Correlation of the Upper Oligocene–Miocene deltaic to shelfal succession onshore Denmark with similar deposits in the northern North Sea and Norwegian Sea shelf based on Sr isotope-, bio- and seismic stratigraphy—a review

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The almost complete, mainly deltaic, upper Paleogene and Neogene succession in Jylland, Denmark, was previously investigated for ⁸⁷Sr/⁸⁶Sr ratios in 143 samples from 18 localities. In the present paper, strontium-isotope data from the Upper Oligocene–Lower Miocene parts and foraminiferal and pyritised diatoms data from 94 of these samples were used to correlate with previously published data from Norwegian wells and boreholes and one borehole in the British sector of the North Sea. For the Middle–Upper Miocene parts of the succession the correlation is based mainly on *Bolboforma* data. The ages of the geological formations in the Danish succession correlate readily with lithological units in the Norwegian North Sea, the Norwegian Sea shelf and the East Shetland Platform, which have all been investigated applying similar methods. The *Bolboforma* assemblages have their origin in the North Atlantic and the Norwegian Sea and confirm the presence of an open strait in the northern North Sea. This strait was the only seaway passage into the North Sea Basin during the Miocene. The glauconitic Utsira Formation sand (approximately 5.7–4.2 Ma), in the threshold area close to the outlet to the Norwegian Sea, overlies erosional unconformities comprising hiatus of 21 my in some areas and 13 my in other areas. We believe that the unconformity below the Utsira Formation was mainly related to a fall in sea level in the Late Miocene, contemporaneous with that partly responsible for the Messinian salinity crisis. *Bolboforma* and dinoflagellate cysts stratigraphy indicate that the base of the Molo Formation in its southern distribution area (Draugen Field, Trøndelag Platform) is of Late Miocene age (close to 9 Ma). This part of the Molo Formation was contemporaneous with the middle/upper part of the Kai Formation.

Keywords: Sr isotope stratigraphy, foraminiferal stratigraphy, *Bolboforma* stratigraphy, upper Paleogene–Neogene correlation, Denmark, North Sea, Norwegian Sea shelf, Norwegian Sea.

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Introduction

A correlation between the well-dated outcropping Upper Oligocene–Miocene succession in Denmark (Eidvin et al., 2014a) and the offshore succession in the Norwegian North Sea, East Shetland Platform and Norwegian Sea shelf (Eidvin, 2016; Eidvin et al., 2013, 2014b) is a key for

understanding the palaeogeography and infill history of the North Sea basin. A proper dating of the sedimentary units and recognition of the extent of hiatuses are necessary for this purpose.

Thin-walled calcareous microfossils such as foraminifera and *Bolboforma* are generally sparse in the Danish

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onshore upper Paleogene and Neogene successions. This is either due to their dissolution by humic acid in the pore water or they were not present in the most marginal marine environments. However, from the stratigraphic borehole Rødding (DGU nr. 141.1141) in southern Jylland (Fig. 1), Eidvin et al. (2013) were able to retrieve foraminifera, *Bolboforma* and mollusc shells from most sections (Figs. 1 & 2). In several sites, investigated for fossil dinoflagellate cysts (dinocysts) by Dybkjær & Piasecki (2010), thick-walled tests of molluscs have been quite resistant to dissolution. These are present where foraminifera are absent, and Eidvin et al. (2014a) succeeded to retrieve molluscs and/or mollusc fragments from a number of samples for strontium isotope analyses from these sites (Table 1).

Eidvin et al. (2014a) presented a comparison and a discussion of the Danish strontium-isotope and dinocyst data. They concluded that the Sr isotope ages from the lower part of the Danish Miocene succession, i.e., the latest Oligocene–Early Miocene Brejning to Odderup formations, agree with the age estimates based on dinocysts. However, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of fossil carbonates from the Middle–Upper Miocene, Hodde to Gram formations consistently indicate ages older than those recorded by the dinocysts (Fig. 2). Post-depositional processes as an explanation for this offset are inconsistent with the good preservation of the shell material. There is also restricted reworking. Eidvin et al. (2014a) suggested that limited oceanic exchange with the inner North Sea Basin might have caused the observed Sr isotope ratios.

Figure 1. Map of onshore and offshore Denmark showing wells, boreholes and outcrops analysed for dinocysts (Dybkjær & Piasecki, 2010), *Bolboforma* and foraminifera (Eidvin et al. 2013). It also shows the sites where shell material has been Sr dated. Small circles: Outcrops and boreholes which formed the basis for the dinocyst study (Dybkjær & Piasecki, 2010). Large circles: Outcrops and boreholes that formed the basis for the dinocyst study (Dybkjær & Piasecki, 2010) as well as the present Sr isotope study.

Table 1. Strontium-isotope analyses (all samples are analysed at the University in Bergen if not stated otherwise. All Sr ratios were corrected to NIST 987 = 0.710248. Numerical ages derived from the SIS Look-up Tables of Howarth & McArthur (1997, 2004). NIST – National Institute for Standard and Technology. DC – ditch cuttings).

Localities	Lithostratigraphy/sample level	Corrected $^{87}\text{Sr}/^{86}\text{Sr}$	2S error	Age (Ma; H. & M., 1997; mean value)	Age (Ma; H. & M., 2004; mean value)	Comments	Analysed fossils
Breining (outcrop)	Breining Fm	0.708202	0.000009	24.84	23.99		One mollusc fragment
Breining (outcrop)	Breining Fm	0.708193	0.000008	24.98	24.16	Same sample as above	One mollusc fragment
Dykær (outcrop)	Breining Fm	0.708272	0.000008	23.74	22.68		Two mollusc fragments
Dykær (outcrop)	Breining Fm	0.708273	0.000008	23.72	22.67	Same sample as above	Two mollusc fragments
Fakkegrav (outcrop)	Breining Fm	0.708163	0.000009	25.53	24.78		One mollusc fragment
Fakkegrav (outcrop)	Breining Fm	0.708161	0.000008	25.57	24.83	Same sample as above	One mollusc fragment
Bøgeskov (outcrop)	Breining Fm	0.708287	0.000008	23.46	22.43		One mollusc fragment
Bøgeskov (outcrop)	Breining Fm	0.708275	0.000008	23.69	22.63	Same sample as above	One mollusc fragment
Jensgård (outcrop)	Breining Fm	0.708164	0.000008	25.51	24.76		One mollusc fragment
Jensgård (outcrop)	Breining Fm	0.708155	0.000008	25.68	24.99	Same sample as above	One mollusc fragment
Lyby Strand (outcrop)	Breining Fm	0.708202	0.000008	24.84	23.99		One mollusc fragment
Lyby Strand (outcrop)	Breining Fm	0.708231	0.000008	24.42	23.93	Same sample as above	One mollusc fragment
Hørup Hav (boreh.)	Breining Fm? 76.8–76.4 m (bucket)	0.708243	0.000009	24.23	23.20		One mollusc fragment
Harre (borehole, core)	Breining Fm, 44.25 m (core)	0.708174	0.000008	25.32	24.53		Two mollusc fragments
Harre (boreh.)	Breining Fm, 44.25 m (core)	0.708212	0.000008	24.70	23.81		Three mollusc fragments
Harre (boreh.)	Breining Fm, 37.25 m (core)	0.708202	0.000008	24.84	23.99		One mollusc fragment
Harre (boreh.)	Breining Fm, 31.25 m (core)	0.708190	0.000009	25.03	24.22		One mollusc fragment
Rødding (boreh.)	Vejle Fjord Fm, 243 m (DC)	0.708265	0.000009	23.86	22.80		One mollusc fragment
Rødding (boreh.)	Vejle Fjord Fm, 241 m (DC)	0.708199	0.000009	24.89	24.05		One mollusc fragment
Salling 1 (outcrop)	Vejle Fjord Fm	0.708313	0.000009	22.88	22.06		Three mollusc fragments
Salling 1 (outcrop)	Vejle Fjord Fm	0.708297	0.000008	23.25	22.28		Six mollusc fragments
Salling 1 (outcrop)	Vejle Fjord Fm	0.708318	0.000008	22.76	21.99	Same sample as the two above	One mollusc fragment
Fasterholt (boreh.)	Vejle Fjord Fm, 170 m (core)	0.708259	0.000009	23.97	22.91		One mollusc fragment
Fasterholt (boreh.)	Vejle Fjord Fm, 170 m (core)	0.708266	0.000008	23.85	22.79		One mollusc fragment
Fasterholt (boreh.)	Vejle Fjord Fm, 170 m (core)	0.708284	0.000008	23.52	22.48		One mollusc fragment
Hørup Hav (boreh.)	Vejle Fjord Fm, 68.8–68.4 m (bucket)	0.708302	0.000009	23.14	22.22		One mollusc fragment
Harre (boreh.)	Vejle Fjord Fm, 19.75 m (core)	0.708252	0.000009	24.08	23.03		One mollusc fragment
Rødding (boreh.)	Vejle Fjord Fm, 238 m (DC)	0.708233	0.000008	24.54	23.39		One mollusc fragment
Rødding (boreh.)	Vejle Fjord Fm, 236 m (DC)	0.708258	0.000008	23.99	22.93		Three mollusc fragments
Rødding (boreh.)	Vejle Fjord Fm, 230 m	0.708232	0.000009	24.41	23.41		One mollusc fragment

