

A new Neogene biostratigraphy for Denmark

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In Denmark most of the water used in private households, in the industry and for irrigation in agriculture comes from sub-surface aquifers. Some of the most important aquifers in Jylland, western Denmark, are sand layers deposited from 23 to 15 Ma ago, in the Early Neogene (Early to Middle Miocene). About 23 Ma ago, in the Early Miocene, the coastline ran NW–SE across present-day Jylland (Rasmussen 2004). Global climatic variations led to major sea-level changes (Zachos *et al.* 2001), which in combination with increased sediment transport from the north (the present Norway) resulted in deposition of several huge, fluvio-deltaic sand systems intercalated with marine clay (e.g. Rasmussen 1961; Rasmussen 2004; Rasmussen & Dybkjær 2005).

The Geological Survey of Denmark and Greenland (GEUS) and the regional Environment Centres (the former counties (amter)) in Jylland are working in close cooperation to study the Early Neogene succession; the main purposes are: (1) to find new aquifers, (2) to map the extent of known aquifers and clarify their mutual relationships, in order to evaluate the size of the water resources and optimise production, and (3) to protect the aquifers from pollution due to leaching from the surface.

In order to map the complex sedimentary succession, it has been necessary to combine several geological disciplines, including seismic interpretation, sedimentology, correlation of geophysical logs, and biostratigraphy (e.g. Dybkjær 2004; Rasmussen 2004; Rasmussen *et al.* 2004; Piasecki 2005; Rasmussen & Dybkjær 2005; Dybkjær & Rasmussen 2007). This article shows some results of a detailed dinoflagellate cyst stratigraphy, which is based on an extensive database (Fig. 1). We present here for the first time a dinoflagellate cyst zonation for the complete Neogene succession in the Danish area.

Dinoflagellates and their cysts

Dinoflagellates are eukaryotic, single-celled organisms that occur as motile cells with two flagella, one which encircles the cell, and one longitudinal flagellum. These organisms, which also occur abundantly at present, include autotrophs, phagotrophs, symbionts and parasites. Photosynthetic species (autotrophs) account for about half of the living genera and play an important role in the marine ecosystem as primary producers. Some marine species produce toxins or cause red tides and several types of shellfish poisoning. Dinoflagellates have left a rich fossil record, mainly of organic-walled cysts, in Mesozoic and

Cenozoic rocks; examples of fossil dinoflagellate cysts are shown in Fig. 2. Some dinoflagellate species form cysts as part of their life-cycle; others form cysts as a survival strategy, during unfavourable environmental conditions (e.g. low sea surface temperatures or lack of nutrients). The morphology of a cyst reflects the morphology of the motile dinoflagellate. The rapid evolution of the relatively complex, fossilisable dinoflagellate cyst wall makes these fossils ideal for biostratigraphic purposes (e.g. Fensome *et al.* 1996).

Material and methods

The dinoflagellate cyst zonation scheme presented here is based on data from more than 50 onshore and offshore boreholes and a series of onshore exposures (Fig. 1). The sediment samples from the boreholes and exposures were processed at the palynological laboratory at GEUS using standard palynological preparation methods.

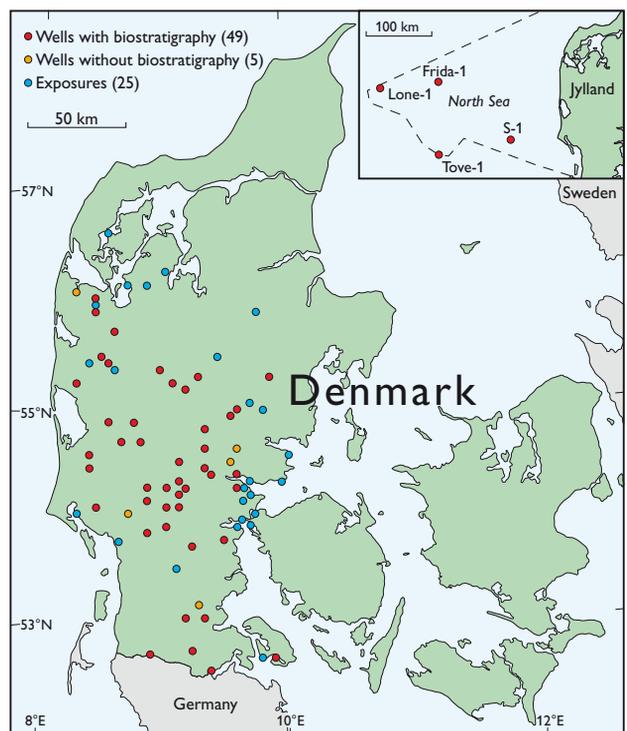


Fig. 1. Map of Denmark showing the location of studied wells and exposures. The insert map shows the location of the offshore exploration wells included in this study.

