved Formation is overlain by the Arnum Formation (e.g. Kvong, Sdr. Vium boreholes, Plate 4), the boundary is placed at a distinct increase in gamma-ray readings separating coarsening-upward units of the Klintinghoved and Arnum Formations.

Distribution. The Klintinghoved Formation is distributed in the northern part of central Jylland and in western and southern Jylland (Fig. 10D).

Biostratigraphy. The *Thalassiphora pelagica* and *Sumatradinium hamulatum* Dinocyst Zones of Dybkjær & Piasecki (2010) are recognised in the Klintinghoved Formation.

Geological age. The Klintinghoved Formation is of late Aquitanian to early Burdigalian (Early Miocene) age.

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

Kolding Fjord Member

new member

History. Sand and organic-rich clayey sediments exposed at Lillebælt were studied by Radwanski *et al.* (1975), E.S. Rasmussen (1995) and Friis *et al.* (1998). In these studies, the sediments were referred tentatively to the Vejle Fjord Formation of previous usage. However, a biostratigraphic study by Dybkjær & Rasmussen (2000) revealed that the sediments were significantly younger than the Vejle Fjord Formation (as recognised here) and equivalent in age to the Klintinghoved Formation (L.B. Rasmussen 1961).

Name. The Kolding Fjord Member crops out at a number of localities along Lillebælt and Kolding Fjord. It is named after Kolding Fjord, where the type locality of Rønshoved is situated.

Type and reference sections. The type section is the exposure at Rønshoved on the southern side of Kolding Fjord (55°29´26.90´´N, 9°38´36.10´´E; Figs 1, 46). Other localities where the member is exposed are Hagenør, Børup, Galsklint and Fænø in the Lillebælt and Kolding Fjord area (Fig. 1). A minor outcrop is also recognised at Gyldendal, Limfjorden. The reference section is the outcrop at Hagenør (Figs 1, 47).

Thickness. The Kolding Fjord Member is 11 m thick at Rønshoved and *c.* 8 m at Hagenør (Figs 46, 47). Although rarely exceeding 10 m, developments up to 20 m thick are recognised locally (e.g. Vonsild and Vind boreholes, Plates 1, 8).

Lithology. The member is composed of white to yellow, fine- to medium-grained sand with a few thin, brown clay layers. At the type section, the basal unit is a gravel layer *c.* 10 cm thick that contains clasts up to 4 cm in diameter. The clasts consist of almost pure quartz and quartzitic sandstone. The succeeding sandy part of the member in the type section is dominated by hummocky and swaley cross-stratified silt and fine-grained sand (Figs 46, 48). 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 up to 2 m thick of dark brown, organic-rich, clayey silt may be intercalated in the sand (Figs 49, 50). Homo-

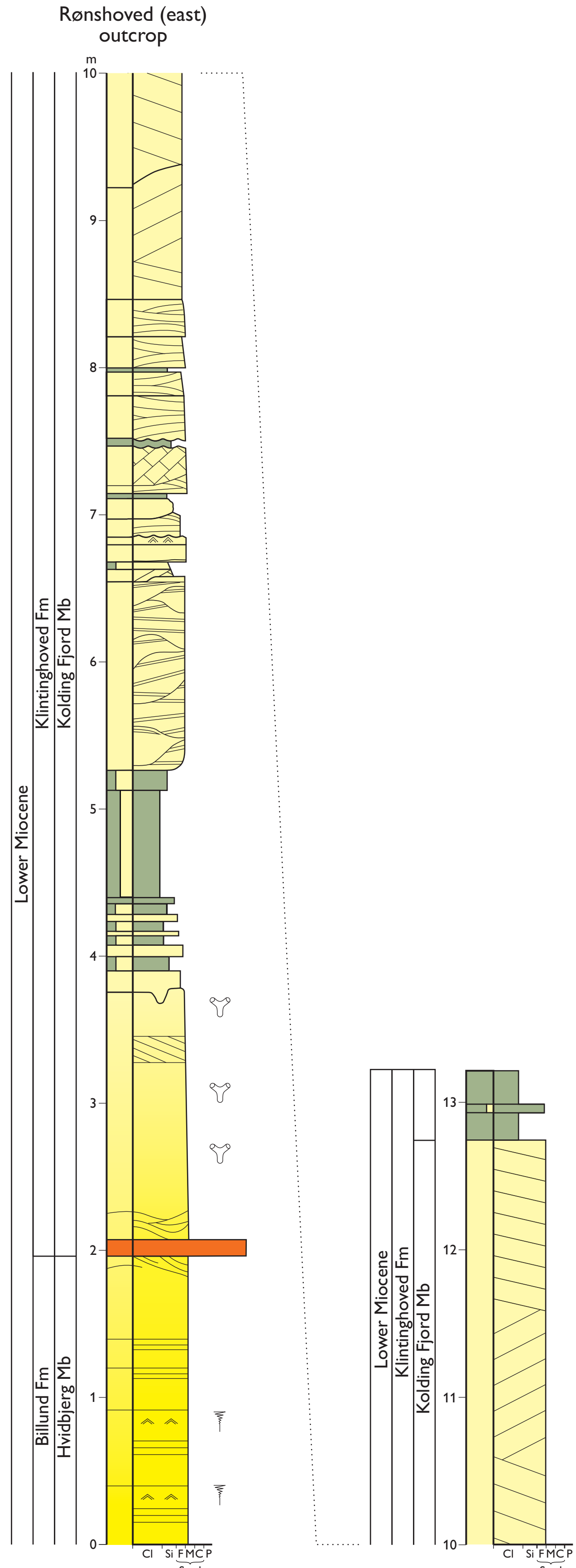


Fig. 46. Type section of the Kolding Fjord Member at Rønshoved, east of Kolding; for legend, see Fig. 8, p. 17.

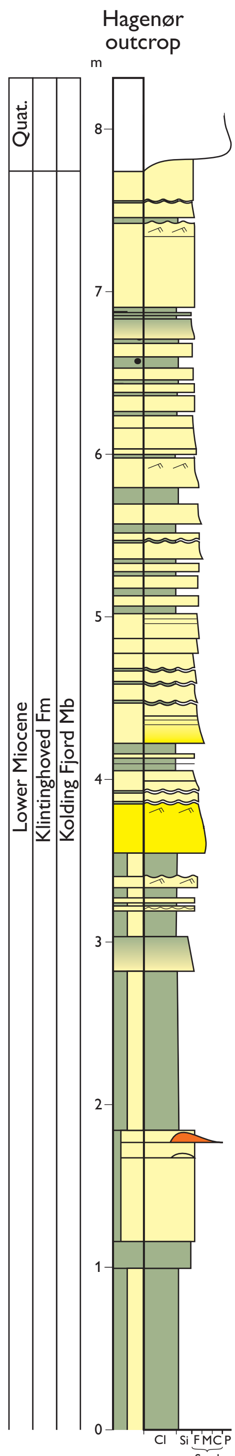


Fig. 47. Reference section of the Kolding Fjord Member at Hagenør; for legend, see Fig. 8, p. 17. **Quat.**: Quaternary.

geneous sand beds capped by wave-ripples are also common on top of lagoonal deposits (Fig. 51); wave-ripple crests are oriented north-west–south-east. Trace fossils, including *Macaronichnus* isp., *Ophiomorpha nodosa* and echinoid burrows, are common in the Kolding Fjord Member (Radwanski *et al.* 1975).