Continues

Table 1. Continued

Localities	Lithostratigraphy/sample level	Corrected $^{87}\text{Sr}/^{86}\text{Sr}$	2S error	Age (Ma; H. & M., 1997; mean value)	Age (Ma; H. & M., 2004; mean value)	Comments	Analysed fossils
Rødding (boreh.)	Vejle Fjord Fm, 228 m	0.708262	0.000009	23.92	22.86		One mollusc fragment
Rødding (boreh.)	Vejle Fjord Fm, 225 m	0.708230	0.000009	24.44	23.45		One mollusc fragment
Rødding (boreh.)	Vejle Fjord Fm, 222 m	0.708276	0.000008	23.67	22.62		One mollusc fragment
Rødding (boreh.)	Vejle Fjord Fm, 220 m	0.708263	0.000009	23.90	22.84		One mollusc fragment
Rødding (boreh.)	Vejle Fjord Fm, 218 m	0.708380	0.000009	21.26	21.09		One mollusc fragment
Rødding (boreh.)	Vejle Fjord Fm, 216 m	0.708387	0.000009	21.13	20.97		One mollusc fragment
Salling 2 (outcrop)	Klintinghoved Fm	0.708462	0.000009	19.96	19.66		One mollusc fragment
Salling 2 (outcrop)	Klintinghoved Fm	0.708447	0.000007	20.19	19.87		One mollusc fragment
Salling 2 (outcrop)	Klintinghoved Fm	0.708439	0.000008	20.31	19.98	Same sample as the two above	Two mollusc fragments
Klinting-hoved (outcrop)	Klintinghoved Fm	0.708389	0.000008	21.10	20.93		One mollusc fragment
Klinting-hoved (outcrop)	Klintinghoved Fm	0.708371	0.000008	21.44	21.24	Same sample as above	One mollusc fragment
Klinting-hoved (outcrop)	Klintinghoved Fm	0.708370	0.000009	21.46	21.25		One mollusc fragment
Klinting-hoved (outcrop)	Klintinghoved Fm	0.708398	0.000009	20.95	20.75		One mollusc fragment
Sønder Vium (boreh.)	Klintinghoved Fm, 283.3 m (core)	0.708395	0.000008	21.00	20.81		One mollusc fragment
Sønder Vium (boreh.)	Klintinghoved Fm, 268.5 m (core)	0.708459	0.000008	20.01	19.70		One mollusc fragment
Prestbjerg (boreh.)	Klintinghoved Fm, 155–154 m (core)	0.708351	0.000008	21.89	21.52		One fragment of a shark tooth
Prestbjerg (boreh.)	Klintinghoved Fm, 155–154 m (core)	0.708349	0.000009	21.93	21.55		One fragment of a shark tooth
Prestbjerg (boreh.)	Klintinghoved Fm, 155–154 m (core)	0.708374	0.000009	21.38	21.19		One fragment of a shark tooth
Hørup Hav (boreh.)	Klintinghoved Fm, 62.75–62.3 m (bucket)	0.708331	0.000009	22.39	21.80		One mollusc fragment
Hørup Hav (boreh.)	Klintinghoved Fm, 54.8–54.3 m (bucket)	0.708323	0.000009	22.63	21.92		One mollusc fragment
Hørup Hav (boreh.)	Klintinghoved Fm, 52.0–51.35 m (bucket)	0.708265	0.000008	23.86	22.80		One mollusc fragment
Hørup Hav (boreh.)	Klintinghoved Fm, 50.9–50.45 m (bucket)	0.708365	0.000009	21.56	21.32		One mollusc fragment
Hørup Hav (boreh.)	Klintinghoved Fm, 49.3–49.1 m (bucket)	0.708348	0.000009	21.96	21.56		One mollusc fragment
Hørup Hav (boreh.)	Klintinghoved Fm, 43.0 m (bucket)	0.708438	0.000008	20.32	20.00		One mollusc fragment
Rødding (boreh.)	Klintinghoved Fm, 185 m (DC)	0.709012	0.000008	5.65	5.67	Probably caved	One mollusc fragment
Sønder Vium (boreh.)	Arnum Fm, 112 m (core)	0.708555	0.000008	18.50	18.44		One mollusc fragment
Sønder Vium (boreh.)	Arnum Fm, 112 m (core)	0.708560	0.000008	18.43	18.38		One mollusc fragment
Sønder Vium (boreh.)	Arnum Fm, 111.15 m (core)	0.708580	0.000008	18.18	18.12		One mollusc fragment
Sønder Vium (boreh.)	Arnum Fm, 111.15 m (core)	0.708543	0.000007	18.66	18.59		One mollusc fragment
Sønder Vium (boreh.)	Arnum Fm, 111.0–109.5 m (core)	0.708572	0.000008	18.28	18.23		One mollusc fragment
Sønder Vium (boreh.)	Arnum Fm, 111.0–109.5 m (core)	0.708611	0.000008	17.83	17.74		One mollusc fragment
Sønder Vium (boreh.)	Arnum Fm, 90.0–88.5 m (core)	0.708529	0.000008	18.86	18.77		One mollusc fragment

