Data and methodology

Twenty-five outcrops, one cored borehole at Sdr. Vium (DGU no. 102.948) and *c.* 50 boreholes, drilled using the airlift drilling technique, were available for the study (Fig. 1). Most of the boreholes were drilled in order to solve stratigraphic problems, but some were drilled in order to test seismic facies interpretations. All boreholes are identified by their DGU borehole numbers, whereas outcrops are referred to by the nearest locality name.

All 25 outcrops and the cored borehole were described sedimentologically and samples taken for biostratigraphy.

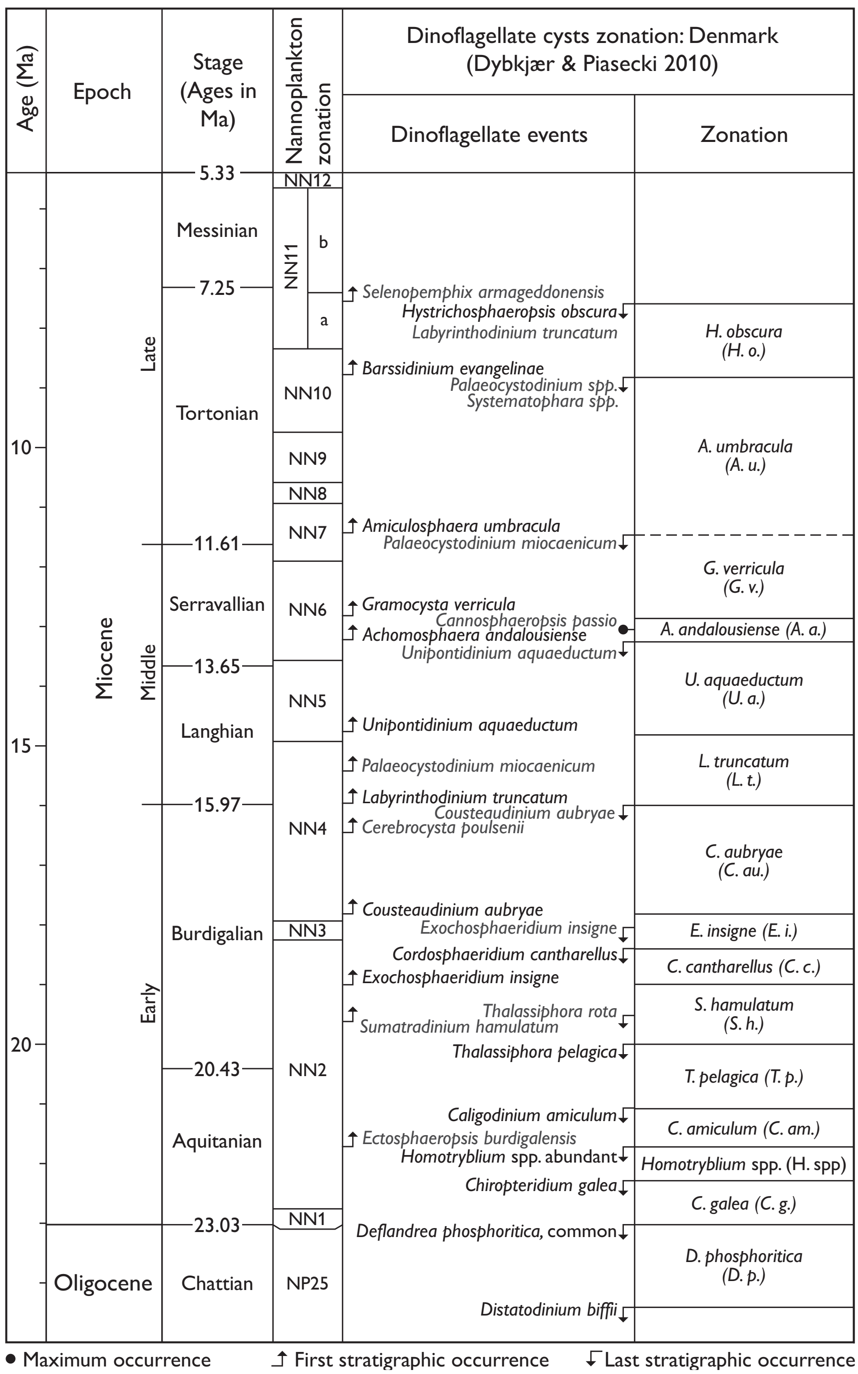

Fig. 6. Dinocyst zonation for the uppermost Oligocene – Miocene succession onshore Denmark, from Dybkjær & Piasecki (2010). The ages of the stage boundaries are from Gradstein *et al.* (2004), the nannoplankton zonation from Martini (1971). **NN**: Neogene nannoplankton zone. **NP**: Palaeogene nannoplankton zone. Dinoflagellate events indicated in black define zone boundaries, those indicated in grey are additional diagnostic events.