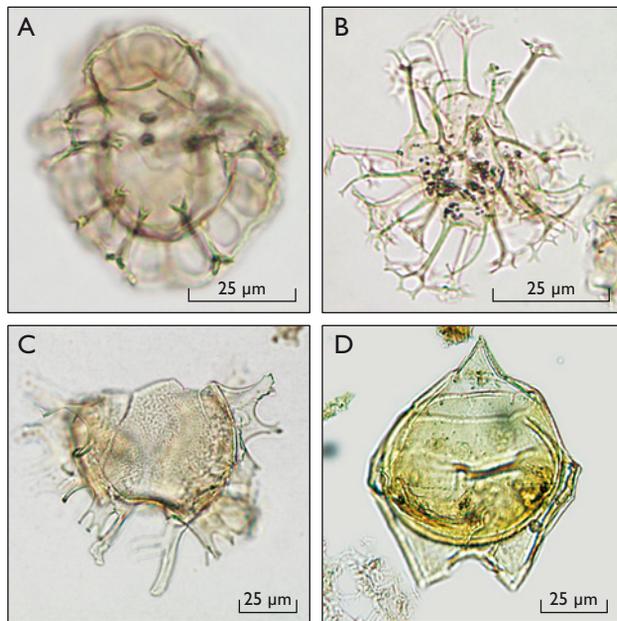


Fig. 2. Stratigraphically significant dinoflagellate cysts from the Miocene of Denmark. **A:** *Unipontidinium aquaeductum*. **B:** *Achomosphaera andalousiense*. **C:** *Chiropteridium galea*. **D:** *Deflandrea phosphoritica*.

The Danish Neogene stratigraphy has traditionally been based on molluscs and foraminifers whereas early studies of dinoflagellate floras were limited (Piasecki 1980). However, new comprehensive studies of dinoflagellate cysts throughout the Danish Neogene have resulted in a high-resolution stratigraphy of the succession, even in marginal marine deposits where foraminifers and molluscs rarely occur. Dinoflagellate cysts in strata of the central North Sea Basin were studied in offshore, hydrocarbon exploration wells, for comparison with the onshore, marginal, marine deposits and to obtain data from the youngest Neogene that is not represented by onshore strata. The resulting stratigraphy is a so-called interval zonation, i.e. all zones are defined as successions of rocks between a lower and an upper event of fossil appearance or disappearance. For example the *Unipontidinium aquaeductum* Zone is defined from the first appearance of *U. aquaeductum* to the first appearance of *Achomosphaera andalousiense* (Figs 2, 3). However, the zone is also characterised by other associated events (stratigraphic first and last occurrences of other characteristic species) and by the dinoflagellate cyst assemblage in general. Species with relatively common and consistent occurrence and with reported stratigraphic potential from outside the North Sea Basin, e.g. in the North Atlantic realm, were preferentially selected for the definition of the zones. The zonation can therefore easily be compared with other international/North Atlantic dinoflagellate zonations, despite the fact that much of the studied material was deposited in the relatively enclosed and possibly periodically brackish environments of the North Sea Basin.

