

Lithostratigraphy of the Palaeogene – Lower Neogene succession of the Danish North Sea

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Lithostratigraphy, biostratigraphy, North Sea Basin, Palaeogene, Neogene.

Cover

Complex fabric created by multiple small-scale sand intrusions (light) into dark mudstones – such enigmatic fabrics are commonly associated with the sand-rich units of the Rogaland Group in the Siri Canyon area, offshore Denmark. The illustrated section of core is about 10 cm across and is from the lower Tyr Member (Lista Formation) in the Cecilie-1B well (2346.8 m). Photograph: Jakob Lautrup.

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Abstract

Schiøler, P., Andsbjerg, J., Clausen, O.R., Dam, G., Dybkjær, K., Hamberg, L., Heilmann-Clausen, C., Johannessen, E.P., Kristensen, L.E., Prince, I. & Rasmussen, J.A. 2007: Lithostratigraphy of the Palaeogene – Lower Neogene succession of the Danish North Sea. *Geological Survey of Denmark and Greenland Bulletin* 12, 77 pp. + 5 plates.

As a result of a lithological, sedimentological and biostratigraphic study of well sections from the Danish sector of the North Sea, including some recently drilled exploration wells on the Ringkøbing–Fyn High, the lithostratigraphic framework for the siliciclastic Palaeogene to Lower Neogene sediments of the Danish sector of the North Sea is revised. The sediment package from the top of the Chalk Group to the base of the Nordland Group is subdivided into seven formations containing eleven new members. The existing Våle, Lista, Sele, Fur, Balder, Horda and Lark Formations of previously published lithostratigraphic schemes are adequate for a subdivision of the Danish sector at formation level. Bor is a new sandstone member of the Våle Formation. The Lista Formation is subdivided into three new mudstone members: Vile, Ve and Bue, and three new sandstone members: Tyr, Idun and Rind. Kolga is a new sandstone member of the Sele Formation. Hefring is a new sandstone member of the Horda Formation. Freja and Dufa are two new sandstone members of the Lark Formation. Danish reference sections are established for the formations, and the descriptions of their lithology, biostratigraphy, age and palaeoenvironmental setting are updated.

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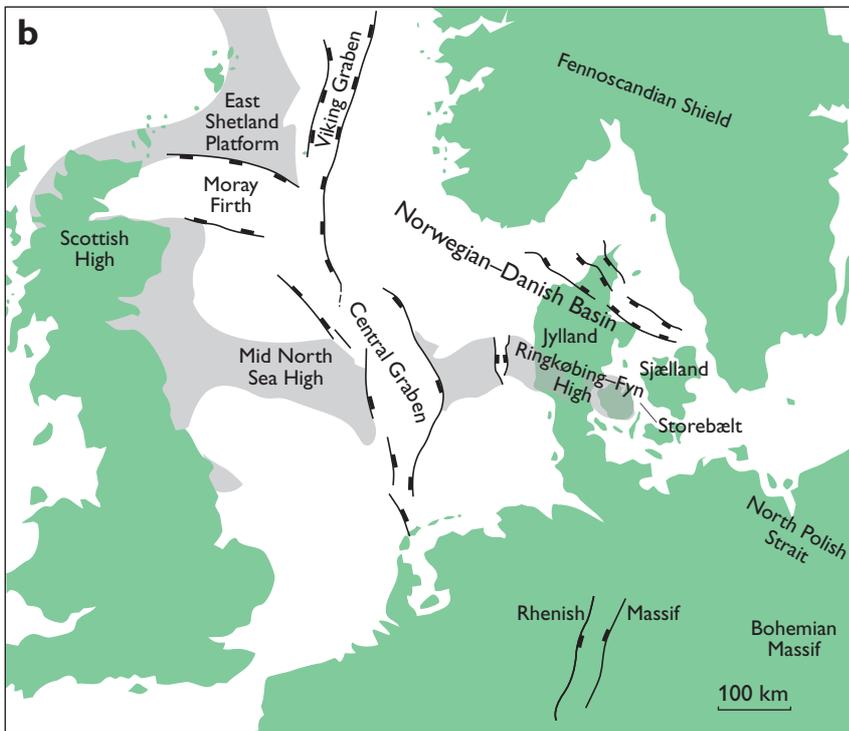
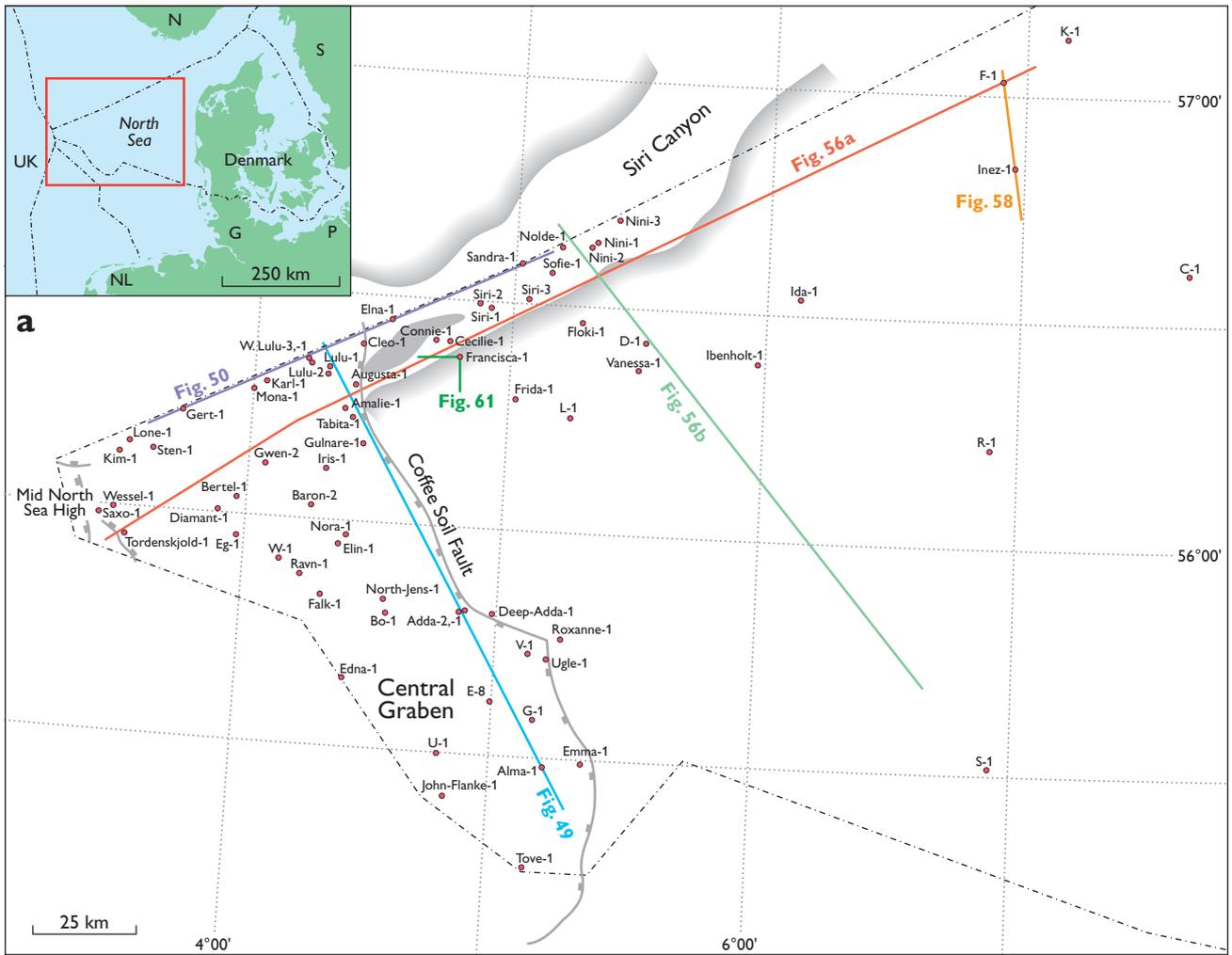