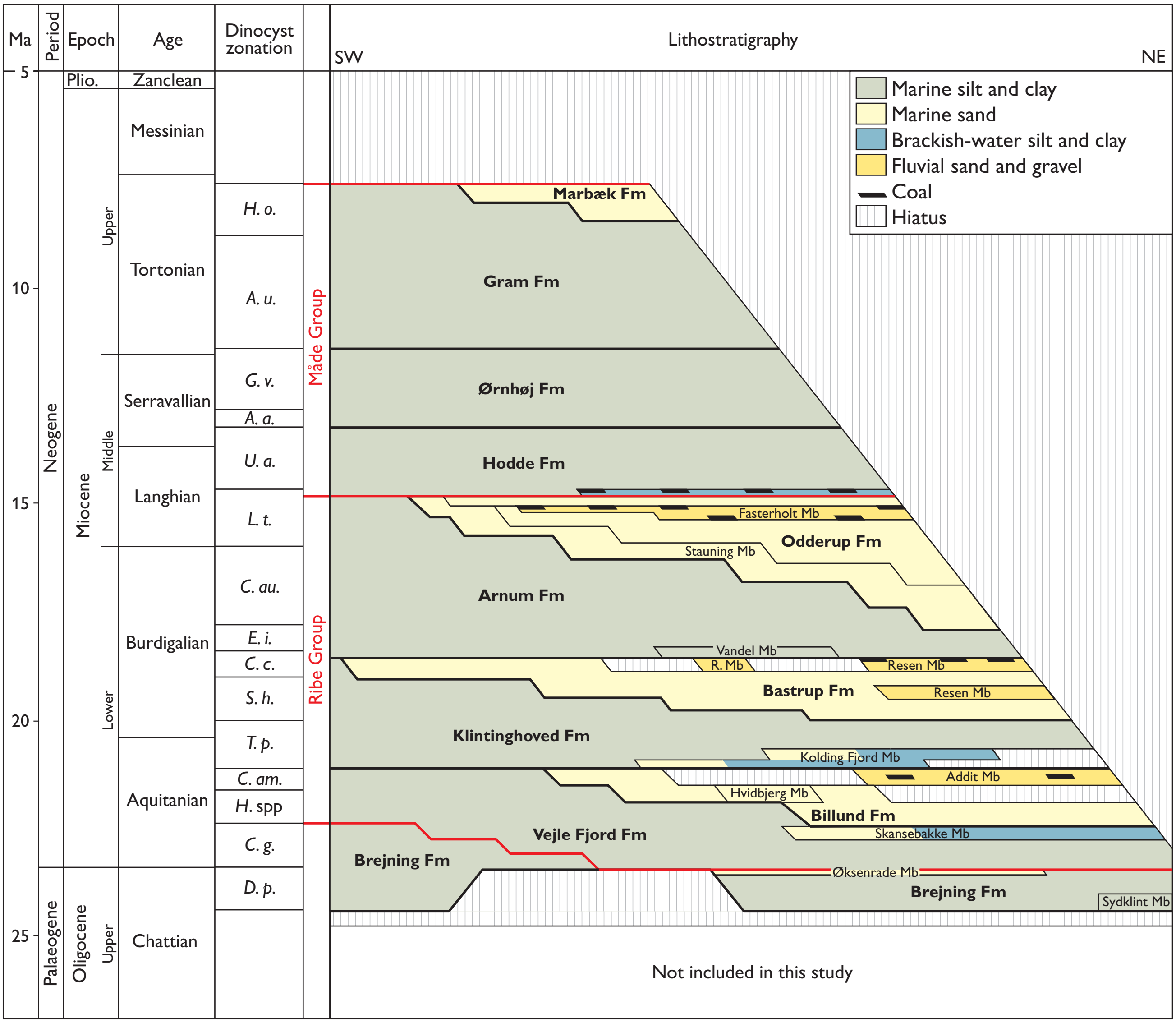

Fig. 7. Revised lithostratigraphic framework of the uppermost Oligocene – Miocene of onshore Denmark, as presented here. **R.**: Resen. **Plio.**: Pliocene.

The grain size and mineralogy of the airlift borehole samples, each representing one metre, were described. In addition, *c.* 40 samples per borehole were taken for biostratigraphic (dinocyst) analysis. The description of the Fasterholt Member, including the sedimentary logs, is based on Koch (1989).

In boreholes drilled using the airlift drilling technique, problems are experienced in retrieving fine-grained sand to the surface, and thus the recovery is commonly low or even zero in such intervals. As an aid to lithological identification, however, a gamma-ray log was obtained from all 50 boreholes. This petrophysical log is typically used to differentiate between sand and clay in siliciclastic sections, although sands rich in heavy minerals, glaucony and mica can give anomalous readings. In the correlation panels presented in this study (see Plates 1–9), the borehole lithologies were described by the first author, with the following exceptions: Fjand (DGU no. 76.635), Fjelstervang (DGU no. 84.2649), Lindved (DGU no. 116.1569), Løgumkloster (DGU no. 159.739), Ribe (DGU no. 140.42), Rømø (DGU no. 148.52), Tinglev (DGU no. 168.1378), Uldum (DGU no. 1444), Ulfborg (DGU no. 73.971), Vester Sottrup (DGU no. 169.799) and Vollerup (DGU no. 160.1378). Lithological descriptions of the latter boreholes are from the 'Jupiter' well database at the Geological Survey of Denmark and Greenland (GEUS). All sample depths from boreholes are adjusted using the gamma-ray log in order to get true depths of the samples. Thus there may be a discrepancy (usually less than 4 m) between depths indicated in the Jupiter database (measured depth: MD) and the depths assigned to the lithostratigraphic units in this study. The measured depth of cuttings samples is, however, indicated in the text.