Localities	Lithostratigraphy/sample level	Corrected $^{87/86}\text{Sr}$	2S error	Age (Ma; H. & M., 1997; mean value)	Age (Ma; H. & M., 2004; mean value)	Comments	Analysed fossils
Sønder Vium (boreh.)	Arnum Fm, 90.0–88.5 m (core)	0.708611	0.000008	17.83	17.74		One mollusc fragment
Sønder Vium (boreh.)	Arnum Fm, 71.15 m (core)	0.708622	0.000009	17.62	17.60		One mollusc fragment
Sønder Vium (boreh.)	Arnum Fm, 71.15 m (core)	0.708545	0.000009	18.64	18.56		One mollusc fragment
Sønder Vium (boreh.)	Arnum Fm, 51.80 m (core)	0.708717	0.000008	16.53	16.04		One mollusc fragment
Sønder Vium (boreh.)	Arnum Fm, 51.80 m (core)	0.708694	0.000007	18.87	16.43		Two mollusc fragments
Sønder Vium (boreh.)	Arnum Fm, 51.80 m (core)	0.708714	0.000009	16.57	16.09		Two mollusc fragments
Sønder Vium (boreh.)	Arnum Fm, 51.50 m (core)	0.708708	0.000008	16.67	16.19		One mollusc fragment
Lille Tønde (boreh.)	Arnum Fm, 87.6 m (DC)	0.708527	0.000009	18.89	18.80		One mollusc fragment
Lille Tønde (boreh.)	Arnum Fm, 82.85–82.35 m (DC)	0.708614	0.000009	17.79	17.70		One mollusc fragment
Lille Tønde (boreh.)	Arnum Fm, 81.35–80.8 m (DC)	0.708614	0.000010	17.79	17.70		One mollusc fragment
Lille Tønde (boreh.)	Arnum Fm, 67.9–67.45 m (DC)	0.708624	0.000009	17.68	17.57		One mollusc fragment
Rødding (boreh.)	Arnum Fm, 135 m (DC)	0.708558	0.000009	18.56	18.28		One mollusc fragment
Rødding (boreh.)	Arnum Fm, 132 m (DC)	0.708424	0.000008	20.53	20.24		One mollusc fragment
Rødding (boreh.)	Arnum Fm, 129 m (DC)	0.708527	0.000008	18.89	18.80		One mollusc fragment
Rødding (boreh.)	Arnum Fm, 127 m (DC)	0.708502	0.000009	19.27	19.12		One mollusc fragment
Rødding (boreh.)	Arnum Fm, 124 m (DC)	0.708440	0.000009	20.29	19.97		One mollusc fragment
Rødding (boreh.)	Arnum Fm, 120 m (DC)	0.708852	0.000009	11.27	11.14	Caved	One mollusc fragment
Rødding (boreh.)	Arnum Fm, 100 m (DC)	0.708846	0.000011	11.49	11.39	Caved	One mollusc fragment
Rødding (boreh.)	Arnum Fm, 99 m (DC)	0.708734	0.000008	16.23	15.78		One mollusc fragment
Rødding (boreh.)	Arnum Fm, 94 m (DC)	0.708746	0.000008	15.97	15.59		One mollusc fragment
Rødding (boreh.)	Arnum Fm, 92 m (DC)	0.708805	0.000008	13.59	13.59	Caved	One mollusc fragment
Rødding (boreh.)	Arnum Fm, 91 m (DC)	0.708718	0.000008	16.51	16.02		One mollusc fragment
Føvling (boreh.)	Odderup Fm, 69 m (core)	0.708688	0.000009	16.95	16.53		One mollusc fragment
Føvling (boreh.)	Odderup Fm, 69 m (core)	0.708696	0.000009	16.84	16.39		One mollusc fragment
Føvling (boreh.)	Odderup Fm, 69 m (core)	0.708655	0.000009	17.35	17.11		One mollusc fragment
Rødding (boreh.)	Odderup Fm, 81 m (DC)	0.707898	0.000009	32.13	32.37	Reworked	One bryozo fragment
Rødding (boreh.)	Odderup Fm, 78 m (DC)	0.708752	0.000008	15.83	15.49		One mollusc fragment
Rødding (boreh.)	Odderup Fm, 72 m (DC)	0.708708	0.000009	16.67	16.19		One small gastropod
Rødding (boreh.)	Odderup Fm, 69 m (DC)	0.708746	0.000009	15.97	15.59		One small gastropod
Rødding (boreh.)	Odderup Fm, 65 m (DC)	0.708860	0.000009	11.01	10.84	Caved	One mollusc fragment
Rødding (boreh.)	Odderup Fm, 64 m (DC)	0.708764	0.000008	15.54	15.32		One mollusc fragment
Rødding (boreh.)	Odderup Fm, 41 m (DC)	0.708731	0.000008	16.29	15.82		One mollusc fragment

The purpose of the present paper is to correlate the data from the Danish succession (published in Eidvin et al., 2014a) with similar data in wells in the northern North Sea (Figs. 1–3; published in Eidvin, 2016 and Eidvin et al., 2013, 2014b). Since Eidvin et al. (2014a) showed that the strontium-isotope data from the Middle–Upper Miocene part of the Danish succession are not reliable and cannot be trusted, we have only used the strontium-isotope data from the Upper Oligocene–Lower Miocene part of this succession (Table 1). For the Middle–Upper Miocene part, the correlation is based on comparing the *Bolboforma* and foraminiferal assemblages in the Rødding borehole with similar assemblages in the Norwegian and British wells and boreholes and the deep-sea record (Figs. 4–8). Dinocyst correlation is also used in some areas. Eidvin et al. (2013, 2014b) have substantiated the approximate synchronicity of the upper Paleogene and Neogene delta and distal sediments in different parts of the North Sea (Figs. 9–12). In the present paper we present a more detailed correlation.

In a number of previous studies, more than 2000 samples, in more than 55 Norwegian wells and boreholes and one British well, have been analysed for benthic and planktonic foraminifera, *Bolboforma* and pyritised diatoms. As an additional control, and in order to increase the stratigraphic resolution, around 1500 samples from the same wells and boreholes, were analysed for $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Eidvin, 2016; Eidvin et al., 2013, 2014b). Most of the analysed samples were ditch cuttings, whereas sidewall cores and conventional core samples were available in some wells. Figures 1 and 2 in Eidvin et al. (2013) and figures 17 and 18 in Eidvin et al. (2014b) show the location of the analysed sidewall cores, conventional core samples and ditch cuttings. Caved material is often a problem when analysing ditch cuttings, whereas reworked material is always a problem regardless of types of samples. This is discussed in the papers where the detailed results of the analysis are presented (Eidvin, 2016; Eidvin & Rundberg, 2007; Eidvin et al. 2007, 2013, 2014b and papers referred to in Eidvin et al. 2013, 2014b). These papers compare the ages provided by Sr isotope correlations with ages given by biostratigraphic correlations and discuss the uncertainties. In the northern North Sea, common soft-sediment deformation and sand injection in the lower part of the Utsira Formation, which are mainly restricted to the depocentres (Riis & Eidvin, 2015, 2016), may also complicate the dating of the sediments. All wells have been tied to high-quality seismic data. The strontium data, which are used for the correlations in the present paper, are based on fossil tests interpreted to be in situ or having an age which does not deviate very much from the depositional age.

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were converted to age estimates using the Strontium isotope stratigraphy (SIS) look-up

♦ = These ages are considerably older than the ages obtained from dinocyst correlations according to Eidvin et al. (2014a).