Fig. 1. Location maps showing the position of wells used in the study (a) and major structural elements in the greater North Sea area (b) mentioned in the text. On the well map (a) are indicated the locations of the seismic sections shown in Figs 49, 50, 56, 58 and 61. Grey shading on this map indicates the margins of the Siri Canyon; grey shading inside the canyon indicates an area of positive relief within the canyon. **G**, Germany; **N**, Norway; **NL**, Netherlands; **P**, Poland; **S**, Sweden; **UK**, United Kingdom.

Introduction

Intense drilling activity following the discovery of the Siri Field in 1995 has resulted in an improved understanding of the siliciclastic Palaeogene sediment package in the Danish sector of the North Sea (Fig. 1). Many of the new wells were drilled in the search for oil reservoirs in sandstone bodies of Paleocene–Eocene age. The existing lithostratigraphy was established on the basis of data from a generation of wells that were drilled with deeper stratigraphic targets, with little or no interest in the overlying Palaeogene sedimentary succession. This means that this early scheme does not include Palaeogene sandstone units in the Danish sector. In order to improve the understanding of the distribution, morphology and age of the Palaeogene sediments, in particular the economically important sandstone bodies, a detailed study of this succession in the Danish sector has been carried out. The main aim was to update the lithostratigraphic framework of the succession on the basis of new data from recently drilled wells.

All of the widespread Palaeogene mudstone units in the North Sea were established with Norwegian or United Kingdom (UK) type wells. In the present work, these units have been maintained unchanged or with only slight modifications. Danish reference wells have been established for the units, however, and lithological descriptions have been expanded to cover the characteristics of these units in the Danish sector.