Approximately 1000 km of 2D high-resolution seismic data have been used to correlate between boreholes and to investigate the overall architecture of the Miocene succession. The correlations are also guided by dinocyst studies of most of the boreholes included here. These studies have resulted in a detailed dinocyst zonation (Fig. 6; Dybkjær & Piasecki 2008, 2010). The geological age assigned to each lithostratigraphic unit is based primarily on this dinocyst stratigraphy (Fig. 7).

Revised lithostratigraphy

The lithostratigraphy of the uppermost Oligocene – Miocene succession of onshore Denmark is herein formally revised according to the guidelines presented by Salvador (1994). Nine lithostratigraphic units are revised and/or elevated in rank, 13 new lithostratigraphic units are erected.

The Oligocene to lowermost Miocene Brejning Clay Member, previously referred to the Vejle Fjord Formation, is elevated to formation status; it includes the Sydklint Member and the Øksenrade Member. The Miocene succession is subdivided into two groups, the Ribe and Måde Groups. The Ribe Group consists of the Vejle Fjord, Billund, Klintinghoved, Bastrup, Arnum, and Odderup Formations. The Vejle Fjord Formation includes the Skansebakke Member, the Billund Formation includes the Hvidbjerg and Addit Members, the Klintinghoved Formation includes the Kolding Fjord Member, the Bastrup Formation includes the Resen Member, the Arnum Formation includes the Vandel Member and the Odderup Formation includes the Stauning and Fasterholt Members. The Måde Group comprises the Hodde, Ørnhøj, Gram, and Marbæk Formations (Fig. 7). It should be noted that particularly distinctive portions of individual formations are defined as members, but the formations are not subdivided at member level in their entirety.

Lithostratigraphic definition of units in complex interdigitating lithologies requires clear recognition of the lithological (or petrophysical in subsurface data) bounding criteria for formations and members. In this study, the following criteria were adopted. The sand-rich formations (e.g. Billund, Bastrup, Odderup Formations) possess over 75% sand and have a minimum thickness of 5 m; intercalated mudstone packets over 5 m thick are referred to the coeval marine, mud-rich formation (i.e. the Vejle Fjord Formation in the case of the sand-rich Billund Formation). Similarly, the marine, mud-dominated formations may contain subordinate sands; sand-rich intervals (with over 75% sand) that exceed 5 m in thickness are referred to the coeval sand formation.

Salvador (1994) and subsequent lithostratigraphic guidelines (NACSN 2005) discourage the use of stratigraphically alternating formations in interdigitating depositional systems; the practical disadvantages in outcropping terranes are clear. In subsurface lithostratigraphy, however, this practise is adopted on occasion (e.g. Johnson & Lott 1993) and is utilised here to emphasise the genetic integrity of the deltaic sandy systems.

Brejning Formation

new formation

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

Name. After the town of Brejning, south of Vejle Fjord (Fig. 1).

Type and reference sections. The exposure at Skansebakke, Brejning (55°40′19.74′′N, 9°41′33.84′′E) forms the type section for the Brejning Formation (Larsen & Dinesen 1959, fig. 12). At low tide, the Brejning Formation is exposed in the basal, south-eastern part of the Skansebakke profile at Brejning. A borehole at Brejning encountered a *c.* 4 m thick (–0.4 to –4.65 m) section referred to the Brejning Formation (Larsen & Dinesen 1959). The reference section is the outcrop at Dykær, Juelsminde (Fig. 8). Other exposures of the formation are found at Sanatoriet and Fakkegrav in the Vejle Fjord area, and at Jensgård at the mouth of Horsens Fjord. In central Jylland, the formation crops out at the Sofienlund clay pit; in the Lim-