Figure 2. Lithostratigraphy of the Danish uppermost Oligocene–Miocene (from Rasmussen et al., 2010). The column to the right shows the palynological stratigraphy of Dybkjær & Piasecki (2010) and the main results of the strontium-isotope datings of mollusc tests from outcrop and borehole samples. Please note that the stratigraphy of Rasmussen et al. (2010) and Dybkjær & Piasecki (2010) is based on the time scale of Gradstein et al. (2004). The strontium-isotope stratigraphy is based on the look-up table of Howarth & McArthur (1997) which again is based on the time scale of Berggren et al. (1995). The use of Howarth & McArthur's (1997) table is to facilitate correlation with successions on the Norwegian continental shelf. In the strontium-isotope analyses (Table 1), age estimates based on Howarth & McArthur (2004) are also listed.

table of Howarth & McArthur (1997; Eidvin et al., 2013, Fig. 3). Consequently, to facilitate correlation with successions on the Norwegian continental shelf, we have also converted the Sr ratios to age estimates using the same look-up table in the present paper. This look-up table is based on the time scale of Berggren et al. (1995), and this time scale is used throughout the present paper. The dinocyst zonation of Dybkjær & Piasecki (2010) is based on the time scale of Gradstein et al. (2004). In the paper of Eidvin et al. (2014a) age estimates are based on the revised look-up table of Howard & McArthur (2004), which in turn is based on the time scale of Gradstein et al. (2004). In the present paper, age estimates based

on the tables of Howarth & McArthur (1997, 2004) are listed (Table 1). There is currently no SIS look-up table that is based on the new time scale of Cohen et al. (2013, updated 2018). Table 2 shows that, for the post-Eocene, absolute ages for the time scales of Berggren et al. (1995) and Cohen et al. (2013, updated 2018) do not deviate very much. The most important difference is that in Cohen et al. (2013, updated 2018), the base Pleistocene is moved from 1.85 to 2.588 Ma.

Figure 3. Map showing wells and boreholes containing Oligocene to Lower Pliocene deposits analysed for strontium isotopes, the location of the interpreted seismic profiles (Figs. 12 & 13) and the Oligocene to Lower Pliocene sandy deposits in the North Sea, Norwegian Sea and on the Norwegian Sea shelf mentioned in the text (the sites indicated in Figure 1 are not included; modified after Eidvin et al., 2013). The extent of the Oligocene sands and wedge units are according to Rundberg & Eidvin (2005). The extent of the Utsira, Eir (informal) and Skade formations in the North Sea is according to the NPD (unpublished data). The extent of the Molo Formation is after Bullimore et al. (2005), and the extent of the Hutton sand (informal) is after Gregersen & Johannessen (2007). The extent of the North Sea Oligocene play (NOL-1) is according to the Norwegian Petroleum Directorate web page (www.npd.no). The provenance study is after Olivarius (2009) and the topographic map is after Olesen et al. (2010).

Geological setting

The Norwegian–Danish Basin was formed during the Permian–Triassic rifting (Ziegler, 1982, 1990; Berthelsen, 1992). The basin is bounded to the northeast by the so-called Sorgenfrei–Tornquist Zone and the southern boundary is formed by the Ringkøbing–Fyn High. Reactivation of fault blocks took place in the Jurassic and especially salt movements were associated with the Mid-Cimmerian tectonic phase (Vejbæk & Andersen, 1987; Berthelsen, 1992; Thybo, 2001). Regional subsidence characterised the basin from the Early Cretaceous. This period was still dominated by a paralic depositional setting. During the Late Cretaceous, inversion of former graben structures occurred, and resumed reactivation of salt structures probably commenced (Mogensen & Korstgård, 1993). The Late Cretaceous period was dominated by deposition of marine chalk, and adjacent to the Sorgenfrei–Tornquist Zone a 1–2 km-thick succession of chalk was formed. However, in the marginal areas of the Fennoscandian Shield, e.g. Scania, uplift of basement resulted in progradation of siliciclastic delta systems (Erlström, 1994). Continued subsidence in the North Sea characterised the Paleogene. Marine chalk, and later on marine clay, accumulated in the basin. Along the Sorgenfrei–Tornquist Zone, minor uplift/inversion of the flanks occurred in the Late Paleocene (Nielsen et al., 2005). Deposition of marine clay continued into the Eocene. Minor reactivation of salt structures commenced at the Eocene/Oligocene boundary. From the Oligocene, mud-dominated, mica-rich, marine sediments were deposited. During the latest Early Oligocene, sandy deltaic deposits started to accumulate in the northeastern part of the basin in the Norwegian sector of the North Sea (Eidvin et al., 2013). The change from clay-dominated to mud- and sand-dominated, mica-rich sediments was associated with progradation of sediments sourced in the Southern Scandes. Inversion of the Norwegian–Danish Basin took place at the Oligocene–Miocene boundary (Rasmussen, 2009, 2013). Early Miocene uplift of the Southern Scandes and a decreasing water depth in the Norwegian–Danish basin resulted in progradation of sand-rich deltaic deposits

in the eastern North Sea Basin throughout this period. During the Middle Miocene, the regional subsidence of the central North Sea Basin accelerated while the basin flanks became uplifted (Ziegler, 1990; Knox et al., 2010; Rasmussen & Dybkjær, 2014). In Denmark, this resulted in flooding of the margins and deposition of marine mud on top of the Lower Miocene deltaic deposits. Resumed delta progradation took place during the Late Miocene (Sørensen et al., 1997), and at this time the deltas reached the central part of the Danish North Sea Basin (Rasmussen et al., 2005, 2008). The Norwegian–Danish Basin was probably a land area during the Pliocene. However, the evidence for that has been destroyed by Quaternary uplift and erosion (Japsen, 1993).

The North Sea Basin is an epicontinental basin, confined by the Scandinavian and British landmasses, with a marine connection in the north to the Norwegian–Greenland Sea (Figs. 3 & 8). In the Norwegian sector, the basin comprises several major, Mesozoic highs and grabens of which the Central Graben in its south-central region and the Viking Graben in the north are dominant (see figure 7 in Eidvin et al., 2013 or figure 15 in Eidvin et al. 2014b). Tectonism ceased in the Cretaceous and the basin was subjected to post-rift subsidence and became filled by sediments sourced by the surrounding topographical highs. In the Paleocene–Eocene, the surrounding landmasses were uplifted and the North Sea Basin deepened. Deltaic sequences prograded into the deep basin from the Shetland Platform and West Norway. Progradation continued in the Oligocene and Miocene, but the source area was then mainly confined to the Shetland Platform (Eidvin & Rundberg, 2001, 2007; Gregersen & Johannessen, 2007; Rundberg & Eidvin, 2005; Eidvin et al., 2013). The depocentres typically contain 200–600 m of Oligocene to Lower Pliocene sands.

The Norwegian Sea and its continental shelf and slope contain various structural elements (see figure 6 in Eidvin et al., 2013 or figure 10 in Eidvin et al., 2014b). The Møre and Vøring basins are characterised by exceptionally thick Cretaceous successions and a complex Cretaceous and Cenozoic tectonic history (Blystad et al., 1995; Brekke, 2000). In Oligocene to Early Pliocene times, the Møre and Vøring basins were located in a distal position relative to sediment supply from Scandinavia, and pelagic ooze makes up a significant part of the succession. Large compressional structures were formed during Eocene and Middle Miocene tectonism. The Trøndelag Platform has remained tectonically stable since the Late Cretaceous. In the Late Miocene to Early Pliocene, there was a pronounced progradation of coastal sediments along the inner Norwegian Sea continental shelf (represented by the sandy Molo Formation, typically 100–200 m thick). Farther west on the present continental shelf, deposition of fine-grained clastic sediment and pelagic ooze prevailed, and contouritic deposits are common (Laberg et al., 2005).