Log characteristics. The member is characterised by low to moderate gamma-ray values. The log pattern is serrated; high gamma-ray values are registered where lagoonal, clay-rich deposits dominate.

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

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

Boundaries. In the type section, the lower boundary is erosional and, as in other exposures (e.g. Børup, Galsklint) and borehole sections (e.g. Stakroge, Plate 3), is defined by a distinct change from the sandy deposits of the Billund Formation to gravel-dominated layers of the lowermost Kolding Fjord Member. In such cases, the gamma-ray log shows a marked decrease in values at the boundary (Plate 3). In the Vonsild borehole, however, located near the type and reference sections, the lower boundary is recognised by a prominent increase in gamma-ray readings, due to the presence of fine-grained, lagoonal sediments in the lower part of the member (Plates 1, 8). It is acknowledged that identification of this boundary may be difficult on the gamma-ray log where shoreface sands occur both beneath and above the boundary and the transgressive lag is thin.

The upper boundary is characterised by a change from the sand-dominated succession of the Kolding Fjord Member to dark brown, clayey silts of the Klintinghoved Formation. The gamma-ray log shows a distinct increase in gamma-ray values.

Distribution. The member is recognised in east Jylland and south-west of Holstebro in west Jylland (Fig. 10D).

Biostratigraphy. The *Thalassiphora pelagica* and *Sumatradinium hamulatum* Dinocyst Zones of Dybkjær & Piasecki (2010) occur in the Kolding Fjord Member.

Geological age. The Kolding Fjord Member is of late Aquitanian to early Burdigalian (Early Miocene) age.

Fig. 48. Heterolithic deposits of the Kolding Fjord Member sharply overlain (at 5.3 m in Fig. 46) by hummocky cross-stratified sand at Rønshoved in the type section. The heterolithic succession is characterised by alternating hummocky cross-stratified sand and sandy clay and various types of ripple-laminated sand. About 3 m of the section is shown.

Fig. 49. Exposure of the Kolding Fjord Member in the reference section at Hagenør. The lower part of the Hagenør outcrop is characterised by two organic-rich, clayey silt deposits separated by bioturbated sand (see Fig. 47). 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.

Fig. 50. Close-up of lagoonal facies in the Kolding Fjord Member at Hagenør. The light brown deposits that are capped by sand ripples and sandwiched between dark lagoonal clays contain marine palynomorphs and represent a short marine incursion; the strike of the ripple crests is NW–SE. The illustrated section is *c.* 2 m high.

Fig. 51. Close-up of the alternating sand and clay layers of the Kolding Fjord Member exposed in the upper part of the Hagenør reference section. Spade handle for scale.

Bastrup Formation

new formation

General. The new Bastrup Formation is recognised primarily in the subsurface. This fluvio-deltaic, sand-dominated formation interdigitates in a complex manner with the more distal, marine, mud-rich Klintinghoved Formation. These formations thus alternate up-section in certain boreholes (e.g. Plates 1, 2, 6).

Name. After Bastrup village, south-west of Kolding (Fig. 1).

Type and reference sections. The type section is the interval from 108 to 84 m (110–84 m MD) in the Bastrup borehole (DGU no. 133.1298; 55°24´21.58´´N, 9°14´47.40´´E; Fig. 52). The reference section is the interval from 160 to 111 m (160–111 m MD) in the borehole at Almstok (DGU no. 114.1858; Fig. 52).

Thickness. The thickness of the Bastrup Formation is 24 m in the type section, but the formation is commonly *c.* 50 m thick (see reference section, Fig. 52 and Plates 2, 3). A maximum thickness of 100 m was penetrated in the borehole at Løgumkloster (Plate 3).

Lithology. The Bastrup Formation consists predominantly of grey, medium- to coarse-grained sand with intercalated gravel layers; the diameter of gravel clasts rarely exceeds 2 cm. Petrologically, the sand is dominated by quartz and quartzite lithic grains with minor content of mica and heavy minerals. In a few boreholes, however, a high concentration of mica has been recorded (e.g. Estrup). Dark brown, organic-rich, silty clay is locally present. The formation is characterised by both coarsening-upward and fining-upward depositional patterns. The upper part of the formation is commonly characterised by a 15–30 m thick fining-upward succession consisting of coarse-grained to fine-grained sand. In the north, gravel commonly forms the base of the fining-upward units. Clay-rich sediments with subordinate intercalations of coal are often sandwiched between sand-rich units.

Log characteristics. The formation is characterised by low gamma-ray values (Fig. 52). The log pattern is serrated and shows both decreasing- and increasing-upward trends through the succession. The decreasing trend is associated with delta progradation and the increasing-upward trend is associated with channel-fill deposits (i.e. point bars) which are common in the upper levels of the formation, and can locally be demonstrated on seismic data (E.S. Rasmussen *et al.* 2007).

Fossils. A sparse foraminifer assemblage occurs in the distal part of the Bastrup Formation (Laursen & Kristoffersen 1999). The dinocyst flora is variable overall, being rich at some levels and very sparse/impoverished at other levels (Dybkjær 2004a; Dybkjær & Piasecki 2010).

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

Boundaries. The lower boundary is either sharp, for example in the type section of the Bastrup borehole or gradational as in the Almstok reference section (Fig. 52). In the type section, the lower boundary is placed where grey mud is sharply overlain by grey, medium-grained sand; on the gamma-ray log, this lower boundary is defined at a marked decrease in gamma-ray values. A gravel layer is commonly present at the base of the Bastrup Formation. In gradational sections showing interbedded sands and muds, becoming sandier upwards, the boundary is defined at the base of the first significant sand interval (at least 5 m thick) in which the sand to mud ratio is greater than 75%. In such gradational sections, the log response reflects the transitional nature of the boundary, showing a minor decrease in gamma-ray values followed by a consistent overall decrease upwards (e.g. the Almstok borehole, Fig. 52).

The upper boundary is defined by a sharp transition from grey and white sand of the Bastrup Formation to dark brown, silty clay of the Arnum Formation. In central Jylland, the Arnum Formation is developed as a grey to white silt, which rests with a sharp boundary on the sand-rich Bastrup Formation. On the gamma-ray log, this upper boundary is typically identified by a prominent shift to higher values.