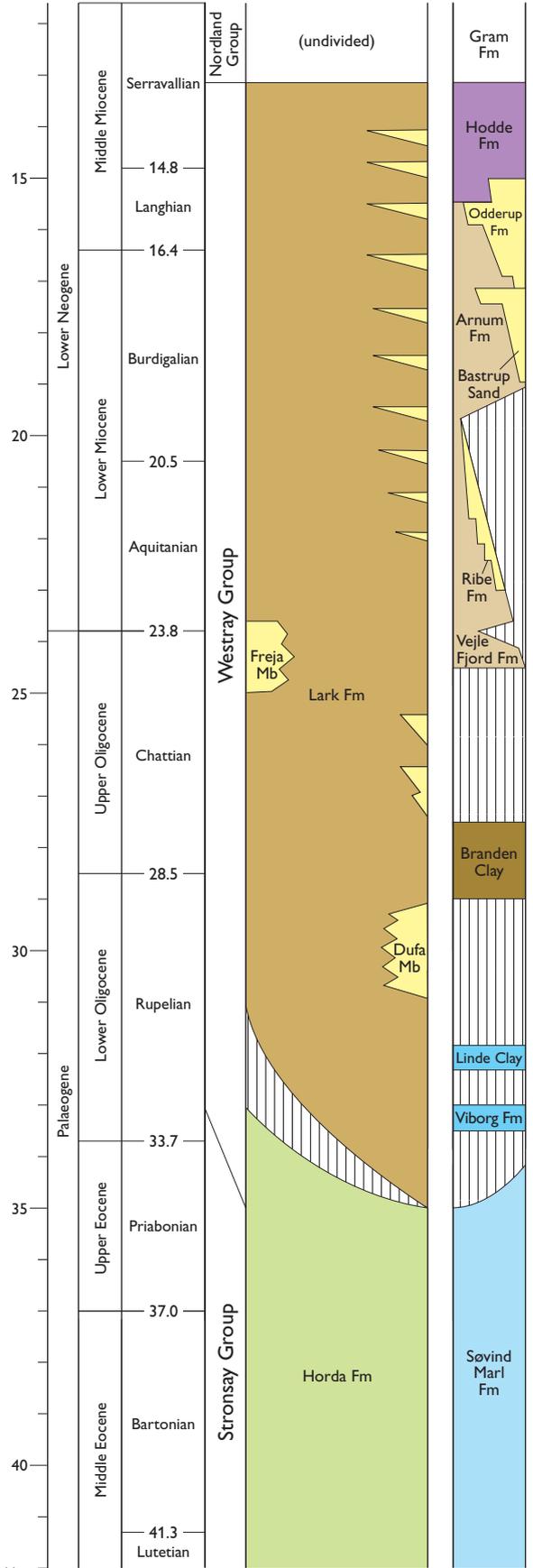
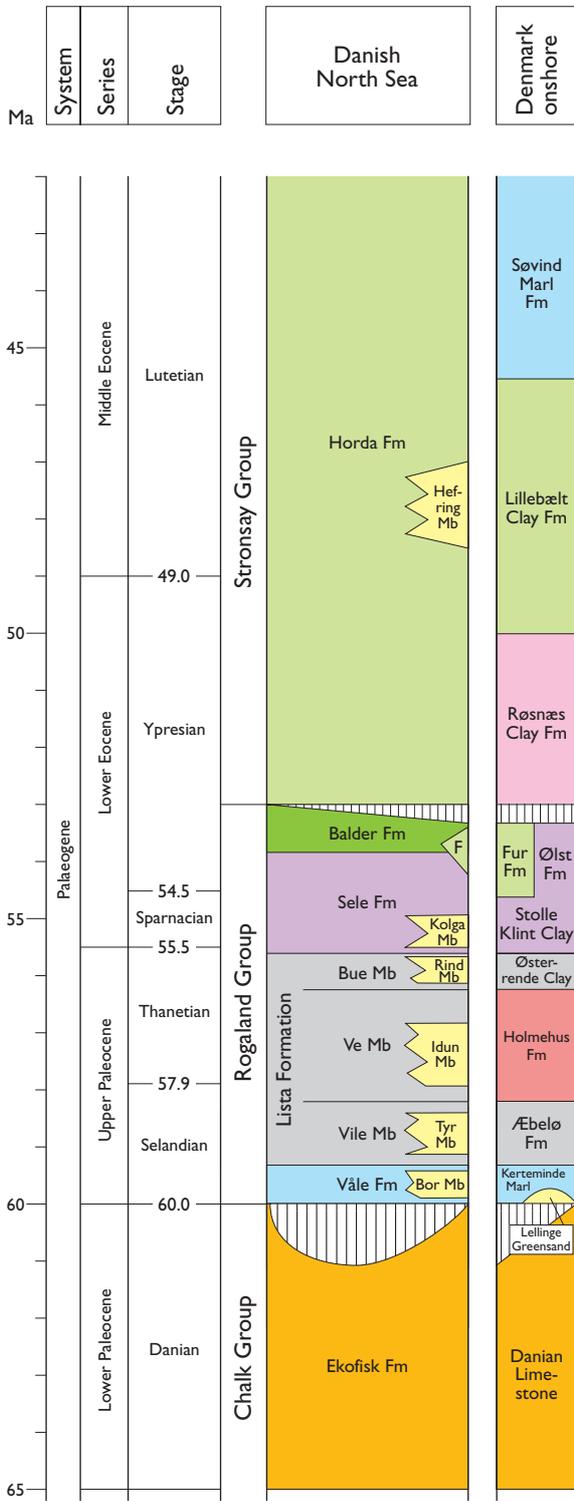
Many of the sandstone bodies recently discovered in the Danish sector have a limited spatial distribution and are derived from sources different from those of most of the contemporaneous sandstone bodies in the Norwegian and UK sectors; furthermore, the Danish sandstone bodies probably neither overlap nor are in contact with the Norwegian/UK sandstones. These units have therefore been established as new in the Danish sector, and have been assigned Danish type and reference sections.

The lithostratigraphy presented herein (Fig. 2) has its base at the top of the Early Paleocene (Danian) Ekofisk Formation (Chalk Group). The top of the study section is at the unconformity between the Late Eocene – Mid-Miocene Westray Group and the Mid-Miocene to Recent Nordland Group.

Oil companies operating in the North Sea have collected a substantial amount of lithostratigraphic data on the Palaeogene successions and a detailed lithostratigraphy has been developed for the Danish and Norwegian sectors (see e.g. Hamberg *et al.* 2005). A number of informal lithostratigraphic units have been introduced that have subsequently found their way into academia and geological survey organisations. It has been the aim of the present work formally to define these new units. This has been done maintaining their original (albeit informal) names whenever feasible.

It has not been the aim of this work to provide a sequence stratigraphic model for the Palaeogene sediments in the central and eastern North Sea; for this the reader is referred to Michelsen *et al.* (1992, 1995, 1998), Mudge & Bujak (1994, 1996a, b), Neal *et al.* (1994) and Danielsen *et al.* (1997). The present contribution does not attempt to review the petroleum-related aspects of the Palaeogene succession. Information about this may be found elsewhere, for example in the annual reports from the Danish Energy Authority.