VØRING PLATEAU

(Spiegler & Jansen 1989,
Müller & Spiegler 1993)
(BASED ON FADs)

NORTH SEA
(King 1989)

SOUTHERN VIKING GRABEN

Well 25/10-2
(Sea floor = 1116 mRKB)

Well 24/12-1
(Sea floor = 135 mRKB)

DENMARK
(onshore)

RØDDING BOREHOLE

L = Lithostratigraphic units
S = Series / subseries
PA = Planktonic foraminiferal or fossil assemblages
PB = Benthic foraminiferal assemblages
mRKB = Depth in metres below the rig floor
Sr (Ma) = Strontium isotope ages in million years ago

Marine mudstone
Marine sandstone
Glauconitic sandstone/mudstone

Figure 4. Correlation of fossil assemblages and selected main results of strontium-isotope analyses between the Rødding borehole and wells 24/12-1 and 25/10-2 calibrated to King's (1989) North Sea zonation and the Bolboforma zonation of the ODP Sites 642 and 643 on the Vøring Plateau (Müller & Spiegler, 1993). Detailed analysis results and discussions are found in Eidvin & Rundberg (2007) and Eidvin et al. (2013). All the samples are ditch cuttings, but the strontium data are based on fossil tests interpreted to be in situ or close to in situ. The IRD curve is after Jansen & Sjøholm (1991) and Fronval & Jansen (1996). Sr data only from the Upper Oligocene and Lower Miocene are shown from the Rødding borehole, since only these particular data are considered to be reliable from this borehole.

Palaeoclimate

The global deep-sea $\delta^{18}\text{O}$ record shows that a cool climate prevailed early in the Late Oligocene, but a warming trend started in the later part of Late Oligocene (Fig. 9). This warming trend is also detected in NW Europe (Utescher et al., 2009; Larsson et al., 2011); consequently, a warm temperate and humid climate persisted in the North Sea realm during the Oligocene. This warm climate continued during the Early Miocene. The mean annual temperature was 19 to 20°C and the winters were frost free. The precipitation was in the order of 1300 to 1500 mm per year (Utescher et al., 2009; Larsson et al., 2010, 2011; Rasmussen, 2013). Minor deteriorations in climate, the so-called Mi events (glaciation events in Antarctica; Miller et al., 1998), resulted in short-spanned decreases in air temperature in the order of 2–5°C (Larsson et al., 2010, 2011; Sliwinska et al., 2014). The global mid Miocene Climatic Optimum apparently did not have any distinct influence on the air temperature in the Danish North Sea area (Larsson et al., 2011). In the Late Miocene and Pliocene, a minor climatic deterioration occurred in Central Europe (Utescher et al., 2009), but in southern Scandinavian this decline is not observed during the Late Miocene (Larsson et al., 2011). Data from Central England also indicate that a relatively warm climate persisted during the Late Miocene (Pound & Ridings, 2015). Also on Iceland, a warm temperate, humid climate existed during the mid to early Late Miocene, with a shift to a cool temperate climate during the latest Late Miocene (Denk et al., 2005).

A study of continuous late Neogene sediment sections from ODP Site 907 on the Iceland Plateau and ODP Sites 642, 643 and 644 on the Vøring Plateau (Norwegian Sea; Fig. 8) showed a gradual and stepwise cooling of the deep water of the Iceland–Norwegian Sea with major cooling events at approximately 11 and 6.4 Ma (Fronval & Jansen, 1996). The oldest ice-rafted debris (IRD) detected is dated to approximately 12.6 Ma. IRD from this event is also recorded in borehole 6704/12-GB1 on the Vøring Plateau (Fig. 3; Eidvin et al., 1998, 2013). This coincides with a decrease in mean annual temperature at middle and high latitudes, an intensification of North Atlantic deep-water production, and a change in circulation patterns within the Iceland–Norwegian Sea, as indicated by a shift from extensive biogenic opal ooze deposition to carbonate accumulation on the Vøring Plateau. IRD records from both the Iceland Plateau and the Vøring Plateau suggest further intensifications of the Northern Hemisphere glaciations at approximately 6 Ma (Messinian). The onset of the large-scale Northern Hemisphere glaciations is dated to 2.75 Ma on the Vøring Plateau and 2.9 Ma on the Iceland Plateau (Fronval & Jansen, 1996). The different timing could imply that the growth of the large ice sheets did not occur simultaneously in Greenland and Scandinavia. There is no evidence for the existence of glaciers along the eastern

seaboard of the Norwegian–Greenland Sea before 2.75 Ma (Fronval & Jansen, 1996).

Description of correlated areas and deposits

Overview

The depocentre in the Norwegian–Danish Basin and Jylland (the eastern North Sea Basin) received sediments from the Southern Scandes mountains, with a general progradation from north to south during the period. The depocentre in the basinal areas of the UK and Norwegian sectors of the North Sea, north of 58°N, received sediments from the Scotland–Shetland area. Because of the sedimentary infilling there was a gradual shallowing of the northern North Sea basin in the Oligocene to the Pliocene. In other local depocentres along the coast of Norway, deposition of sandy sediments took place only occasionally (Eidvin et al., 2013).

Onshore Denmark (eastern North Sea Basin)

In Jylland, Denmark, large areas have upper Paleogene and Neogene successions below the Quaternary glacial deposits. The Lower Miocene succession is characterised by coarse-grained, dominantly sand-rich, fluvio-deltaic deposits interfingering with marine clay (Larsen & Dinesen 1959; Rasmussen & Dybkjær, 2005; Hansen & Rasmussen, 2008; Rasmussen et al., 2010). The delta was sourced from the Southern Scandes in Norway and Central Sweden and prograded towards the south and southwest (Figs. 3 & 8). The deltaic succession, referred to the Ribe Group, is composed of three discrete units referred to sequences B, C and D by Rasmussen (2004) and is approximately 200 m thick with a gross thickness of sand up to 150 m. The abrupt incursion of sand in the southern part of the Norwegian–Danish Basin in the earliest Miocene is interpreted to be the result of an inversion of the basin and a possible coincident uplift of the source area. The Ribe Group is succeeded by the mud-dominated Måde Group (Lower Nordland Group). The Måde Group was deposited in a fully marine depositional setting that lasted from Middle–Late Miocene time in the eastern North Sea Basin. Onshore, the Måde Group is up to 140 m thick and is subdivided into three sequences; E, F1 and F2 (Møller et al., 2009; Rasmussen, 2017).

These deposits have been studied palynologically in more than fifty boreholes (including some offshore boreholes) and about twenty-five outcrops (Fig. 1). Dinocysts occur in nearly all of the deposits. The palynological studies have resulted in a dinocyst zonation scheme of nineteen dinocyst zones spanning from the Oligocene–Miocene transition to the Pliocene (Dybkjær & Piasecki, 2010).

SOUTHERN VIKING GRABEN

DENMARK
(onshore)

RØDDING BOREHOLE

This vertical scale (in Ma) differs from that of the three wells which are in metres.

Marine mudstone
Marine sandstone
Glauconitic sandstone/mudstone

L = Lithostratigraphic units
S = Series / subseries
PA = Planktonic foraminiferal or fossil assemblages
PB = Benthic foraminiferal assemblages
mRKB = Depth in metres below the rig floor
Ma (or Ma) = Strontium isotope ages in million years ago

Figure 5. Correlation of fossil assemblages and selected, main results of strontium-isotope analyses between the Rødding borehole and wells 25/2-10 S and 25/1-8 S calibrated to King's (1989) North Sea zonation and the Bolboforma zonation of the ODP Sites 642 and 643 on the Vøring Plateau (Müller & Spiegler, 1993). Detailed analysis results and discussions are found in Eidvin & Rundberg (2007) and Eidvin et al. (2013). All the samples are ditch cuttings, but the strontium data are based on fossil tests interpreted to be *in situ* or close to *in situ*. The IRD curve is after Jansen & Sjøholm (1991) and Fronval & Jansen (1996). Sr data only from the Upper Oligocene and Lower Miocene are shown from the Rødding borehole, since only these particular data are considered to be reliable from this borehole.