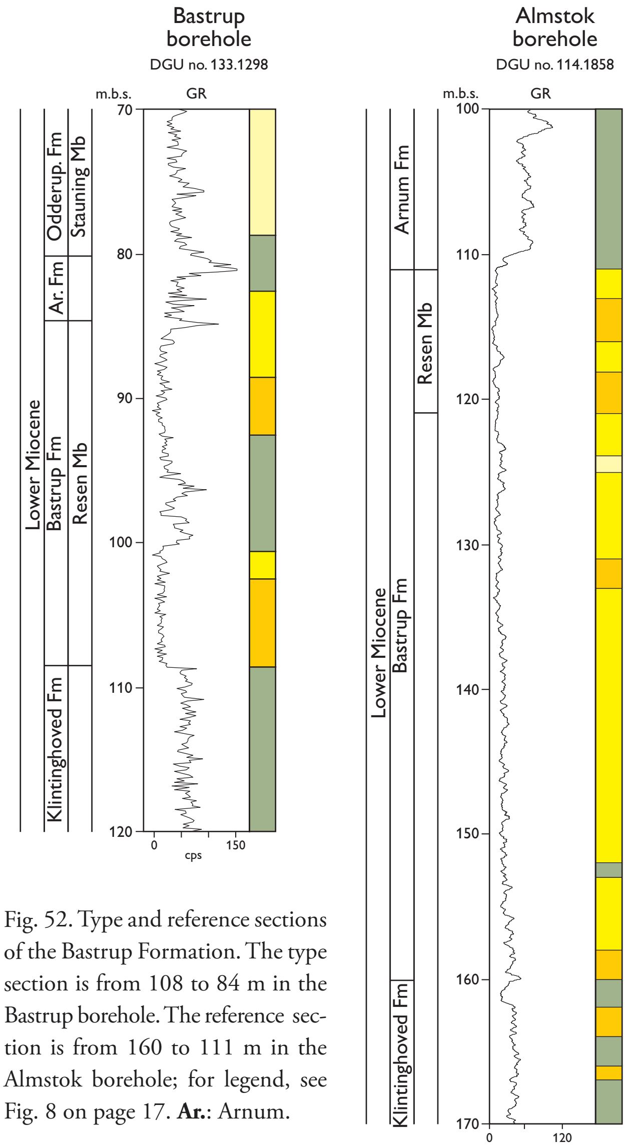


Fig. 52. Type and reference sections of the Bastrup Formation. The type section is from 108 to 84 m in the Bastrup borehole. The reference section is from 160 to 111 m in the Almstok borehole; for legend, see Fig. 8 on page 17. **Ar.**: Arnum.

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. 10E).

Biostratigraphy. The *Sumatradinium hamulatum* and *Cordosphaeridium cantharellus* Dinocyst Zones of Dybkjær & Piasecki (2010) occur in the Bastrup Formation.

Geological age. The Bastrup Formation is of early Burdigalian (Early Miocene) age.

Subdivision. The Bastrup Formation includes the new Resen Member.

Resen Member

new member

General. This member is recognised widely in the Bastrup Formation, representing fluvial-dominated facies that commonly are inferred to be incised into the undifferentiated Bastrup Formation deltaic facies. It is mainly recognised in the subsurface, but coal was formerly mined in a pit near Resen, south of Skive (Fig. 1).

Name. After the village of Resen, south of Skive, where a brown-coal pit was mined (Fig. 1).

Type and reference sections. The type section is the composite interval from 124 to 112 m and from 97 to 70 m (125–113 m MD, 97–71 m MD) in the borehole at Hammerum, east of Herning (DGU no. 85. 2429; 56°07´55.45´´N, 9°05´33.52´´E; Figs 1, 53). The reference section is the interval from 104 to 67 m (105– 67 m MD) in the Egtved borehole, south-west of Vejle (DGU no. 124.1159; Figs 1, 53).

Thickness. The member is 39 m thick in the type section (Fig. 53) and is typically in the range 10–40 m thick (Plates 2, 3, 6, 7).

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 10–30 m thick fining-upward successions; a number of boreholes show stacked, fining-upward cycles that may be separated by intervals referred to the Bastrup Formation (undifferentiated).

Log characteristics. The member is characterised by low gamma-ray readings. The log pattern is serrated and, where simply developed (e.g. Billund, Plate 2), shows an increasing trend upwards, reflecting the origin of these sand-rich units as channel fill deposits. In some boreholes, such channel sands are separated by finer-grained deposits showing moderate–high gamma-ray values (Fig. 53).

Fossils. The dinocyst flora is variable overall, being rich at some levels and very sparse/impoverished at other levels (Dybkjær 2004a; Dybkjær & Piasecki 2010).

Depositional environment. Deposition took place in fluvial environments, and well-developed point bars and fluvial channels are common (E.S. Rasmussen *et al.* 2007; E.S. Rasmussen 2009b). The intercalated mud represents flood-

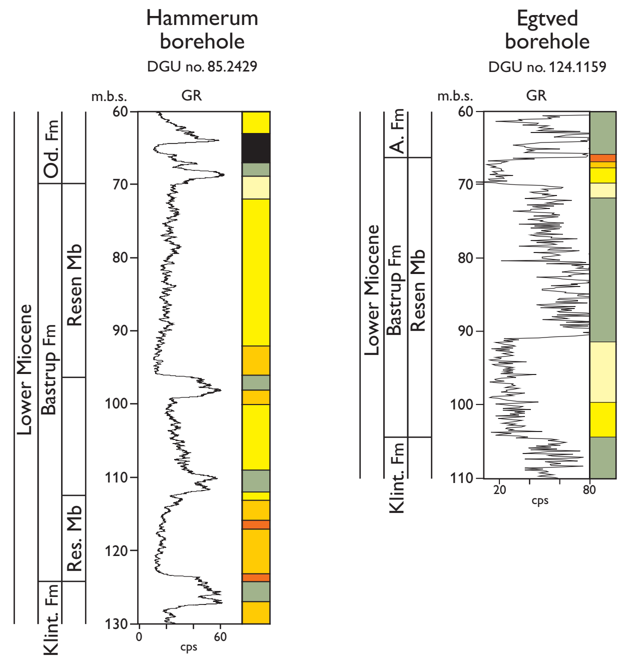


Fig. 53. Type and reference sections of the Resen Member. The composite section (124–112 m, 97–70 m) in the Hammerum borehole is designated as the type section. The reference section is the interval from 104 to 67 m in the Egtved borehole; for legend, see Fig. 8, p. 17. **A.**: Arnum. **Klint.**: Klintinghoved. **Od.**: Odderup. **Res.**: Resen.

plain deposition and some marine influence has also been recognised, especially in the southern part. The most extensive coal formation was within freshwater lakes and mires developed in the rim synclines around salt diapirs, e.g. the Sevel and Mønsted salt structures south of Skive (Japsen & Langtofte 1991).

Boundaries. The Resen Member is bounded both by sand-rich units (e.g. Bastrup Formation beneath, Vandel Member above) and by mud-rich units (Klintinghoved Formation beneath, Arnum Formation above). Where succeeding the Klintinghoved Formation, the boundary is sharp and placed where dark brown, clayey silts of the Klintinghoved Formation are sharply overlain by grey, medium- to coarse-grained sands, locally with a basal gravel layer. On the gamma-ray log, this relationship is recorded by an abrupt shift to lower values (Fig. 53). In sections where the Resen Member succeeds the undifferentiated Bastrup Formation, the boundary is defined at the base of coarser sand/gravel deposits at a shift from decreasing-upward gamma-ray values (Bastrup Formation) to increasing-upward gamma-ray values (Resen Member channel sands).

The upper boundary is typically defined by a sharp transition from grey and white sands of the Resen Member to dark brown, silty clay of the Arnum Formation; on the gamma-ray log this is reflected by an abrupt increase in values. In central Jylland, the upper boundary is characterised by a sharp change from grey and white sand to grey and white silt of the Vandel Member. On the gamma-ray log, this facies transition is reflected by an increase in gamma-ray values that continues up through the Vandel Member.

Distribution. The member is present in southern and central Jylland (Fig. 10E; Plates 1, 2, 6). 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 (2010) occur in the Resen Member.