Preliminary results from the present work, including a revised lithostratigraphic scheme, were previously published in a brief review paper (Schiøler *et al.* 2005). The present contribution formally describes the new stratigraphic units suggested in the review paper and further documents the Palaeogene – Lower Neogene lithostratigraphy in the Danish sector of the North Sea.



Geological setting

The Danish sector of the North Sea is situated in the central and eastern North Sea and comprises three major structural elements: the Central Graben, the Norwegian–Danish Basin (the eastern part of the northern North Sea Basin of Rhys 1974) and the Ringkøbing–Fyn High (Fig. 1; the geographic terminology and names of structural elements in the North Sea used herein are adapted from Rhys 1974, Rønnevik *et al.* 1975, Deegan & Scull 1977 and Fyfe *et al.* 2003). The western boundary of the Danish sector largely coincides with the eastern boundary of the Mid North Sea High, the southern boundary largely coincides with the southern limit of the Ringkøbing–Fyn High, and the northern boundary is in the Norwegian–Danish Basin. This basin as well as the Ringkøbing–Fyn High are Early Permian structures. Active rifting occurred in the Central Graben from the Middle to Late Jurassic along pre-established Palaeozoic fault trends. Major tectonic activity around the Palaeozoic and Jurassic structures had largely ceased by Late Cretaceous time, and the sediment basin below the central North Sea was largely characterised by regional subsidence (Ziegler 1981). During the Late Cretaceous to Danian sea-level high, pelagic chalk sediments draped the structural highs and the northern and southern North Sea Basins became one North Sea Basin delimited by the Fennoscandian Shield to the north-east, the Rheinisch–Bohemian Massif to the south and the British massifs, highs and platforms to the west (see Ziegler 1981 fig. 16 for details). Chalk sedimentation continued through to the end of the Danian Stage when it gave way to hemipelagic and siliciclastic sedimentation. This was probably caused by uplift of the basin margins to the west and east (Ahmadi *et al.* 2003). However, most of the siliciclastic sediments were derived from

the Scottish High and the East Shetland Platform, uplifted by the Iceland plume (Ahmadi *et al.* 2003). By the time of peak uplift, in the mid-Thanelian, large sand systems were building out towards the central North Sea. Most sediment came from the west, but the Siri Canyon system, a depression in the top chalk surface, was fed from the Fennoscandian Shield in the north-east and north (Fig 1; Ahmadi *et al.* 2003; Hamberg *et al.* 2005).

Thermal subsidence centered above the Central Graben continued through the Eocene as sea level fell and the temperature decreased. Shallow-marine sediments characterised the margins of the North Sea Basin, especially its western margin, whereas basinal mudstone continued to accumulate in the basin centre and in the eastern part of the basin (Joy 1996). Inversions controlled by compression between the Atlantic spreading zone to the north-west and the orogenesis of the Alps to the south added to further uplift of the basin margins and submarine fans and turbidites were deposited near the centre of the basin (Jones *et al.* 2003).

During the Oligocene, the North Sea Basin became part of a larger NW European basin. Connection with the North Atlantic broadened and enhanced communication with the oceanic water mass to the north-west, whereas the connection to the south through the North Polish Strait became closed for the deep water (Fyfe *et al.* 2003). Glacio-eustatic sea-level changes became more frequent and controlled the sedimentary cycles. The eastward progradation direction of the Paleocene and Eocene sediments gave way to sediment supply from the European massifs to the far south (Fyfe *et al.* 2003). Continued subsidence above the Mesozoic rift structures created accommodation space for thick sediment packages of basinal mudstones, and few sandstone units reached the basin depocentre above the Mesozoic rifts (Fyfe *et al.* 2003). In the Neogene Epoch, sediment started to be derived from the Fennoscandian Shield to the north, and the progradation direction changed to the south-west and west in the Danish sector of the North Sea.

Facing page:

Fig. 2. Lithostratigraphic column for the Palaeogene and Lower Neogene of the Danish North Sea sector showing the approximate correlation with Danish onshore stratigraphic units. Timescale from Hardenbol *et al.* (1998), except for the age of the Paleocene–Eocene boundary, which is adapted from Berggren & Aubry (1996) and the age of the Sparnacian–Ypresian boundary, which is from Aubry *et al.* (2003). Stratigraphy and ages of pre-Chatian onshore lithostratigraphic units are based on Heilmann-Clausen (1995) and Clemmensen & Thomsen (2005). Post-Rupelian onshore stratigraphy and ages are from Dybkjær & Rasmussen (2000) and Rasmussen (2004a). F, Fur Formation.

Previous work

The Permian to Recent lithostratigraphy of the North Sea was described in two pioneering stratigraphic works. Rhys (1974) provided an overview of the structural elements of the North Sea and gave a brief description of the Palaeogene sediments. Deegan & Scull (1977) compiled a detailed lithostratigraphic subdivision and lithological description for the central and northern North Sea (Figs 3, 4). They subdivided the siliciclastic Palaeogene, Neogene and Quaternary sediments into five major groups: the Montrose, Moray, Rogaland, Hordaland and Nordland Groups. The Montrose and Moray Groups established for the Outer Moray Firth – Forties area are proximal equivalents to the Rogaland Group and are not present in the Danish sector, whereas the Rogaland, Hordaland and Nordland Groups have widespread distribution in the Danish sector. The succession of major mudstone formations contained within the three basinwide groups has

formed the backbone of all subsequent lithostratigraphic schemes for the central and northern North Sea, including that of the present contribution.

The post-Danian Cainozoic succession of the Danish Central Graben was divided into seven informal units by Kristoffersen & Bang (1982). The Palaeogene comprised five units: North Sea Marl and CEN-1–4 (Fig. 4). The ranks of the units were not stated. Although descriptions and interpretation of the CEN units were detailed, they are essentially informal and have been little used.