Central and northern North Sea

According to Eidvin et al. (2013), during late Rupelian to Chattian, sediments in the northernmost part of the North Sea Basin were sourced from the northwestern part of the South Scandes Dome, which was a topographic high throughout the Paleogene. In the northeastern part of the northern North Sea off Nordfjord, sandy gravity-flow sediments were deposited (Ull formation, an informal name suggested by Eidvin et al., 2013). Farther south off Hordaland and Sogn and Fjordane, a distinct wedge of Rupelian organic-rich mudstones was formed along the coast. Deltaic complexes prograded southwards into the Norwegian–Danish Basin (Vade Formation and the sand-rich part of the Lark Formation, and the Dufa and Freja members in Danish waters). In the latest Rupelian to Chattian there was a large input of sandy sediments from the Shetland Platform into the northern North Sea. Most of the sediments were laid down in the southern Tampen area (the informal Ull formation). Farther south, Chattian deposits are recorded below the Skade Formation in the Frigg Field area, i.e., within the area belonging to the Hutton Sand according to Gregersen & Johannessen (2007). Elsewhere, in the central and northern North Sea, mainly argillaceous sediments were deposited.

In large parts of the Viking Graben (northern North Sea), a sandy section, sourced from the East Shetland Platform, makes up a great proportion of the Lower Miocene Skade Formation. More than 500 exploration wells have penetrated the Lower Miocene deposits, and selected wells have been investigated for benthic and planktonic foraminifera, pyritised diatoms and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (marked with red dots in Fig. 3; Eidvin et al., 2013). One well from the East Shetland Platform, in the British North Sea sector, has also been investigated (Eidvin, 2016). The Skade Formation reaches a maximum thickness of up to 400 m (Eidvin et al., 2013). In the British sector, the Lower Miocene sandy deposits constitute a part of the Hutton sand succession. Hutton sand is an informal term used in the UK sector by several oil companies to describe all sands above the Lower Eocene Balder Formation in the Northern North Sea (British Geological Survey, 2000). The Skade Formation comprises a succession of amalgamated sands

in alternation with thinner mudstones. In most parts, the deposits are probably turbiditic in origin and were probably deposited in quite deep parts of the shelf. The sandy successions in the wells 25/2-10 S and 25/1-8 S and the British well 9/09a-A 23 (Fig. 3) contain common mollusc fragments and lignite coal and have probably been deposited in mainly shallow water (Eidvin et al., 2013; Eidvin, 2016). All of these wells are situated within the deltaic Hutton sand area as defined by Gregersen & Johannessen (2007). As seen in figure 3, the Hutton sand extends into the Norwegian sector and continues into the deeper water Skade Formation. The Skade sands pinch out towards the lower slope of the Norwegian margin to the east. It has been suggested that the sandy deposits are a result of an Early Miocene tectonic uplift event affecting the East Shetland Platform, possibly associated with a renewed compressional tectonic phase along the northwestern European margin (Rundberg & Eidvin, 2005).

During the Middle Miocene, sediments continued to be deposited from the East Shetland Platform. In the northern North Sea, these deposits form a part of the Hutton sand succession in the UK sector and represent the basal part of the Nordland Group occurring as an infilling unit within the Viking Graben in the Norwegian sector. The sediments are sandy on the East Shetland Platform and in the western and northern parts of the Viking Graben. In the eastern and southern parts and south of the Viking Graben, the deposits are mainly silty and clayey. Sandy Middle Miocene sediments are recorded in wells 25/1-8 S, 25/2-10 S (western Viking Graben), 26/10-1 (southeastern Viking Graben), 9/09a-A 23 (East Shetland Platform, UK sector), 16/3-5 (southern Viking Graben, may be part of an injectite), 15/9-13 (southern Viking Graben) and 30/5-2 and 30/6-3 (170 m thick; northern Viking Graben; Fig. 3; Eidvin et al., 2013; Eidvin, 2016). Especially the Middle Miocene section in well 25/1-8 S was probably deposited at a very shallow-marine site. In the shallow-marine environment it may be difficult to distinguish these sands from sands of the Utsira Formation above and the Skade Formation below, and they are believed to act as one aquifer system (Halland et al., 2011, updated 2019; Eidvin et al., 2013). In spite of being noisy, seismic data show that in the Middle Miocene or possible Lower Miocene, an eastward-prograding delta system was developed in the Frigg area. Wells 25/1-8 S and 9/09a-A 23 penetrated the sandy deposits in the delta plain while well 25/2-10 S was drilled east of the clinoform belt. A thick depocentre of Middle Miocene sands was developed east and north of the Frigg area in a more distal shelf environment (sands penetrated in wells 30/5-2 and 30/6-3; figure 12 in Eidvin et al., 2013). The Middle Miocene sandy sections appear to form mappable units which are clearly younger than the Skade Formation and older than the Utsira Formation in the Viking Graben. Eidvin et al. (2013) tentatively introduced the name Eir formation, after an Æsir (god) in Norse mythology, for these units in the

DENMARK
(onshore)

SOUTHERN VIKING GRABEN

EAST SHETLAND PLATFORM

RØDDING BOREHOLE

Norwegian sector, representing a new formation in the Nordland Group (Fig. 10).

During the Late Miocene to Early Pliocene, the northern North Sea apparently formed a narrow seaway between the deeper water in the Møre Basin and the central North Sea. The central North Sea received large amounts of coarse sand (Utsira Formation). The Utsira Formation represents a huge sedimentary depositional system in the northern North Sea (about 450 km long and 90 km wide; Fig. 3), comprising one large sandy depocentre (250–300 m in the southern Viking Graben) and an area with 80–100 m-thick sandy deposits in the northern Viking Graben (figure 11 in Eidvin et al., 2013; Halland et al., 2011, updated 2019). The western central area of the Viking Graben comprises a large deltaic system which prograded eastwards in the Early and Middle Miocene. Here, Upper Miocene to Lower Pliocene sediments of the Utsira Formation are thin or absent due to lack of accommodation space (Fig. 10). Numerous wells have penetrated these deposits, and several of these have been investigated for benthic and planktonic foraminifera, *Bolboforma* and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (marked with red dots in Fig. 3; Eidvin et al., 2013). Apparently, the progradation of the delta front stopped in the Middle/Late Miocene. The sediments were transported to the delta slope and the shallow shelf beyond the delta, suggesting a relative fall in sea level. In the Tampen area to the north, the Utsira Formation is represented by a thin glauconitic unit dated to the latest Miocene to Early Pliocene. There, it is overlying Oligocene and Lower Miocene deposits. Offshore western Norway, north of the Troll Field a sandy deltaic system developed. This delta was probably fed by the Sognefjorden paleo-valley (Fig. 13). In the western part of the Norwegian sector blocks 30 and 25, the Utsira Formation merges with parts of the Hutton sand (see Fig. 3).