Dinoflagellate cyst zonation

The Danish Neogene is formally divided into 19 dinoflagellate cyst zones from the uppermost Oligocene to the top of the Pliocene, with one zone in the Oligocene, 15 zones in the Miocene and three zones in the Pliocene (Fig. 3). The Pliocene is considered tripartite; Zanclean, Piacenzian and Gelasian (see Gradstein *et al.* 2004). The zonation has a high resolution in the uppermost Oligocene, the Lower Miocene and the Middle Miocene (1, 8 and 4 zones respectively) and a lower resolution in the Upper Miocene and Pliocene (3 and 3 zones respectively). The zones will be formally defined in a forthcoming paper. The proposed dinoflagellate cyst stratigraphy for Denmark correlates well with other formal stratigraphies in the North Sea Basin, e.g. in Germany (Köthe 2003), the Netherlands (Munsterman & Brinkhuis 2004), Belgium (e.g. Louwe *et al.* 1999) and the United Kingdom (e.g. Head 1998), as well as with dinoflagellate cyst stratigraphies outside this basin in the North Atlantic realm (de Verteuil & Norris 1996), in spite of differences in selection of diagnostic species. The new Danish biozonation is also correlated with Neogene chronostratigraphy and with nannoplankton biostratigraphy (see Gradstein *et al.* 2004).

Geological results

The new dinoflagellate cyst stratigraphy has been extensively tested in boreholes and exposures throughout Jylland (Fig. 1). The application provides a detailed stratigraphic framework for improved geological interpretations. Three major, prograding deltaic sand systems with excellent potential as reservoirs for drinking water are recognised in the Lower Miocene to lowermost Middle Miocene in the central parts of Jylland: the Billund sand, the Bastrup sand and the Odderup Formation (e.g. Dybkjær 2004; Rasmussen 2004). In addition, several problematic issues of Neogene geology in the Danish region have been solved:

1. The stratigraphic position of the Vejle Fjord Formation (Larsen & Dinesen 1959) is now definitively established as latest Oligocene (Brejning Clay) to earliest Miocene (Vejle Fjord Clay and Sand) (Dybkjær 2004; Dybkjær & Rasmussen 2007).
2. The upper, silty and sandy part of the Sofienlund Formation is time equivalent to the Vejle Fjord Clay and Sand. The lower Ulstrup Clay and the Sofienlund Clay are time equivalent with the Brejning Clay (Unpublished data 2006, K. Dybkjær).
3. The Oligocene–Miocene boundary can be recognised in the eastern North Sea Basin as the last occurrence of common *Deflandrea phosphoritica* (Figs 2, 3). This event corresponds to the transition from the Brejning Clay to the Vejle Fjord

Age (Ma)	Epoch	Stage	Nannoplankton zonation	Dinoflagellate cysts zonation					
				Dinoflagellate events	Onshore zonation	Offshore zonation			
5 10 15 20	Holocene		NN21						
			NN20						
	Pleistocene		NN19						
		L	1.81	NN18	↑ <i>Bitectatodinium tepikiense</i> ↓ <i>Amiculosphaera umbracula</i>		<i>I. multiplexum</i>		
	Pliocene	M	2.59	NN17	↑ <i>Impagidinium multiplexum</i> ↓ <i>Barssidinium pliocenium</i>		<i>B. pliocenium</i>		
		E	3.60	NN16		<i>Melitasphaeridium choanophorum</i>	<i>M. choanophorum</i>		
				NN15/ NN13		<i>Reticulosphaera actinocoronatum</i>			
			5.33	NN12		<i>Barssidinium evangelinae</i> <i>Erymnodinium delectabile</i>			
	Miocene	L	Messinian	NN11	a		<i>S. armageddonensis</i>		
					b	↑ <i>Selenopemphix armageddonensis</i> ↓ <i>Hystrichosphaeropsis obscura</i>	<i>H. obscura</i>	<i>H. obscura</i>	
		Tortonian		NN10	↑ <i>Barssidinium evangelinae</i> ↓ <i>Palaeocystodinium spp.</i>				
				NN9 NN8			<i>A. umbracula</i>	<i>A. umbracula</i>	
		Serravallian		NN7	↑ <i>Amiculosphaera umbracula</i> ↓ <i>Palaeocystodinium miocaenicum</i>		<i>G. verrucula</i>	<i>G. verrucula</i>	
				NN6	↑ <i>Gramocysta verrucula</i> ↓ <i>Achomosphaera andalusiense</i> <i>Unipontidinium aquaeductum</i>		<i>A. andalusiense</i>	<i>A. andalusiense</i>	
			M	13.65	NN5	↑ <i>Unipontidinium aquaeductum</i>		<i>U. aquaeductum</i>	<i>U. aquaeductum</i>
				15.97	NN4	↑ <i>Labyrinthodinium truncatum</i> ↓ <i>Cousteaudinium aubryae</i>		<i>L. truncatum</i>	<i>L. truncatum</i>
		E	Burdigalian		NN3		<i>Exochosphaeridium insigne</i> <i>Cordosphaeridium cantharellus</i>	<i>E. insigne</i>	<i>E. insigne</i>
					NN2	↑ <i>Exochosphaeridium insigne</i> ↓ <i>Sumatradinium hamulatum</i> <i>Thalassiphora rota</i> <i>Thalassiphora pelagica</i>		<i>C. cantharellus</i>	<i>C. cantharellus</i>
	Aquitanian			NN2	↑ <i>Sumatradinium hamulatum</i> ↓ <i>Thalassiphora pelagica</i>		<i>S. hamulatum</i>	<i>S. hamulatum</i>	
				NN2	↑ <i>Caligodinium amiculum</i> ↓ <i>Ectosphaeropsis burdigalensis</i> <i>Homotryblium spp. abundant</i> <i>Chiropteridium galea</i>		<i>T. pelagica</i>	<i>T. pelagica</i>	
			NN1	↑ <i>Ectosphaeropsis burdigalensis</i> ↓ <i>Homotryblium spp. abundant</i> <i>Chiropteridium galea</i>		<i>C. amiculum</i>	<i>C. amiculum</i>		
			NN1	↑ <i>Chiropteridium galea</i> ↓ <i>Deflandrea phosphoritica, common</i>		<i>Homotryblium spp.</i>	<i>Homotryblium spp.</i>		
Oligocene	Chattian	NN1	↑ <i>Deflandrea phosphoritica, common</i> ↓ <i>Distatodinium biffii</i>		<i>C. galea</i>	<i>C. galea</i>			
		NN25			<i>D. phosphoritica</i>	<i>D. phosphoritica</i>			