A revised lithostratigraphy for the Palaeogene and Neogene of the Norwegian North Sea sector was published by Hardt *et al.* (1989). Their lithostratigraphic scheme includes a number of new Palaeogene and Neogene sandstone bodies observed in the Norwegian and British sectors of the North Sea (Fig. 4). Some of the names of the new sandstone units established by Hardt *et al.* (1989) were subsequently used informally for comparable sandstone units discovered in the Danish sector.

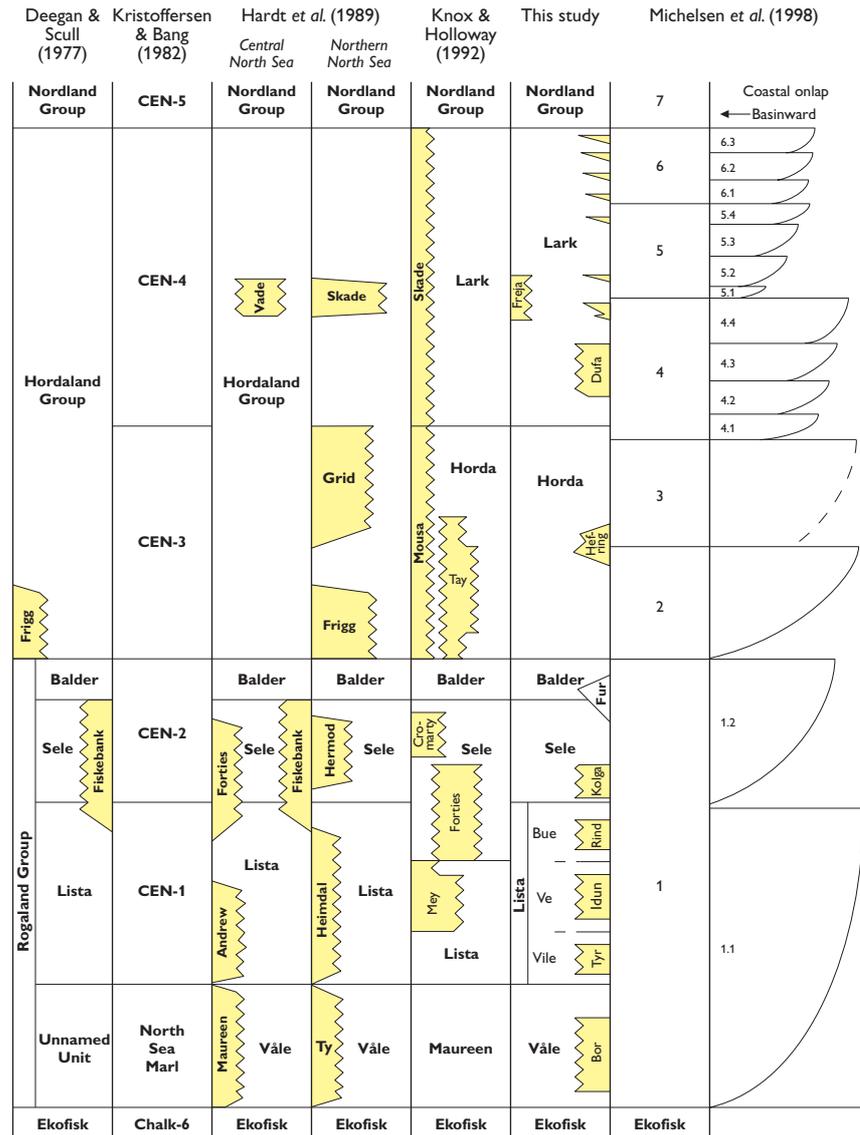
Mudge & Copestake (1992a, b) presented a revised Palaeogene stratigraphy for the Outer Moray Firth and northern North Sea Basins. In their papers they redefined the Moray and Montrose Groups of Deegan & Scull (1977) and abandoned the Rogaland Group. The authors also demoted the previously established sandstone formations within the two former groups to the rank of members. Besides, in an innovative approach they allowed for a greater influence of biostratigraphic data on the characterisation of the various lithostratigraphic units, an approach which is also followed herein.

Knox & Holloway (1992) updated the lithostratigraphic scheme for the Palaeogene in the British and Norwegian central and northern North Sea (Figs 3, 4). The authors followed Mudge & Copestake (1992a, b) in abandoning the Rogaland Group of Deegan & Scull (1977), and used Mudge & Copestake's revised definition of the Montrose and Moray Groups for the central North Sea as well. Furthermore, the thick and hitherto undivided Hordaland Group was subdivided into two new groups, the Stronsay Group succeeded by the Westray Group, each containing a distal and a proximal formation. The two distal formations of the two groups, the Horda and Lark Formations, together constitute the bulk of the Palaeogene sediments in the Danish sector of the North Sea and are adopted herein (Figs 2–4). Although sandstone units occur in both the Horda and Lark Formations in the Danish sector, the two proximal sandstone formations of the

Deegan & Scull (1977) Hardt <i>et al.</i> (1989)		Knox & Holloway (1992)		This study	
Nordland Group		Nordland Group		Nordland Group	
Hordaland Group		Westray Group	Skade Lark	Westray Group	Lark
		Stronsay Group	Mousa Horda	Stronsay Group	Horda
Rogaland Group	Balder	Moray Group	Balder	Rogaland Group	Balder
	Sele		Sele		Sele
	Lista	Montrose Group	Lista	Lista	Lista
	Unnamed unit/ Våle		Maureen	Våle	
Chalk Group		Chalk Group		Chalk Group	

Fig. 3. Correlation chart showing the approximate correlation between key lithostratigraphic schemes for the central and eastern North Sea at group and formation levels.