Norwegian Sea shelf

In the Late Miocene, coastal plains and deltas of the Molo Formation built out along the inner continental shelf of the Norwegian Sea (Eidvin et al., 2013; Grøsfjeld et al., in press and unpublished dinocyst data (personal observations)). In the northern distribution area off Vesterålen, this has been interpreted to be due to a relative sea-level fall probably mainly caused by uplift of the coastal zone/mainland (Grøsfjeld et al., in press). Here, in the northeastern part of the distribution of the Molo Formation (well 6610/3-1), the progradation of coastal sand initiated in the Tortonian (Grøsfjeld et al., in press). In the southern part of its distribution, the Molo Formation (Draugen Field, Trøndelag Platform) contains glauconite sand (Eidvin et al., 2013). On the shelf to the west, clayey and hemipelagic sediments accumulated, whereas on the slope and rise pelagic ooze was deposited (middle/upper part of the Kai Formation).

Material and methods

Strontium isotope analyses

Eidvin et al. (2014a) obtained $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 143 samples from 18 localities from the Upper Oligocene to Upper Miocene Danish succession. Fifty-four of these samples were from the Rødding well (Fig. 1). The analyses were mainly carried out on fragments of mollusc shells, tests of foraminifera and *Bolboforma*, in addition to one sample representing a shark tooth. The collected shell material was supplemented with mollusc shells picked from the collection of Leif Banke Rasmussen, stored at the Geological Museum in Copenhagen (Rasmussen, 1966). The results were presented in Eidvin et al. (2014a). However, since the strontium isotope data from the Middle–Upper Miocene are uncertain, as mentioned above, only strontium isotope data from the Upper Oligocene–Lower Miocene part (94 samples from 18 localities) have been used for the correlation in the present paper. These are listed in Table 1.

Biostratigraphy

Micropalaeontological investigations in the Rødding borehole were based on analyses of planktonic and benthic foraminifera and *Bolboforma*. Pyritised diatoms were also used to establish a stratigraphy for the Upper Oligocene–Lower Miocene part (see Eidvin et al., 2013).

The fossil assemblages are mainly correlated with the micropalaeontological zonation for Cenozoic sediments of King (1983, 1989). The zonations based on *Bolboforma* species (Spiegler & Müller, 1992; Müller & Spiegler, 1993; Spiegler, 1999) from ODP and DSDP drillings in the Norwegian Sea and the North Atlantic are very important for dating the Middle–Upper Miocene part of the column. Correlation with these zones yields the most accurate age determinations, because the zones are calibrated with both nannoplankton and palaeomagnetic data.

Correlation

The strontium isotope analyses of samples from the Danish Brejning, Vejle Fjord, Klintinghoved, Arnum and Odderup formations gave ages between 25.7 (Late Oligocene) and 15.5 Ma (early Middle Miocene; Fig. 2). These sediments, which have also been analysed for foraminifera and pyritised diatoms in the Rødding borehole (Figs. 1 and 3; Eidvin et al., 2013), can be correlated with deposits from a number of lithological units in the Norwegian North Sea and the East Shetland

NORWEGIAN SEA SHELF

DENMARK
(onshore)

RØDDING BOREHOLE

Trøndelag Platform

Well 6407/9-5
(Sea floor = 319 mRKB)

Heigeland Basin

Well 6508/5-1
(Sea floor = 435 mRKB)

L = Lithostratigraphic units
S = Series / subseries
PA = Planktonic foraminiferal or fossil assemblages
PB = Benthic foraminiferal assemblages
PD = Dinoflagellate zones
mRKB = Depth in metres below the rig floor
Sr (Ma) = Strontium isotope ages in million years ago

VØRING PLATEAU

(Spegler & Jansen 1989,
Müller & Spegler 1993)
(BASED ON FADs)

NORTH SEA
(King 1989)

This vertical scale (in Ma) differs from that of the three wells which are in metres.

Figure 7. Correlation of *Bolboforma* between the Rødding borehole and wells 6407/9-5 and 6508/5-1, calibrated to King's (1989) North Sea zonation and the *Bolboforma* zonation of the ODP Sites 642 and 643 on the Vøring Plateau (Müller & Spiegler, 1993). Detailed analysis results and discussions are found in Eidvin et al. (2007, 2013). All the samples are ditch cuttings, but the strontium data are mainly based on fossil tests interpreted to be in situ or close to in situ. The IRD curve is after Jansen & Sjøholm (1991) and Fronval & Jansen (1996). Sr data only from the Upper Oligocene and Lower Miocene are shown from the Rødding borehole, since only these particular data are considered to be reliable from this borehole.

Platform, which have been investigated applying similar methodology. These include the Hutton sand (informal; East Shetland Platform), clay-rich deposits of the Hordaland Group (central, southeastern and northern North Sea), the sandy Skade Formation (northern North Sea) and the sandy Eir formation (informal; Figs. 10 & 11). Some of these correlations are visualised in detail (Figs. 4–7).

Figure 4 shows that, based on Sr isotope and benthic foraminiferal data, the Brejning Formation in the Rødding borehole correlates with the Upper Oligocene part of the Hordaland Group in wells 24/12-1 and 25/10-2 in the southern Viking Graben and King's (1989) NSB Zone 8 from the North Sea. The Vejle Fjord Formation in the Rødding borehole correlates with the Lower Miocene part of the Hordaland Group, below the Skade Formation, in well 24/12-1, the Lower Miocene part of the Hordaland Group, lower part of the Skade Formation in well 25/10-2 and the lower main part of the NSB Zone 9 of King (1989). The Klintinghoved, Bastrup, Arnum and Odderup formations correlate with the main part of the Skade Formation in well 24/12-1 and the upper main part of the Skade Formation in well 25/10-2 and King's (1989) NSB Zone 10 and the upper part of NSB Zone 9.

The correlation of the Hodde, Ørnhøj and Gram formations in the Rødding borehole is based on *Bolboforma* assemblages. Similar *Bolboforma* assemblages, in the Hodde and Gram formations, are recorded from the Gram, Lille Tønde and Borg-1 boreholes on the Ringkøbing High and in the North German Basin (southern Jylland) by Laursen & Kristoffersen (1999, Fig. 8). Figure 4 shows that the *Bolboforma badenensis*–*Bolboforma reticulata* assemblage in the Hodde Formation correlates with similar assemblages in the fine-grained lowermost part of the Nordland Group situated between the sandy Skade and Utsira formations in wells 24/12-1 and 25/10-2 (see also Eidvin et al., 2013). These assemblages correlate in turn with the *Bolboforma badenensis*–*Bolboforma reticulata* Zone of Müller & Spiegler (1993) from the Vøring Plateau (Norwegian Sea; Fig. 8), which has been dated accurately to slightly older than 14 to 11.7 Ma (Middle Miocene; Spiegler & Müller, 1992). *Bolboforma* of a *Bolboforma laevis* assemblage and a *Bolboforma*

metzmacheri assemblage are recorded in the Ørnhøj and Gram formations. In well 24/12-1, a *Bolboforma fragori* assemblage is recorded from the lowermost part of the Utsira Formation. In well 25/10-2 a *Bolboforma fragori* assemblage and a *Bolboforma metzmacheri* assemblage are recorded from the lower part of the Utsira Formation (see also Eidvin et al., 2013). These assemblages correlate with a *Bolboforma fragori*/*Bolboforma subfragori* Zone (accurately dated to 11.7–10.3 Ma, earliest Late Miocene), *Bolboforma laevis* Zone (10.3–10.0 Ma, Late Miocene; *B. laevis* is also present in the *B. fragori*/*Bolboforma subfragori* Zone) and *Bolboforma metzmacheri* Zone (10.0–8.7 Ma, Late Miocene) on the Vøring Plateau (Quale & Spiegler, 1989; Spiegler & Müller, 1992; Müller & Spiegler, 1993).