Geological age. The Resen Member is of early Burdigalian (Early Miocene) age.

Arnum Formation

revised formation

General. The marine clay-dominated Arnum Formation is only recognised in the subsurface where it shows complex interdigitation with the nearshore sand-rich Odderup Formation. These two formations thus altenate up-section in some boreholes (Plates 1–9).

History. The Arnum Formation was defined by Sorgenfrei (1958) to encompass the dark micaceous marine clays occurring stratigraphically above the Ribe Formation (of previous usage).

Name. After Arnum village in southern Jylland (Fig. 1).

Type and reference sections. The Arnum Formation was penetrated in two boreholes at Arnum (DGU no.150.13, DGU no.150.25b; both at 55°14´48.07´´N, 8°58´18.48´´E) from 107 to 40 m and from 107.5 to 40 m respectively (Sorgenfrei 1958); together these sections form the type section. The composite interval 132–111 m and 98–51 m in the cored borehole, Sdr. Vium (DGU no. 102.948) is designated as the reference section (Fig. 54). A secondary reference section is defined as the interval from 55 to 37 m (56–39 m MD) in the Store Vorslunde borehole (DGU no. 104.2325; Fig. 55).

Thickness. The formation is *c.* 93 m thick in the type borehole (Sorgenfrei 1958). The formation is commonly only a few tens of metres thick in the north-east of the area but thickens west and south (Plates 4, 7, 9); about 130–150 m were encountered in the Borg-1 and Rømø boreholes and nearly 200 m in the Forumlund borehole (Plate 4).

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 commonly display 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 sharp erosive upper boundaries overlain by mud (Fig. 56A–C). Thin sand beds and silt layers may have a high content of heavy minerals; glaucony is present and locally forms discrete lamina (Fig. 56D).

Log characteristics. The formation is characterised by moderate–high gamma-ray values (Figs 54, 55). The log pattern is serrated (reflecting subordinate interbedded sands) and commonly shows an overall decreasing trend upwards. Discrete gamma-ray peaks may be related to silt and sand beds rich in heavy minerals.

Fossils. The Arnum Formation contains a rich assemblage of marine molluscs (Sorgenfrei 1958; L.B. Rasmussen 1961). Rich foraminifer and dinocyst assemblages also occur in this formation (Laursen & Kristoffersen 1999; Dybkjær & Piasecki 2010).

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 the presence of scours and wave-rippled sand may indicate rather shallow water with frequent reworking and sorting of sediments.

Boundaries. The Arnum Formation is typically bounded by sand-rich formations, the Bastrup Formation or Vandel Member beneath and the Odderup Formation, both beneath and above. In the former case, the lower boundary is defined by a sharp transition from grey and white sand of the Bastrup Formation to dark brown, silty clay of the Arnum Formation, recorded on the gamma-ray log as an abrupt increase in values. In central Jylland, the lower boundary is defined at the change from grey and white sand to grey

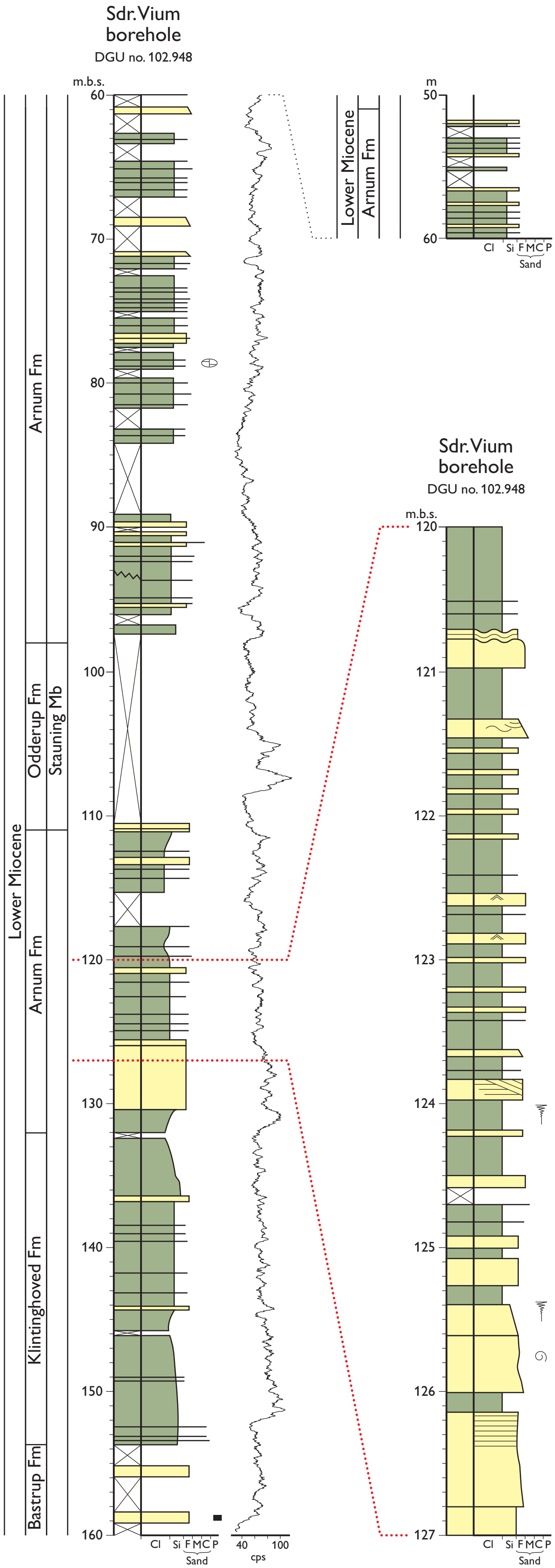


Fig. 54. The primary reference section of the Arnum Formation is the composite interval (132–111 m, 98–51 m) in the cored Sdr. Vium borehole; for legend, see Fig. 8, p. 17.

and white silt of the Vandel Member. In western and southern sections, the Bastrup Formation is absent and the clay-rich Arnum Formation succeeds silty clays of the Klintinghoved Formation (Fig. 54). This boundary may be difficult to locate but is typically placed where the consistently decreasing-upward gamma-ray trend of the uppermost Klintinghoved Formation is succeeded by the 'noisy', serrated pattern of the Arnum Formation (e.g. Fig. 54; Kvong borehole, Plate 4).

The upper boundary is placed at the base of the first significant occurrence of grey fine-grained sand, commonly with a high content of heavy minerals, that is thicker than 5 m with a sand/mud ratio of at least 75%. On the gamma-ray log, the upper boundary with the Stauning Member may be difficult to recognise but is marked by a shift from serrated and moderate–high gamma-ray values to low–moderate values, albeit still serrated in nature (e.g. Stauning borehole, Plate 6). At Rømø, in the far south-west (Plate 9), the Odderup Formation is absent and the Arnum Formation is overlain by the Hodde Formation (Måde Group); the boundary is placed at the shift from consistent moderate–high gamma-ray values to increasing-upward values.