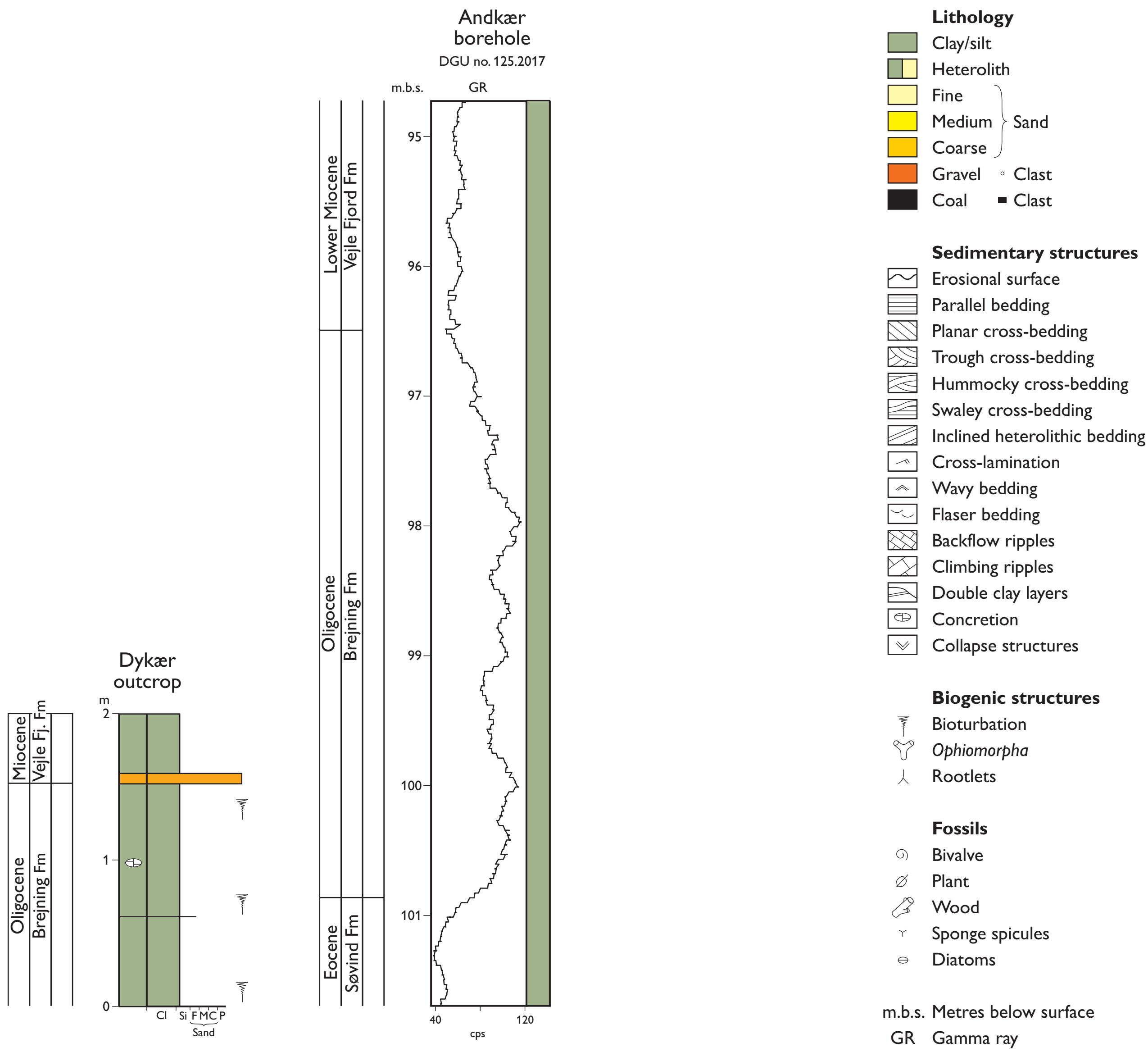

Fig. 8. Reference sections for the Brejning Formation. The primary reference section is the Dykær outcrop located south-west of Juelsminde and the secondary reference section is the interval from 100.9 to 96.5 m in the Andkær borehole. The accompanying legend is applicable to all outcrop and borehole logs shown in this study. **Vejle Fj.**: Vejle Fjord.

fjorden area, the formation is exposed at Lyby and Mogenstrup. Periodically, the formation is exposed at Søvind, Sønder Vissing, and in the Ølst and Hinge clay pits. The reference borehole section is the interval from 100.90 to 96.50 m (101–97 m MD) in the Andkær borehole (DGU no. 125.2017; Fig. 8).

Thickness. The Brejning Formation is normally 2–4 m thick, but is over 20 m thick in a number of wells (Plates 2, 5), and a 50 m thick succession referred to the Brejning Formation was encountered in the Borg-1 borehole (Plate 9).

Lithology. The Brejning Formation consists of greenish to brown, glaucony-rich clay with scattered pebbles (Fig. 9). In the upper part, there is an increased content of organic matter, silt and sand. Siderite concretions are also common in the upper part of the formation. The clay mineralogy is dominated by illite, but smectite, kaolinite and gibbsite are also present (Friis 1994; E.S. Rasmussen 1995). Mica is common in the upper part of the formation.

Log characteristics. High gamma-ray readings characterise the Brejning Formation (Fig. 8); the lower part, in particular, may show extremely high gamma-ray values due to

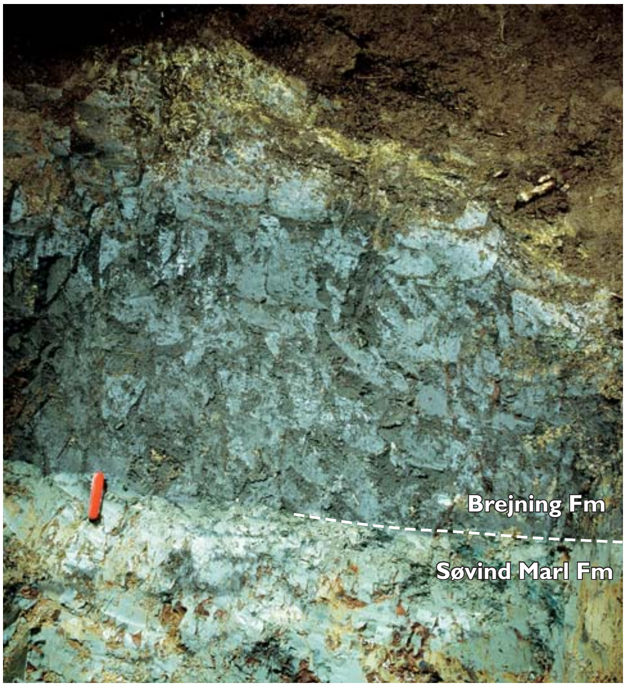

Fig. 9. The Brejning Formation at Øksenrade showing the lower part of the formation and the lower boundary with the underlying, light greenish-grey Middle Eocene Søvind Marl Formation (photograph courtesy of Peter Warna-Moors). Red penknife for scale, *c.* 10 cm long.

the high content of glaucony (e.g. Rødding borehole, Plate 8), although expanded sections (e.g. Borg borehole, Plate 9) may show uniform intermediate values.