Fig. 4. Correlation chart showing approximate correlation between key lithostratigraphic schemes for the central and eastern North Sea and the Norwegian part of the northern North Sea at formation and member levels. The sequence stratigraphic subdivision of Michelsen *et al.* (1998) is added for comparison. Sandstone-dominated units indicated in yellow.



Stromsøy and Westray Groups, the Mousa and Skade Formations, are absent from the Danish sector.

Following detailed analysis of new, high-resolution seismic surveys covering the succession in the eastern North Sea area, efforts were focused on establishing a sequence stratigraphic subdivision of the Palaeogene–Neogene sediment package. The sedimentary succession was interpreted in a series of publications from a working group at the University of Aarhus (e.g. Michelsen *et al.* 1992, 1995, 1998; Michelsen 1993; Danielsen *et al.* 1997; Huuse &

Clausen 2001). The result of that work was a subdivision of the Palaeogene to mid-Neogene sediment package covered by the present work into six genetic units (Fig. 4). The sequence stratigraphy of the upper Oligocene to Miocene in the eastern North Sea was dealt with by Rasmussen (2004b). Further sequence stratigraphic contributions covering the larger North Sea Basin including the British and Norwegian sectors are given by Armentrout *et al.* (1993), Mudge & Bujak (1994, 1996a, b) and Neal *et al.* (1994).

Material and methods

The present lithostratigraphic subdivision represents the combined results from studies of petrophysical logs, biostratigraphy and seismic profiles, cuttings samples and cored sections. Petrophysical logs from *c.* 70 wells in the Danish sector have been scrutinised (see Fig. 1 for well locations). The wells have been correlated using petrophysical logs, predominantly gamma-ray and sonic logs. Five log panels form the basis for the log correlation (Plates 1–5).

Lithostratigraphic well correlation has been supported by biostratigraphic data: biostratigraphic reports from 29

wells have been re-assessed with the aim of identifying key micropalaeontological and palynological events that occur consistently within the study area (taxa used are planktonic and benthic foraminifers, diatoms, radiolaria, sporomorphs and dinoflagellate cysts). Moreover, biostratigraphic sample suites from 11 North Sea wells have been prepared at the Geological Survey of Denmark and Greenland in order to further determine the biostratigraphic event succession. The bulk of material studied for biostratigraphy is based on cuttings samples, and only few

Table 1. Well data for the new type and reference wells in the Danish sector of the North Sea

Well	Type (t) or reference (r) well for listed units:	Coordinates	Operator	Spud date	TD (logger's depth in m)	KB/RT elevation (m above msl)	Water depth (m)
Augusta-1	Bor Mb(t), Bue Mb(t), Ve Mb(t)	56°17'57.40"N 04°24'04.64"E	DONG E&P a/s	04.03.2001	2991.0 MDRT	37.8 RT	65
Cecilie-1	Bor Mb(r), Tyr Mb(r)	56°24'23.73"N 04°45'42.00"E	DONG E&P a/s	15.10.2000	2361.0 MDRT	37.8 RT	59.4
Cleo-1	Bue Mb(r), Lista Fm(r), Ve Mb(r), Vile Mb(r)	56°23'23.54"N 04°25'22.70"E	Chevron Petroleum Co.	06.02.1984	4866.1 MDKB	40.5 KB	63.1
Connie-1	Idun Mb(t), Rind Mb(t)	56°24'28.34"N 04°42'30.36"E	DONG E&P a/s	02.02.2001	2351.8 MDRT	37.8 RT	61.5
E-8	Bue Mb(r), Lista Fm(r), Ve Mb(r), Vile Mb(r), Våle Fm(r)	55°38'13.42"N 04°59'11.96"E	Maersk Oil & Gas a/s	08.04.1994	2527.4 MDKB	36.6 KB	43.6
F-1	Dufa Mb(r)	57°01'53.4"N 06°54'28.6"E	Gulf Oil Company	06.10.1968	2421.6 MDKB	37.19 KB	40.8
Floki-1	Hefring Mb(t)	56°27'48.58"N 05°16'47.11"E	Kerr-McGee Int. aps	29.08.2000	1878 MDRT	35.8 RT	53.2
Francisca-1	Freja Mb(t)	56°22'27.95"N 04°48'05.30"E	Dansk Operatørselskab i/s	20.07.1998	1888.5 MDRT	36.4 KB	60
Frida-1	Freja Mb(r)	56°17'14.15"N 05°01'50.20"E	Dansk Operatørselskab i/s	26.07.1997	2274 MDRT	39.0 RT	54.3
Inez-1	Dufa Mb(t), Fur Fm(r)	56°50'28.39"N 06°57'41.62"E	Chevron Petroleum Co.	11.09.1977	1983.9 MDKB	35.1 KB	35.4
K-1	Fur Fm(r)	57°07'37.74"N 07°09'43.11"E	California Oil Co.	22.01.1970	2292.4 MDKB	37.2 KB	56.4
Mona-1	Balder Fm(r), Horda Fm(r), Lark Fm(r)	56°16'35.94"N 04°00'15.81"E	Chevron Petroleum Co.	03.10.1982	4241.6 MDKB	36.6 KB	65.5
Nini-3	Kolga Mb(r), Tyr Mb(t)	56°41'31.96"N 05°24'12.35"E	DONG E&P a/s	12.01.2001	1851.2 MDRT	37.3 RT	58.2
Sandra-1	Rind Mb(r)	56°35'13.33"N 05°01'35.19"E	Statoil E&P a/s	18.06.1998	2139 MDRT	36 KB	65
Siri-1	Horda Fm(r), Lark Fm(r), Sele Fm(r), Våle Fm(r)	56°29'11.10"N 04°54'57.49"E	Statoil E&P a/s	28.11.1995	2220 MDKB	23 KB	60
Siri-2	Idun Mb(r)	56°29'40.53"N 04°52'13.26"E	Statoil E&P a/s	03.08.1996	2297.5 MDRT	36.6 RT	60.6
Siri-3	Balder Fm(r), Kolga Mb(t), Vile Mb(t)	56°30'34.92"N 05°03'48.27"E	Statoil E&P a/s	30.08.1996	2171.5 MDRT	36.6 RT	60.1
Tabita-1	Sele Fm(r)	56°13'37.50"N 04°23'47.56"E	Statoil E&P a/s	10.09.1983	4353 MDKB	40 KB	65