Fig. 3. Stratigraphic scheme presenting the new dinoflagellate cyst zonation correlated with the Neogene nannoplankton zonation and chronostratigraphy. The time scale is according to Gradstein *et al.* (2004). The diagnostic dinoflagellate cyst species are shown in red.

Clay and to the Sequence Boundary B (Rasmussen 2004; Dybkjær & Rasmussen 2007).

4. A significant hiatus is recognised between the Vejle Fjord and Arnum Formations in the northern and central parts of Jylland. In the southern parts of Jylland a time-equivalent fluvial-deltaic sand system, the Ribe Formation, was de-

posited (Dybkjær & Rasmussen 2000; Dybkjær 2004; Rasmussen 2004; Rasmussen & Dybkjær 2005).

5. The sand-rich succession in the Salten profile and in nearby gravel pits (Addit, Voervadsbro) was formerly referred to the late Early Miocene to early Middle Miocene Odderup Formation. Dinoflagellate cyst analysis has shown that this

succession is older than previously assumed and is part of the Vejle Fjord Formation/Billund sand system (Rasmussen *et al.* 2006).

6. The Hodde transgression occurred in the early Langhian, earliest Middle Miocene and limits the age of the underlying Odderup Formation to latest Early Miocene – earliest Middle Miocene (Piasecki 2005).

7. The youngest onshore Neogene deposits are of Tortonian age (Late Miocene) as no Messinian or Pliocene dinoflagellate cysts have been recorded. The earlier Sød Formation, upper Gram Formation sand and the Neogene sand in cliffs at Ho Bugt are considered of Tortonian age and referred to the Gram Formation (Piasecki 2005).

8. A series of maps of the Cenozoic succession in the Danish North Sea area was produced by Rasmussen *et al.* (2005). The age determinations of the Neogene succession are based on the dinoflagellate cyst stratigraphy presented here.

Future perspectives

The new dinoflagellate cyst zonation is not only a valuable tool for unravelling the Danish Neogene succession. The Neogene succession in Denmark is presently being correlated with other Neogene successions, e.g. in Germany, the Netherlands and Poland, in order to elucidate the Neogene geology of the North Sea Basin.

The zonation also leads to an improved understanding of the subsidence and tilting of the North Sea Basin during the Neogene, and a better understanding of the petroleum systems in the hydrocarbon-producing provinces in the North Sea area. This may lead to new discoveries and increased production from known oil/gas-fields (Rasmussen *et al.* 2005). It is also an important tool for solving problems such as the evidence for and the timing of the Neogene uplift of Norway.

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