Fossils. The marine clay of the Brejning Formation contains a rich mollusc fauna (Ravn 1907; Eriksen 1937; Schnetler & Beyer 1987, 1990). Marine microfossils, such as foraminifers (Larsen & Dinesen 1959; Ulleberg 1987, 1994; Laursen & Kristoffersen 1999), calcareous nannofossils (von Salis Perch-Nielsen 1994) and dinocysts (Dybkjær 2004a, b; Rasmussen & Dybkjær 2005), are represented, and foraminifers and dinocysts are abundant and diverse. In the upper part of the formation, a gradual change/detoriation in the mollusc fauna was interpreted to reflect a shallowing-upward trend. Similarly, in the Dykær and Jensgård exposures, the abundance and diversity of foraminifers (Larsen & Dinesen 1959) and dinocysts decrease in the upper part of the formation whereas the abundance and diversity of spores, pollen and freshwater algae increase (Dybkjær 2004a, b; Rasmussen & Dybkjær 2005). Echinoids, crinoids, asteroids, anthozoans, otoliths, sharks' teeth, brachiopods, crustaceans and bryozoans have also been found.

Depositional environment. The Brejning Formation was deposited in a fully marine, sediment-starved environment (Larsen & Dinesen 1959; Schnetler & Beyer 1990; E.S. Rasmussen 1995; Rasmussen & Dybkjær 2005). The water depth was probably more than 200 m in the Norwegian–Danish Basin based on otoliths (Schnetler & Beyer 1990) and benthic foraminifera (C. Morigi, personal communication 2009). The heights of clinoforms (offshore Denmark) associated with early Oligocene delta progradation indicate a minimum water depth of 200 m (Danielsen *et al.* 1997), and since the Late Oligocene was warmer than the Early Oligocene (Zachos *et al.* 2001), relatively deep water probably prevailed within the Norwegian–Danish Basin during deposition of the Brejning Formation. Schnetler & Beyer (1990) reported a mixed mollusc fauna, some elements indicating deep marine conditions and some indicative of shallow water; the shallow marine fauna is most likely reworked, i.e. transported down the delta or shelf slope to the basin floor. On the Ringkøbing–Fyn High, shallower water prevailed. The upward increase in silt and sand indicates progradation of the shoreline in the latest Oligocene associated with a relative sea-level fall (Rasmussen & Dybkjær 2005).

Boundaries. In southern and western Jylland, the Brejning Formation rests with a sharp and erosional boundary on the Eocene Søvind Marl Formation (Fig. 9; Heilmann-Clausen *et al.* 1985). In this area, the boundary is marked by a distinct change in colour and grain size from the greenish grey clay of the Søvind Marl Formation to the greenish brown and commonly silty Brejning Formation. The boundary may locally be intensively bioturbated and consequently more gradational. In central and northern Jylland, the boundary is defined where dark brown clay of the Branden Formation (lower Upper Oligocene) is overlain by greenish glaucony-rich clay of the Brejning Formation. The base of the Brejning Formation is marked by a prominent shift to higher values on the gamma-ray log in the Andkær borehole, but may locally be more gradational due to glaucony-filled burrows in the upper part of the Søvind Marl Formation.

The upper boundary is typically sharp and characterised by a change from greenish, dark brown, glaucony-rich clayey silt of the Brejning Formation to dark brown clayey silt of the overlying Vejle Fjord Formation. A change in the degree of consolidation is also observed at the boundary in most parts of Jylland from the well-consolidated sediments of the Brejning Formation to the relatively loose sediments of the Vejle Fjord Formation. A gravel layer commonly occurs immediately above the upper boundary. At the type locality, the upper boundary is recognised by a dis-