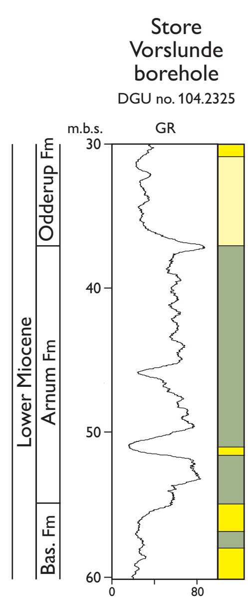


Fig. 55. The secondary reference section for the Arnum Formation is the interval from 55 to 37 m in the Store Vorslunde borehole; for legend, see Fig. 8, p. 17. **Bas.**: Bastrup.

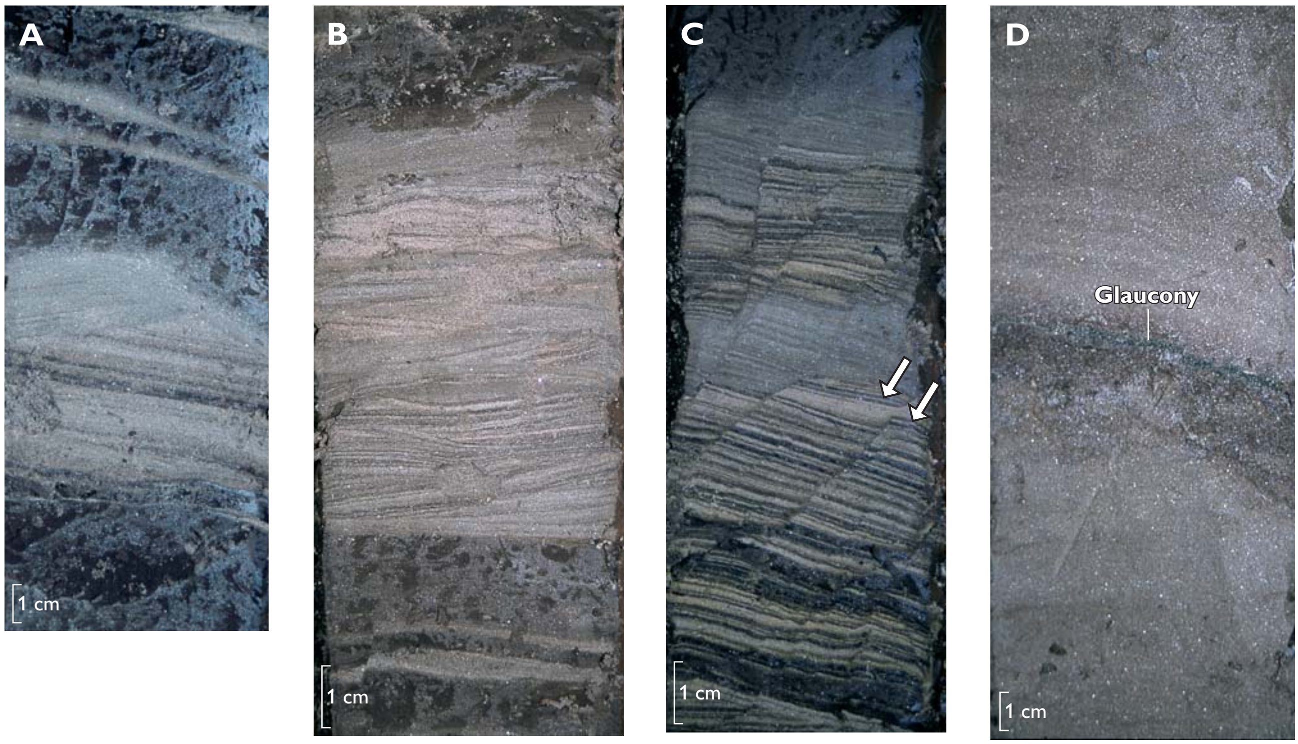


Fig. 56. Slabbed core sections from the Sdr. Vium borehole showing typical lithologies of the Arnum Formation. **A**: Dark brown clayey silt interbedded with hummocky cross-stratified sand; 59.20 m (base of illustrated core). **B**: Hummocky cross-stratified sand bed bounded by dark brown silty clays; 73.40 m (base). **C**: Heterolithic deposits showing double clay layers (arrows); 95.60 m (base). Note the small-scale faults cutting the succession, possibly due to contemporaneous seismic activity. **D**: Bioturbated clay with a 1 mm lamina rich in glaucony; 125.00 m (base).

Distribution. The formation is recognised in Jylland, south-west of a line from Struer to Horsens (Figs 1, 10F).

Biostratigraphy. The *Cordosphaeridium cantharellus, Exochosphaeridium insigne, Cousteaudinium aubryae* and *Labyrinthodinium truncatum* Dinocyst Zones of Dybkjær & Piasecki (2010) occur in the Arnum Formation.

Geological age. The Arnum Formation is of Burdigalian to early Langhian (Early – early Middle Miocene) age.

Subdivision. The Arnum Formation includes the new Vandel Member.

Vandel Member

new member

General. The lack of exposure of this member precludes detailed description and environmental interpretation. It is defined as a discrete member of the Arnum Formation since it forms a recognisable marker interval between the coarse siliciclastics of the Bastrup Formation beneath and the mud-rich facies of the Arnum Formation above.

Name. After the village of Vandel, east of Billund (Fig. 1).

Type and reference sections. The type section is the interval from 114 to 102 m (112–102 m MD) in the Vandel Mark borehole (DGU no.115.1371; 55°42´47.99´´N, 9°10´54.82´´E; Figs 1, 57). The reference section is the interval from 100 to 97 m (100–97 m MD) in the Grindsted borehole (DGU no. 114.2038; Fig. 57).

Thickness. The thickness of the member rarely exceeds the 12 m recorded in the borehole at Vandel Mark (Plate 7).

Lithology. In both the Vandel and the Grinsted boreholes, log and/or cuttings data indicate a lowermost sand or gravel layer, fining upwards into mud-rich deposits. The diagnostic feature of the Vandel Member, however, is the occurrence of grey to white silt with a high content of heavy minerals; clasts of reworked reddish Eocene clay may be present.

Log characteristics. The member shows intermediate gamma-ray readings overall with subordinate low values near the base (sandy beds) and localised high peaks (? heavy mineral sands).

Fossils. No fossils have been recorded.

Depositional environment. The depositional setting is unclear but the member caps fluvio-deltaic deposits (Resen Member) of the Bastrup Formation. The absence of fossils could point towards a floodplain depositional environment.

Boundaries. The lower boundary is defined by a lithological shift from grey sand to grey and white silt as observed in borehole cuttings samples. This boundary is difficult to position on the gamma-ray log alone; a minor increase in values is observed in the type section (Fig. 57), followed by a weak increasing-upward trend.

The upper boundary is placed at the top of the interval of white to grey silt. A slight, but distinct decrease in gamma-ray values is recognised at the upper boundary in the type section.

Distribution. The member is recognised in central Jylland (Fig. 10F).

Biostratigraphy. The Vandel Member is barren of dinocysts, but the *Cordosphaeridium cantharellus* Dinocyst Zone (Dybkjær & Piasecki 2010) occurs in the lithostratigraphic units below and above.

Geological age. The Vandel Member is of Burdigalian (late Early Miocene) age.