Fm: Formation. Mb: Member. MDRT: Measured Depth below Rotary Table. MDKB: Measured Depth below Kelly Bushing.

a Geo- chronology Ma	Chronostratigraphy (Berggren <i>et al.</i> 1995)		Selected biostratigraphic events used in the present study		North Sea Biozones (King 1989)		Litho- stratigraphy			
	Series	Stage	Planktonic foraminifers <i>Benthic foraminifers</i> <u>Diatoms and radiolaria</u>	Dinoflagellate cysts	Planktonic microfossils	Benthic microfossils	Fm	Mb		
50	Eocene (pars)	Lower (pars)	← <i>Uvigerina batjesi</i> <i>Turrillina brevispira</i> <i>Gaudryina hiltermanni</i> common <i>Subbotina</i> ex gr. <i>linaperta</i>	← <i>Dracodinium condylos</i>	NSP6 (pars)	NSB4 (pars)	Horda			
				← <i>Fenestrella antiqua</i> , foraminifers very rare	← <i>Deflandrea oebisfeldensis</i> acme <i>D. oebisfeldensis</i> , influx <i>Inaperturopollenites</i> spp., common <i>H. tubiferum</i> common <i>Cerodinium</i> <i>wardenense</i>	NSP5b			NSB3b	
				← common <i>F. antiqua</i> and <i>Coscinodiscus morsianus</i>		NSP5a			NSB3a	
55				Sparnacian 54.5 55.5	← impoverished benthic agglutinated assemblage	← <i>Apectodinium augustum</i> ← <i>Apectodinium augustum</i> , acme <i>Apectodinium</i> spp.	NSP4	NSB2	Balder	Sele
	Paleocene	Upper	← <i>Cenodiscus</i> spp., <i>Cenosphaera</i> spp. increasing diversity of cal- careous benthic foraminifers	← <i>Alisocysta margarita</i>	NSP3	c	Lista	Bue		
			Thonetian 57.9	← reappearance of planktonic foraminifers <i>Globanomalina</i> cf. <i>compressa</i> , <i>S. trivialis</i> increasing diversity of calcareous foraminifers				← <i>acme A. gippingensis</i>	← <i>P. pyrophorum</i> , <i>P. australinum</i> abundant <i>P. pyrophorum</i> ← <i>Isabelidium?</i> <i>viborgense</i>	Ve
			Selandian 60.0	← common <i>Globoconusa</i> <i>daubjergensis</i>				← <i>Alisocysta reticulata</i>	NSP2	Vile
60	Lower	Danian	← <i>Senoniasphaera inornata</i>	← <i>Palynodinium grallator</i> , <i>Dinogymnium</i> spp.	NSP1	NSB1	Våle	Ekofisk		
65				Maastrichtian (pars)	← Cretaceous foraminifers		a		Tor	

Fig. 5. Chronostratigraphy and biostratigraphy of the Paleocene – Middle Miocene. **a:** Paleocene–Eocene. **b:** Eocene–Oligocene. **c:** Oligocene – Middle Miocene. Calibration of chronostratigraphic units follows Hardenbol *et al.* (1998), Berggren & Aubry (1996) for the Paleocene–Eocene boundary and Aubry *et al.* (2003) for the Sparnacian–Ypresian boundary. Key dinoflagellate datums are calibrated mainly using age estimates from Hardenbol *et al.* (1998) and Williams *et al.* (2004). Key microfossil datums are calibrated via their correlation with calibrated dinoflagellate datums as suggested by Mudge & Bujak (1996b), using age estimates from Hardenbol *et al.* (1998) and Williams *et al.* (2004). The combined event succession is correlated with the North Sea microfossil zonation of King (1989) and lithostratigraphic units treated herein. In the microfossil event column, the planktonic foraminifer events appear in normal font, benthic foraminifers in italics; diatoms and radiolarians are underlined.