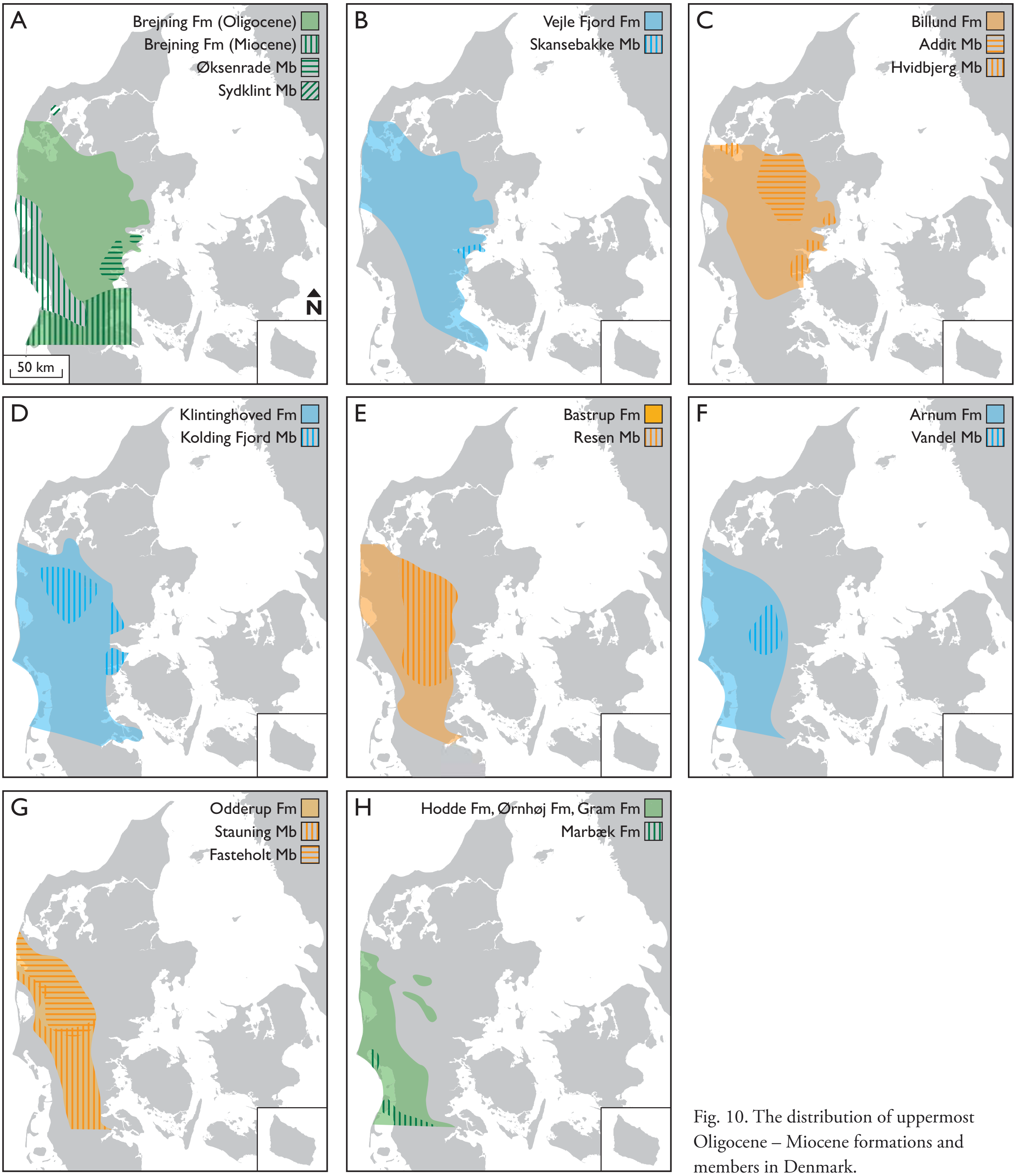

Fig. 10. The distribution of uppermost Oligocene – Miocene formations and members in Denmark.

tinct decrease in the content of glaucony passing from the Brejning Formation to the Vejle Fjord Formation (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 to the dark brown, clayey silt of the Vejle Fjord Formation.

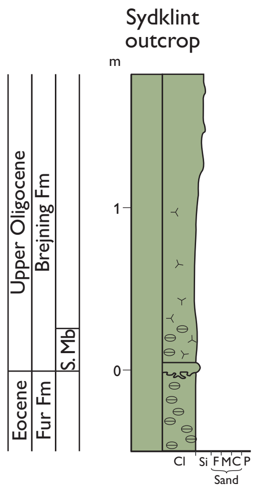

Fig. 11. Type section of the Sydklint Member. Modified after Heilmann-Clausen (1997); for legend, see Fig. 8, p. 17. **S.**: Sydklint.

Fig. 12. Contact between the light grey Lower Eocene Fur Formation and the brown Upper Oligocene Sydklint Member at Silstrup Sydklint. A thin glauconitic layer occurs at the boundary between the two units. *Thalassinoides* burrows extend from the glauconitic layer down into the topmost Fur Formation. Knife for scale.

Distribution. The Brejning Formation is present in much of central and southern Jylland but is typically absent on the Ringkøbing–Fyn High (Fig. 10A). Due to the diachronous nature of the upper boundary (see below), the youngest beds referred to the Brejning Formation are only present in southern and western Jylland. The northern and eastern limit closely follows that of the Miocene deposits (Fig. 3).

Biostratigraphy. The *Deflandrea phosphoritica* Dinocyst Zone of Dybkjær & Piasecki (2010) is recorded in the Brejning Formation. In addition, the *Chiropteridium galea* Zone is recorded in the upper part of the formation in the southern parts of Jylland.

Geological age. The Brejning Formation is of late Chattian to early Aquitanian (latest Late Oligocene to earliest Early Miocene) age. The dinocyst stratigraphy indicates that the upper boundary of the Brejning Formation is diachroneous. In central parts of Jylland, the boundary broadly correlates with the Oligocene–Miocene boundary (E.S. Rasmussen 2004b; Rasmussen & Dybkjær 2005; Dybkjær & Rasmussen 2007). In the southern part of Jylland, deposition of the glaucony-rich clay of the Brejning Formation apparently continued into the early Aquitanian.

Subdivision. The Brejning Formation includes the Sydklint Member and the new Øksenrade Member.

Sydklint Member

History. A thin diatomite layer of Oligocene age, unconformably overlying the Lower Eocene Fur Formation and overlain by Upper Oligocene micaceous clay, was observed in the cliff section at Silstrup, near Thisted, by Heilmann-Clausen (1982). Although noted by Bøggild (1918), he apparently considered the layer to represent a glaciotectonically derived slice of the Fur Formation (see Heilmann-Clausen 1997). The silicoflagellate assemblage in the diatomite layer was described by von Salis (1993). The lithology of the Oligocene diatomite layer and the contact to the underlying Fur Formation were described in more detail by Heilmann-Clausen (1997) who also proposed a model for the genesis of the diatomite. Heilmann-Clausen (1997) formally defined the unit as the Sydklint Member, which he provisionally referred to the Vejle Fjord Formation.