Odderup Formation

redefined formation

History. The Odderup Formation was defined by L.B. Rasmussen (1961), from the borehole at Odderup Brickworks where the succession of brown coal and quartz sand from 40.3 to 28.2 m was defined as the type section. Koch (1989) subsequently erected the Fasterholt Member and included this in the Odderup Formation. The formation is redefined here, based on the more extensive subsurface database now available, to include the marine sand-dominated succession, commonly rich in heavy minerals, that is associated with the largely terrestrial sediments recognised in the early work.

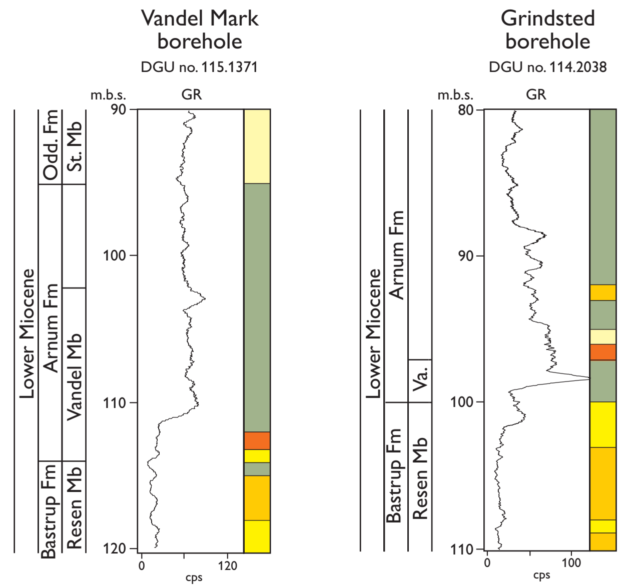


Fig. 57. Type and reference sections of the Vandel Member. The type section is the interval from 114 to 102 m in the Vandel Mark borehole. The reference section is the interval from 100 to 97 m in the Grindsted borehole; for legend, see Fig. 8, p. 17. **Odd.**: Odderup. **St.**: Stauning. **Va.**: Vandel Mb.

Name. After Odderup village in western Jylland (Fig. 1).

Type and reference sections. Following L.B. Rasmussen (1961), the type section is the borehole at Odderup (DGU no. 103.150; 55°52´19.05´´N, 8°37´42.28´´E) from 40.3 to 28.2 m. The formation is exposed at the Abildaa Brown Coal Museum near Ørnhøj but only the brown-coal-bearing Fasterholt Member is present here. The primary reference section is the interval from 37 to 1 m (39–1 m MD) in the borehole at Store Vorslunde (DGU no. 104.2325). The secondary reference section illustrates the alternation of the Odderup and Arnum Formations that is observed in a number of boreholes (Plates 2–9); the Odderup Formation is represented in the intervals from 118 to 110 m (118–111 m MD) and 90 to 41 m (90– 42 m MD) in the Rødding borehole (DGU no. 141.1141; Fig. 58).

Thickness. The formation is *c.* 12 m thick at the type section and about 36 m thick in the primary reference section. In central Jylland, it commonly exceeds 40 m (Plates 2, 7) and an exceptionally thick development was recorded in the Tinglev borehole (*c.* 165 m; Plates 1, 9).

Lithology. The formation consists of fine- to coarse-grained sand with some intercalation of clay beds and brown coal. The formation consists of quartz and clast of quartzites with minor content of mica. Heavy minerals are locally very common. The sand is characterised by low-angle cross-bedding dipping towards the south-west, and is enriched in heavy minerals (Fig. 59). The fine-grained part of the formation is dominated by hummocky cross-stratified sand and homogenous to laminated sand.

The Odderup Formation is characterised by a succession of sand with subordinate clay layers; the Odderup Formation is differentiated from the Arnum Formation in being sand-dominated with a sand/mud ratio of at least 75% and a minimum thickness of 5 m.

Log characteristics. The formation is characterised by low to moderate gamma-ray values (Fig. 58); an overall decreasing-upward gamma-ray trend is typical. High gamma-ray values are associated with beds rich in heavy minerals.

Fossils. Marine molluscs as well as dinocysts occur in the south-western sections of the Odderup Formation (Stauning Member; Piasecki 1980; Dybkjær & Piasecki 2010). Foraminifers reported from coarser-grained (more proximal) intervals (Laursen & Kristoffersen 1999) may be the result of caving from higher strata. Fossil seeds, leaves and wood are abundant in coal beds and lacustrine sands and muds of the terrestrial Fasterholt Member.

Depositional environment. The Odderup Formation was deposited in the lower to upper shoreface and swash zone of a prograding coastal-plain (Odderup Formation undifferentiated and Stauning Member). The coals and associated sediments are the deposits of freshwater lakes, lagoonal swamps and mires (Fasterholt Member; Koch 1989).

Boundaries. The lower boundary is placed where fossiliferous, dark brown, silty clays with subordinate, fine-grained sand layers referred to the Arnum Formation are overlain by a significant thickness (> 5 m) of grey fine-grained sand (sand: mud > 75%), commonly with a high content of heavy minerals. On the gamma-ray log, the lower boundary may be an abrupt shift to lower values, particularly where the Fasterholt Member directly overlies the Arnum Formation. This boundary may be more difficult to locate where the Stauning Member forms the lowermost Odderup Formation but the increase in the proportion of sand at this level is generally reflected by a fall in the gamma-ray values (e.g Ulfborg borehole, Plate 5).

The upper boundary is a marked change in lithology from the white, fine- to medium-grained sand of the Odderup Formation to the dark brown, clayey silt of the Hodde Formation. The boundary is typically sharp but locally is marked by a gravel layer, the base of which defines the boundary. The gamma-ray log typically shows a prominent shift (to higher values) at the boundary.