C Geo- chronology Ma	Chronostratigraphy (Berggren et al. 1995)		Selected biostratigraphic events used in the present study		North Sea Biozones (King 1989)		Litho- stratigraphy		
	Series	Stage	Planktonic foraminifers Benthic foraminifers Diatoms and radiolaria	Dinoflagellate cysts	Planktonic microfossils	Benthic microfossils	Fm	Mb	
15	Miocene (pars)	Upper (pars)	Tortonian (pars) 11.2	← <i>Bolboforma metzmacheri</i> ← <i>Bulimina elongata</i>	← <i>Cannosphaeropsis passio</i>	NSP14b	NSB13a	Nordland Group	
		Middle	Serravallian	← <i>Bolboforma spiralis</i> ← <i>Bolboforma clodiusi</i>		NSP14a	NSB12c		
				← <i>Asterigerina staeschei</i> , ← <i>Elphidium inflatum</i> , ← <i>Meanis pompilioides</i>	← <i>Apteodinium spiridoides</i>	NSP13	NSB12b NSB12a		
		Lower	Langhian	14.8	← <i>Uvigerina tenuipustulata</i>	← <i>Coosteaudinium aubryae</i>	NSP12	NSB11	Lark
				16.4					
			Burdigalian		← <i>Hystriocholpoma cinctum</i> ← <i>Cordosphaeridium cantharellus</i>		NSP11	NSB10	
					← <i>Aulacodiscus allorgei</i> ← <i>Turrillina alsatica</i> ← <i>Plectofrondicularia seminuda</i> ← <i>Spirosigmoinella compressa</i>	← <i>Thalassiphora pelagica</i>			
	Oligocene (pars)	Upper	Aquitanian	20.5	← <i>Aulacodiscus insignis quadrata (small)</i> , ← <i>B. antiqua</i> , <i>G. girardana</i>	← <i>Chiropteridium</i> spp. ← <i>Membranophoridium aspinatum</i>	NSP10	NSB9	
				23.8	← <i>Pararotalia canui</i>	← <i>Distatodinium biffi</i>			
			Chatthian		← <i>Aulacodiscus insignis quadrata (large)</i> ← common <i>A. guerichi</i> , ← <i>Paragloborotalia opima</i> s.s. ← <i>Gyroidina mamillata</i>	← <i>Wetzeliella gochtii</i>	NSP9c	NSB8c NSB8b	
		28.5		← <i>Rotaliatina bulimoides</i> ← <i>Cibicoides mexicanus</i>	← <i>Rhombodinium draco</i>				
		Lower (pars)	Rupelian (pars)		← "Turborotalia" ampliapertura	← <i>Phthanoperidinium amoenum</i> ← <i>Enneadocysta pectiniformis</i>	NSP9b	NSB7b	
					← <i>Karrulina conversa</i> ← <i>Uvigerina germanica</i>	← <i>Achilleodinium bififormoides</i> ← <i>P. comatum</i> ← <i>Corrudinium incompositum</i>			
						NSP9a (pars)	NSB6b (pars)		

Fig 5c. Chronostratigraphy and biostratigraphy of the Oligocene – Middle Miocene.

core samples have been available. As the use of stratigraphic lowest occurrences (LO) of taxa in cuttings samples may be hampered due to downhole caving, the event succession comprises almost exclusively stratigraphic highest occurrences (HO) of taxa (a single significant LO is included in the succession). The event succession is shown in Fig. 5a–c; its correlation with international and North Sea biozones is shown in Fig. 6a–c.

Seismic sections from the 2-D and 3-D seismic surveys CGD85, DK-1, RTD81–RE94, UCG96 and UCGE97 have been used to further support the well correlation and to map the stratigraphic units in areas with only scattered well coverage. The combined results from the correlation and mapping procedures are presented as isochore maps for individual stratigraphic units.

Inspection of cuttings samples from 16 key wells supplemented with sedimentological studies of cored inter-

vals from 23 wells have formed the basis for the lithological and sedimentological descriptions of the units.

The well depths mentioned in the lithostratigraphy section are loggers' depths measured either from rotary table (MDRT) or kelly bushing (MDKB). Supplementary data for new type and reference wells are provided in Table 1.

The names assigned to the new lithostratigraphic units defined herein are derived from Nordic mythology and thus follow the nomenclatural tradition previously established for the Norwegian North Sea (Isaksen & Tonstad 1989).

It should be noted that the micropalaeontology-based palaeoenvironmental terminology used herein was originally developed for a passive margin situation (e.g. the terms 'neritic' and 'bathyal' to indicate the physiographic zones 'shelf' and 'shelf-slope', respectively). Its application herein to the epicontinental North Sea Basin solely relates to depositional depth.

Offshore and onshore lithostratigraphic nomenclature

There is a high degree of lithological similarity between the Palaeogene–Neogene mudstone succession in Danish offshore boreholes and that in onshore exposures and boreholes. However, the status of the Danish onshore units is quite varied since many units were named before a standard for description of a lithostratigraphic unit was established; some fulfil these requirements, whereas others are still informal. If a previously established onshore unit and an offshore unit can be demonstrated to be identical (e.g. the Holmehus Formation and the new Ve Member proposed herein), the name of the onshore unit theoretically has priority over the name of the offshore unit (Salvador 1994). In other cases, names of offshore units can be argued to have priority over onshore units (e.g. Sele and Balder Formations over Ølst Formation). However, in order to acknowledge the traditional distinction between offshore and onshore stratigraphic nomenclature, the two sets of nomenclature are kept separate herein. Whenever possible, comments are given in the text to explain the relationship between offshore and onshore Danish stratigraphic nomenclature. A correlation between the two sets of nomenclature is shown in Fig. 2.

Chronostratigraphy and biostratigraphy

Age assessment of the lithostratigraphic units in the North Sea sedimentary succession is based on correlation between key biostratigraphic events encountered in the units and the calibrated standard chronostratigraphy published by Berggren *et al.* (1995), with modification for the Paleocene–Eocene boundary following ratification of its position by the International Union of Geological Scientists (Aubry *et al.* 2002). The key events are from biostratigraphic zonation schemes established for the North Sea area. Planktonic and benthic microfossils are covered by the zonation schemes of King (1983, 1989; Figs 5a–c, 6a–c). Dinoflagellates from the Paleocene and Eocene Epochs are covered by the zonation scheme of Mudge & Bujak (1996b; Fig. 6a, b); the Oligocene and Miocene Epochs are covered by the zonation schemes of Costa & Manum (1988) with modifications by Köthe (1990, 2003; Fig. 6b, c). Key events from these schemes used in this study are listed in Fig. 5a–c.

For the dinoflagellate events, geochronological calibration has been largely established using age estimates from Hardenbol *et al.* (1998), Munsterman & Brinkhuis (2004) and Williams *et al.* (2004). For events not mentioned in these three publications, the works of Mudge & Bujak