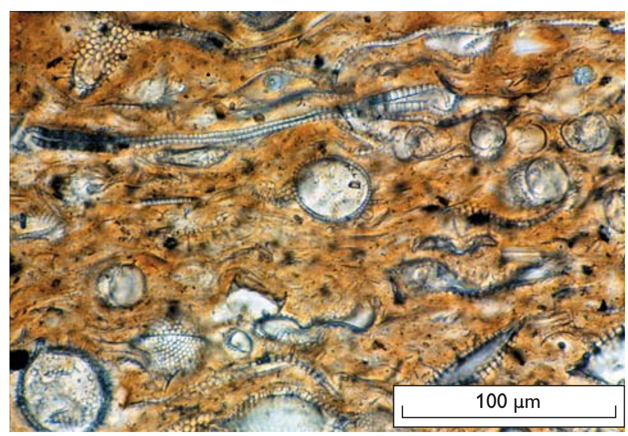

Fig. 13. Photomicrograph of a vertical thin-section through the diatomaceous Sydklint Member.

Name. After the coastal cliff of Silstrup Sydklint, south of Thisted (Fig. 1).

Type section. The type section is the coastal cliff of Silstrup Sydklint (56°55´15.49´´N, 8°39´20.76´´E; Fig. 11).

Thickness. The member is up to 28 cm thick.

Lithology. The Sydklint Member includes a basal 1–8 cm thick clay layer rich in coarse-grained glaucony and reworked clasts of the Fur Formation (Figs 11, 12). Sporadic extra-basinal pebbles and a single 25 cm large, partly glauconitised gneiss clast have been found in the basal layer. The glaucony-rich basal layer is succeeded by 20 cm of brown, clayey diatomite (Fig. 13).

Log characteristics. The member is only recognised at outcrop, and log data are not available.

Fossils. The Sydklint Member contains well-preserved siliceous and organic-walled microfossils, including diatoms, silicoflagellates, sponge spicules, dinocysts, pollen and spores (Fig. 13).

Depositional environment. The Sydklint Member was deposited in a marine, probably shelf environment.

Boundaries. The Sydklint Member has a sharp lower boundary separating the glaucony-rich basal layer from the underlying Fur Formation. An omission suite of shallow *Thalassinoides* burrows extends 5–8 cm down into the topmost Fur Formation. The upper boundary is gradational over a few centimetres.

Distribution. The Sydklint Member is only known from outcrops at Silstrup Sydklint and nearby Klovbakker at Sundby, Mors.

Biostratigraphy. The member is referred to the silicoflagellate *Distephanus speculum haliomma* Subzone of Bukry (1981) by von Salis (1993) and to the *Deflandrea phosphoritica* Dinocyst Zone of Dybkjær & Piasecki (2010) by Heilmann-Clausen (C. Heilmann-Clausen, personal communication 2010).

Geological age. The Sydklint Member is of late Chattian (latest Late Oligocene) age.

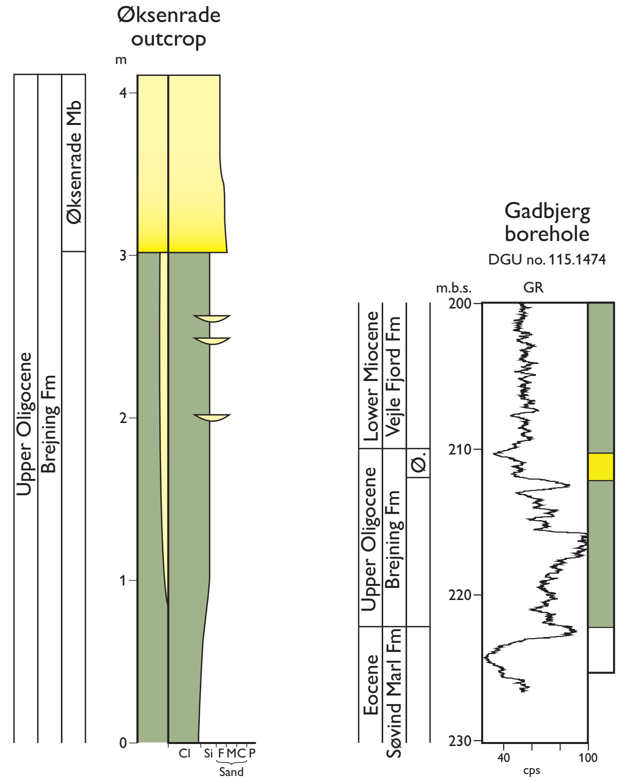

Fig. 14. Type and reference sections of the Øksenrade Member (**Ø.**). The type section is the Øksenrade outcrop located south-west of Middelfart; the top of the member is not seen. The reference section is the interval from 212 to 210 m in the Gadbjerg borehole; for legend, see Fig. 8, p. 17.

Øksenrade Member

new member

History. The succession defined here as the Øksenrade Member was termed 'Middelfart malm' by L.B. Rasmussen (1975). Equivalent oolitic ironstones cropping out at Jensgård at the mouth of Horsens Fjord were described by Friis *et al.* (1998).

Name. After Øksenrade Skov, just north of the coastal type locality (Fig. 1).

Type and reference sections. The type section is the coastal cliff facing Fænø Sund, south of Øksenrade Skov, Middelfart (55°29´39.61´´N, 9°42´47.29´´E; Fig. 14). The reference section is the interval from 212 to 210 m (214–212 m MD) in the borehole at Gadbjerg (Fig. 14; DGU no. 115.1474).