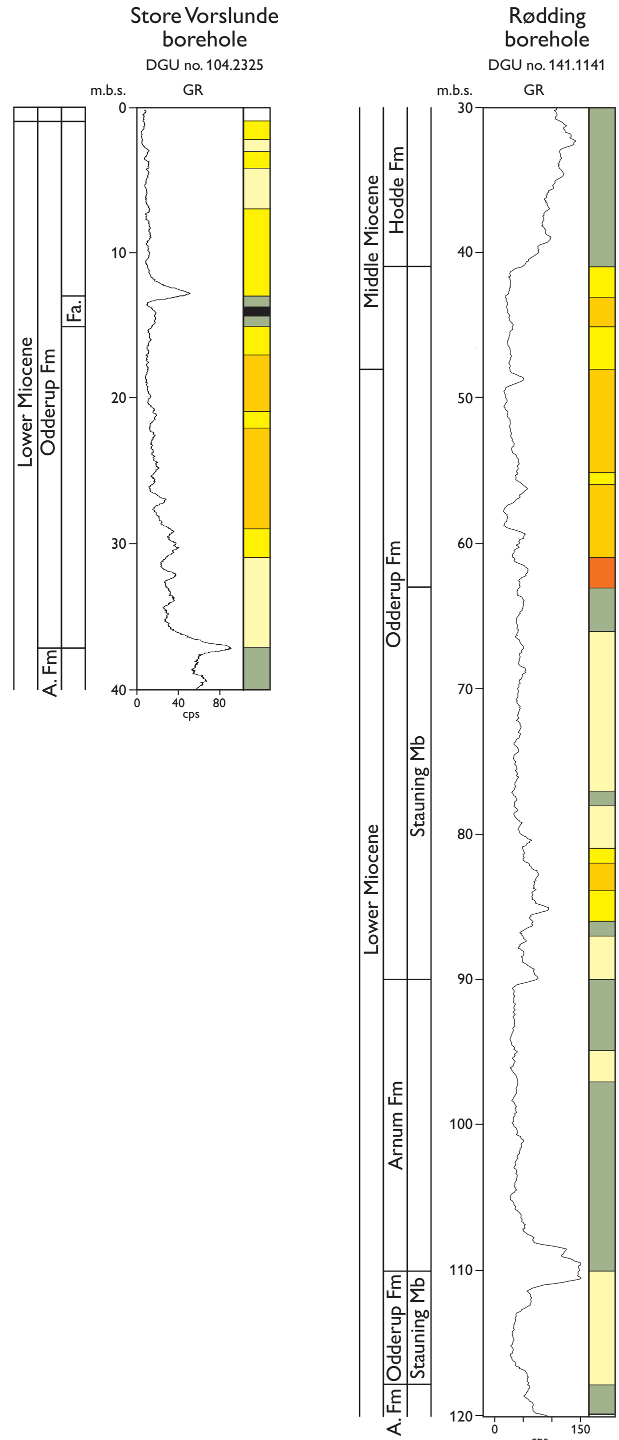


Fig. 58. Reference sections of the Odderup Formation; for legend, see Fig. 8, p. 17. The primary reference section is the interval from 37 to 1 m in the Store Vorslunde borehole. The secondary reference section is the composite interval (118–110 m, 90–41 m) in the Rødding borehole. **A.**: Arnum. **Fa.**: Fasterholt Mb.

Fig. 59. Exposure (Isenvad gravel pit) of the Odderup Formation showing low-angle cross-bedded sand with concentrations of dark heavy minerals; the sand was deposited in the swash zone of a beach. The height of the illustrated section is 0.4 m.

Distribution. The Odderup Formation is distributed in west, central and southern Jylland (Fig. 10G).

Biostratigraphy. The *Cordosphaeridium cantharellus, Exochosphaeridium insigne, Cousteaudinium aubryae* and *Labyrinthodinium truncatum* Dinocyst Zones of Dybkjær & Piasecki (2010) occur in the marine parts of the Odderup Formation.

Geological age. The Odderup Formation is of Burdigalien to early Langhian (Early to earliest Middle Miocene) age.

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

Stauning Member

new member

History. Knudsen *et al.* (2005) recognised that fine-grained sand layers with a high content of heavy minerals occurred in the Arnum Formation in a number of boreholes in south and central Jylland; these sand layers were informally referred to as the 'Stauning Sand'. On gamma-ray logs, the sand beds are characterised by extremely high gamma-ray values. Exploration for these heavy mineral sands was intensive during the latter part of the 1990s in the Stauning and Give areas.

Name. After the village of Stauning (Fig. 1) where the member subcrops Quaternary deposits at relatively shallow depths.

Type and reference sections. The type section of the Stauning Member is defined in the interval from 95 to 76 m (95–76 m MD) in the Vandel Mark borehole (DGU no. 115.1371; 55°42′47.99′′N, 9°10′54.82′′E; Fig. 60). The reference section is the intervals from 118 to 110 m (118–111 m MD) and 90 to 63 m (90–64 m MD) in the Rødding borehole (DGU no. 141.1141; Fig. 60).

Thickness. Intervals referred to the Stauning Member commonly range from 10 to 40 m in thickness (e.g. Plates 2, 3), but over 100 m has been found in the extreme southern part of the study area, for example in the Tinglev borehole (Plate 9).

Lithology. Intervals assigned to the Stauning Member, by definition, have a sand/mud ratio of at least 75% and are more than 5 m thick. The member is typically composed of grey to white, fine-grained sand, with a high content of heavy minerals, intercalated with dark brown, clayey silt (Fig. 61).

Log characteristics. The member typically shows a highly serrated gamma-ray log (e.g. Plate 6, Stauning borehole) although some sections show more stable low gamma-ray values (e.g. Tinglev borehole, Plate 9). Extremely high gamma-ray readings (e.g. Kvong borehole, Plate 4; Løvlund borehole, Plate 7) 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 2010).

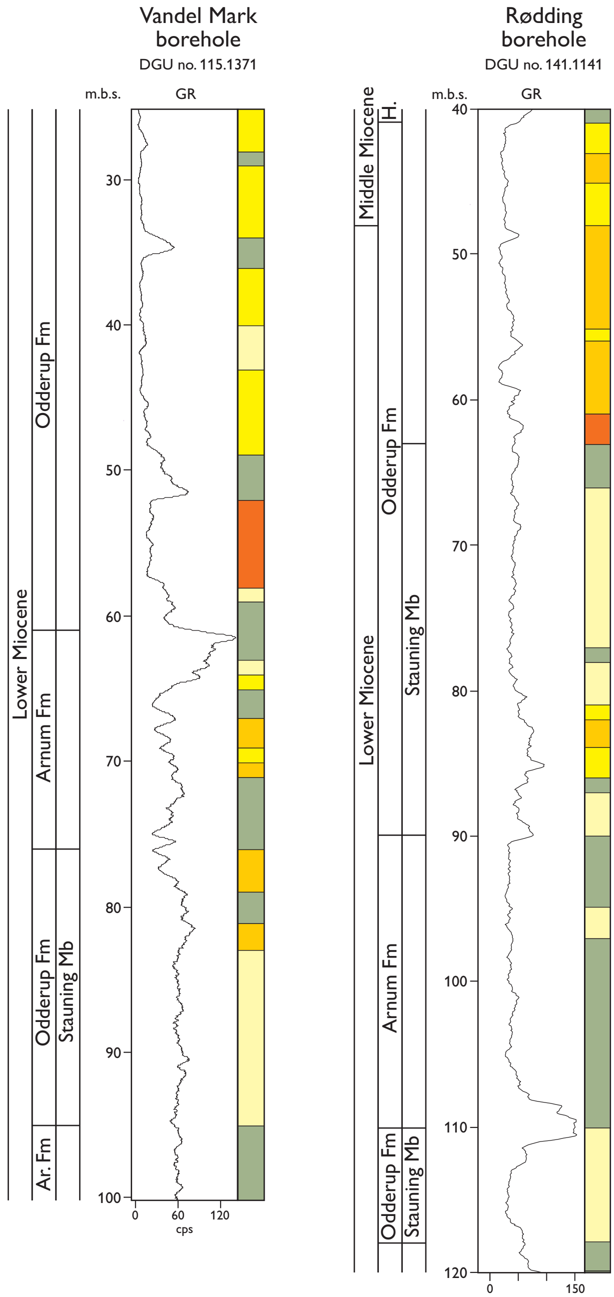


Fig. 60. Type and reference sections of the Stauning Member; for legend, see Fig. 8, p. 17. The type section is the interval from 95 to 76 m in the Vandel Mark Borehole. The reference section is the composite interval (118–110 m, 90–63 m) in the Rødding borehole. **Ar.**: Arnum. **H.**: Hodde Fm.