Fig. 15. Brejning Formation and the Øksenrade Member in the coastal cliff at Øksenrade Skov, south-west of Middelfart. This outcrop constitutes the type section of the Øksenrade Member; spade for scale (*c.* 1.3 m long).

Thickness. The member is *c.* 1 m thick at the type locality (Fig. 14), but the top is not seen; boreholes indicate a maximum thickness of 5 m (Fig. 14; Plate 8).

Lithology. The Øksenrade Member is composed of reddish ooids and grey, well-sorted, fine-grained quartz sand (Figs 15, 16) and ranges lithologically from a sand with dispersed ooids to a sandy ooid grainstone. At Jensgård, the Øksenrade Member consists of planar cross-bedded sand, sets are up to 40 cm thick and typically show asymptotic toesets. The foresets are inclined towards the north. The ooids are composed of concentric layers of goethite, commonly with a core of glaucony grains or pellets (H. Friis, personal communication 2010); at the type section, shells or quartz grains also form ooid cores. The cement consists of siderite with some calcite; the iron content of the sediment is up to 30% (E.S. Rasmussen 1987). Moulds of mollusc shells are common.

Log characteristics. The Øksenrade Member is typified by relatively low gamma-ray readings (Fig. 14) but distinct spikes may occur due to horizons rich in glaucony.

Fossils. The Øksenrade Member is characterised by abundant moulds of mollusc shells (L.B. Rasmussen 1975; Gravesen 1990).

Depositional environment. The Øksenrade Member was deposited above storm wave base as indicated by cross-bedding (Rasmussen & Dybkjær 2005). The bivalve and gastropod faunas (L.B. Rasmussen 1975) also indicate a shallow-water depositional environment. The transgressive lag that is locally found on the Ringkøbing–Fyn High at the base of the Vejle Fjord Formation is indicative of exposure and terrestrial sedimentation prior to transgressive reworking (Rasmussen & Dybkjær 2005). Such a shallowing and local emergence at the transition from the Oligocene to the Miocene is also indicated by the presence of freshwater algae in the upper part of the Brejning Formation (Rasmussen & Dybkjær 2005).

Boundaries. The Øksenrade Member rests with a sharp erosional boundary on the undifferentiated Brejning Formation beneath (Figs 15, 16). The lower boundary is also marked by a change from dark brown, clayey silt with scat-

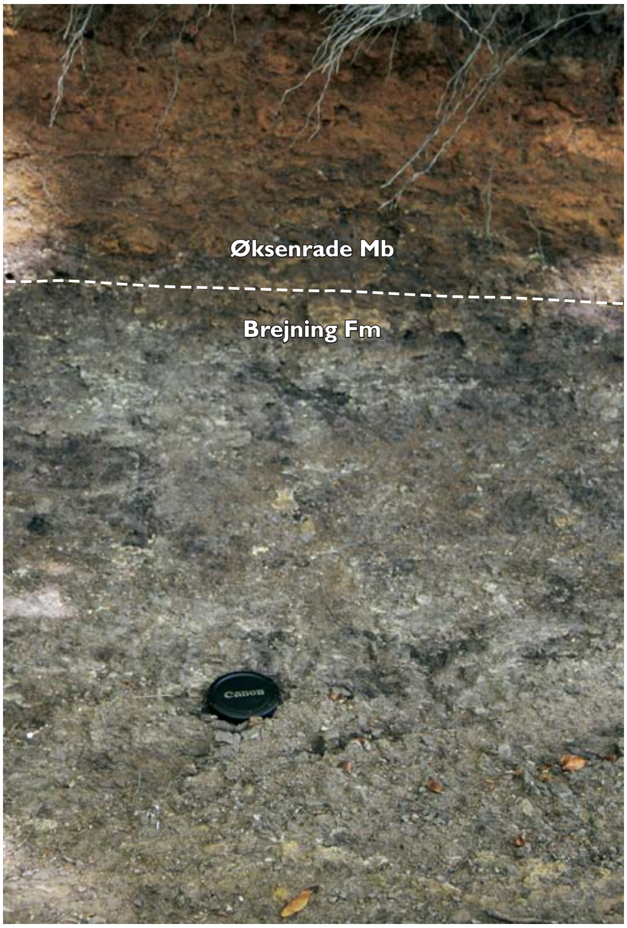

Fig. 16. Boundary between the Brejning Formation and the Øksenrade Member, marked by a distinct colour change from dark brown clayey silt to red sand. Lens cap for scale.

tered sand lenses to fine-grained, reddish sand; on the gamma-ray log, this facies shift is reflected by a shift towards lower values. The upper boundary is characterised by a marked change from the sand deposits of the Øksenrade Member to dark brown, clayey silts of the Vejle Fjord Formation; this boundary is marked by a prominent shift on the gamma-ray log from low to high values.

Distribution. The Øksenrade Member is present in east Jylland and the extreme western part of Fyn, from Horsens in the north to Middelfart in the south (Fig. 10A). The westernmost limit is defined by exposures at Gadbjerg near Give where the member occurs on a footwall crest at the boundary fault of the Brande Trough.

Biostratigraphy. No samples from this member have been analysed for palynology; the mollusc fauna is non-specific.

Geological age. Based on stratigraphic context, the Øksenrade Member is considered of latest Chattian (latest Late Oligocene) age.