Fig. 61. Cores of the Stauning Member showing homogenous to laminated, grey sand with some intercalated dark brown muds. Note the high content of shells in **C** (arrows), especially in the lower part of the sand beds. **A**: 15.72 m (base of illustrated core); **B**: 23.73 m (base); **C**: 26.94 m (base). Cores from a shallow borehole to investigate the heavy mineral potential of Stauning Member sands; 2 km due west of Skjern.

Depositional environment. The Stauning Member was deposited as storm sand layers on the inner shelf, the sands being primarily of storm origin.

Boundaries. The lower boundary is placed at the base of sand-dominated (>75% sand) successions at least 5 m thick, overlying the mud-rich Arnum Formation. In some wells, this boundary is marked by a general upward decrease in the background gamma-ray values (e.g. Hellevad borehole, Plate 1; Føvling borehole, Plate 3) but anomalous examples are also observed (e.g. Rødding borehole, Fig. 60), possibly due to the heavy mineral content of the sands.

The upper boundary is defined where the fine-grained sand-rich succession is overlain by dark brown, silty clay of the Arnum Formation or medium- to coarse-grained sand of the Odderup Formation. Where the Odderup Formation succeeds the Stauning Member, the upper boundary is commonly reflected by a shift from a dominantly serrated gamma-ray log pattern to a steady and gradually decreasing gamma-ray log pattern (e.g. Plates 1, 2).

Distribution. The Stauning Member is found in southern, central and western Jylland (Fig. 10G).

Biostratigraphy. The *Cordosphaeridium cantharellus, Exochosphaeridium insigne, Cousteaudinium aubryae* and *Labyrinthodinium truncatum* Dinocyst Zones of Dybkjær & Piasecki (2010) are recognised in the Stauning Member.

Geological age. The Stauning Member is of Burdigalian to early Langhian (Early to earliest Middle Miocene) age.

Fasterholt Member

History. The Fasterholt Member was defined by Koch (1989). Brown-coal-bearing layers were mentioned by Forchhammer (1835) and brown-coal beds that crop out in the banks of the Skjern Å (river) were 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.* After the village of Fasterholt (Fig. 1).

Type and reference sections. The formation has previously been exposed in several brown-coal pits in central and western Jylland and the Fasterholt brown-coal pit (56°00´52.60´´N, 9°06´16.05´´E) is the type locality of Koch (1989; Figs 1, 62). The member is only exposed today in a small pit at Abildå near Ørnhøj (Fig. 1). The reference section is defined in the Store Vorslunde borehole (DGU no. 104.2325) from 15 to 13 m (15–13 m MD; Fig. 62).

Thickness. The member is *c.* 8.5 m thick in the type section and is commonly about 10 m thick elsewhere in central Jylland (Plate 2). It is not recognised in south-west Jylland (Fig. 10G).

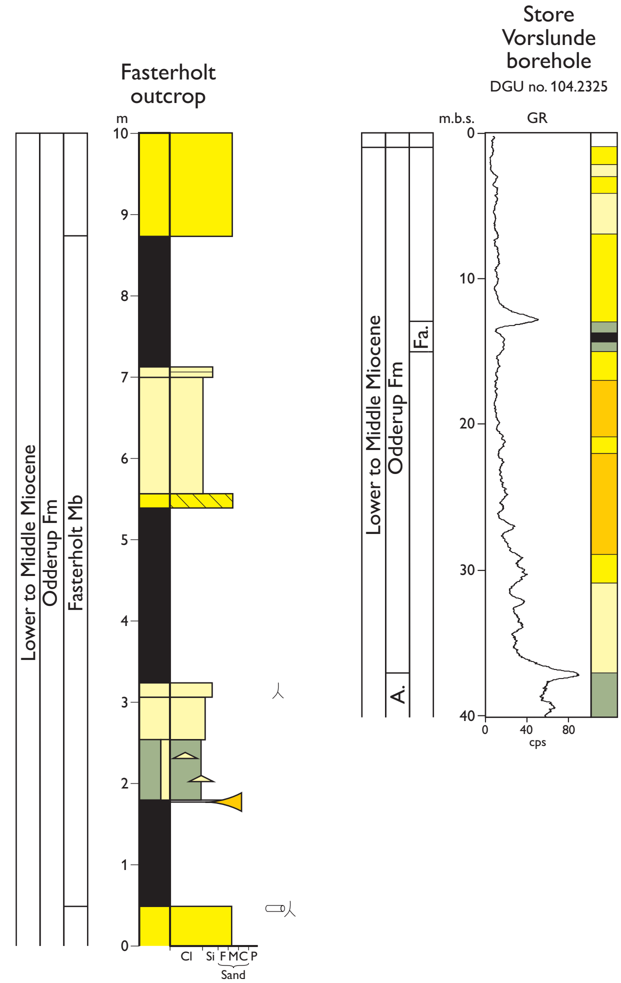


Fig. 62. Type and reference sections of the Fasterholt Member; for legend, see Fig. 8, p. 17. The type section is the Fasterholt Brown Coal Pit, north-west of Brande; this section is no longer exposed. The log is redrawn from Koch (1989). The reference section is the interval from 15 to 13 m in the Store Vorslunde borehole. **A.**: Arnum Fm. **Fa.**: Fasterholt Mb.

Lithology. The Fasterholt Member consists of interbedded sands, clays and brown coals. In the type section, it consists of three sedimentary units, each typically showing a fining-upward trend from a basal sandy lower part passing upward into silty clay and capped by a brown-coal layer (Fig. 62).

Fossils. Marine fossils are absent but spores and pollen, fossil seeds, leaves and wood occur abundantly (Christensen 1975, 1976; Friis 1975, 1979; Koch 1977, 1989; Koch & Friedrich 1970; Koch *et al.* 1973; Wagner & Koch 1974).

Depositional environment. The member is interpreted to represent deposition in a terrestrial setting that included lacustrine and mire environments (Koch 1989). The concentration of brown coals in the depocentre of the Norwegian–Danish Basin, particularly adjacent to pre-existing faults indicates a structural control on the deposition.

Boundaries. The lower boundary is sharp, being placed where white sands are overlain by a succession dominated by silty clay and brown coal, with intercalated sands. The lower boundary may be marked by a dense root horizon with tree stumps. On the gamma-ray log, the boundary is characterised by a prominent shift towards high gamma-ray values.

The upper boundary is also sharp, being typically marked by the incoming of the sand-rich upper part of the Odderup Formation; this lithological change is indicated on the gamma-ray log by a distinct shift to lower readings. Where overlain by clay-rich sediments of the Arnum Formation (e.g. Vind borehole, Plate 4) or the Hodde Formation (e.g. Fjelstervang borehole, Plate 3), the gamma-log values show an abrupt increase.

Distribution. The Fasterholt Member is restricted to central Jylland (Fig. 10G).

Biostratigraphy. In the absence of marine fossils, the Fasterholt Member is stratigraphically constrained by the presence of the *C. aubryae* Dinocyst Zone below (in the marine Odderup or Arnum Formations) and the *L. truncatum* Dinocyst Zone above (in the overlying Arnum Formation) (Dybkjær & Piasecki 2010).

Geological age. Due to the absence of marine fossils, the Fasterholt Member is dated indirectly by the biostratigraphy of the under- and overlying marine strata. The age of the Fasterholt Member is thus constrained to Burdigalian to early Langhian (Early to earliest Middle Miocene).