Based on Sr and benthic foraminiferal data, the Brejning Formation in the Rødding borehole correlates with the Upper Oligocene part of the Hordaland group in wells 25/2-10 S and 25/1-8 S in the southern Viking Graben and King's (1989) NSB Zone 8 from the North Sea (Fig. 5). The Vejle Fjord, Klintinghoved and Bastrup formations and the lower part of the Arnum Formation in the Rødding borehole correlate with the Skade Formation in well 25/2-10 S. The Vejle Fjord, Klintinghoved and Bastrup formations and the whole of the Arnum Formation correlate with the Skade Formation in well 25/1-8 S. All of these units correlate in turn with the NSB 9 Zone and NSB 10 Zone of King (1989).

According to Figure 5, the correlation of the Hodde Formation in the Rødding borehole is based mainly on *Bolboforma* assemblages. The *Bolboforma badenensis*–*Bolboforma reticulata* assemblage correlates with similar assemblages in the sandy lowermost part of the Nordland Group (suggested to be named the Eir formation by Eidvin et al., 2013) situated between the Skade and Utsira formations in wells 25/2-10 S and 25/1-8 S. These assemblages correlate in turn with the *Bolboforma badenensis*–*Bolboforma reticulata* Zone of Müller & Spiegler (1993) from the Vøring Plateau (Norwegian Sea; Fig. 8), dated to slightly older than 14 to 11.7 Ma (Middle Miocene). Sediments with the same age as the Ørnhøj and Gram formations in the Rødding borehole are not present in the wells 25/2-10 S and 25/1-8 S (Fig. 5).

Figure 6 shows that, based mainly on Sr data, the Vejle Fjord, Klintinghoved, Bastrup, Arnum and Odderup formations in the Rødding borehole correlate with the upper main part of the Hutton sand in well 9/09a-A 23.

The Hodde Formation, based on the *Bolboforma badenensis*–*Bolboforma reticulata* assemblage in the Rødding borehole, is correlated with a similar assemblage in well 9/09a-A 23. These assemblages correlate again with the *Bolboforma badenensis*–*Bolboforma reticulata* Zone of Müller & Spiegler (1993) from the Vøring Plateau (Norwegian Sea; Fig. 8) which, as noted above,

has been dated accurately to slightly older than 14 to 11.7 Ma (Middle Miocene; Spiegler & Müller, 1992). The Ørnhøj and Gram formations in the Rødding borehole are tentatively correlated with the uppermost part of the Hutton sand in well 9/09a-A 23.

Figure 6 also shows that, based on Sr and benthic foraminiferal data, most of the lower part of the Hutton sand in well 9/09a-A 23 correlates with the Hordaland Group in well 25/1-8 S and King's (1989) NSB Zone 8 from the North Sea. Based on the same kind of data, the middle part of the Hutton sand in well 9/09a-A 23 correlates with the Skade Formation in well 25/1-8 S and the NSB 9 Zone and NSB 10 Zone of King (1989). Based on Sr and benthic foraminiferal data, Figure 6 also shows that the Middle Miocene part of the Hutton sand in well 9/09a-A 23 correlates with the lower part of the Nordland Group in well 25/1-8 S. Sediments with a similar age as the uppermost part of the Hutton sand in well 9/09a-A 23 are not present in well 25/1-8 S.

Figure 7 shows that, based on Sr and pyritised diatoms (Diatom sp. 4 assemblage), the Klintinghoved and Bastrup formations and lower part of the Arnum Formation in the Rødding borehole correlate with the upper part of the Brygge Formation in well 6407/9-5 (Trøndelag Platform) and Zone NSP 10 of King (1989) from the North Sea. This correlation is verified by unpublished dinocyst data (personal observations). The upper part of the Gram Formation in the Rødding borehole is of a similar age as the lower part of the Molo Formation in well 6407/9-5 and the middle part of the Kai Formation in well 6508/5-1 (Helgeland Basin; see Fig. 14), which again correlates with the *Bolboforma metzmacheri* Zone (10.0–8.7 Ma, Late Miocene) on the Vøring Plateau (Spiegler & Müller, 1992; Müller & Spiegler, 1993; also verified by unpublished dinocyst data (personal observations)).

Discussion

The idealised palaeogeography for the Middle–Late Miocene advocated by Løseth & Henriksen (2005) shows a situation with a large land area stretching from present-day Shetland Island to southern Norway (their figure 15). Our divergent views on the geological history have led to a discussion in geoscience journals including the following articles: Eidvin et al. (2013, 2014b), Løseth et al. (2013), Rundberg & Eidvin (2016ab), Løseth et al. (2016b), Løseth & Øygarden (2016), Eidvin & Rundberg (2016a, b) and Løseth (2016). In the present paper we want to document and elaborate our view more thoroughly.

According to several authors, including Knox et al. (2010) and Rasmussen et al. (2008), during the Miocene

the North Sea was not in contact with an open ocean towards the east, west and south (Fig. 8). According to Løseth & Henriksen (2005) and Løseth et al. (2013) a compressional phase and related major regression would have led to an isolation of the North Sea Basin. This compressional phase is shown as terminating approximately at the top Miocene (their figure 17). This partly reflects their estimate of the age of the Utsira Formation to the Early Pliocene. An opening to the south, in addition an opening to the north, formed first as late as in the late Pleistocene when repetitive mega-floodings, caused by breaching of rock dams at the Dover Strait, instigated catastrophic drainages of large pro-glacial lakes in the southern North Sea Basin. Two periods with catastrophic floods, after 450,000 but before 180,000 years ago, formed bedrock-floored valleys. Thus, Britain was isolated from continental Europe during high sea-level stands during the Eemian and Holocene (Sanjeev et al., 2007; Gibbard, 2007, Gibbard & Cohen, 2015).

A major sea-level fall within the Late Miocene is indicated by a number of features, including deep channelling beneath the Tortonian Deurne Member in Belgium (Houthuys, 2014; Vandenberghe, 2014), incision of Upper Miocene delta systems within the central North Sea (Møller et al., 2009) and the rapid progradation of the Eridanos Delta into the central North Sea Basin (Overeem et al., 2014; Kuhlmann et al., 2006; Patruno et al., 2019). However, there are no stratigraphic or sedimentological data suggesting a closure of the basin. The incision of the pre-Deurne Member channels implies strong tidal currents, which are unlikely to have been generated in a closed sea. In addition, in the thick and apparently continuous Upper Miocene succession in the central North Sea there are no signs of stratification, reduced salinity or lowered oxygenation which can be deduced from the sediments or the microfauna. The key evidence is provided by the plankton. Several *Bolboforma* zones, described from and accurately dated in scientific boreholes from the Norwegian Sea and North Atlantic, up to and including the *B. metzmacheri* Zone (c. 10.0–8.7 Ma, through the Serravallian to mid Tortonian; Spiegler & Müller, 1992; Müller & Spiegler, 1993), are represented in the central North Sea Basin, onshore southern Denmark and in other onshore areas (King, 1989; Laursen & Kristoffersen, 1999; Eidvin & Rundberg, 2007; Eidvin et al., 2013), indicating the existence of an open connection to the North Atlantic/Nordic seas throughout this period. The succeeding *B. intermedia* Zone (c. 8.8–5.9 Ma: late Tortonian and Messinian; Spiegler & Müller, 1992) is also identified (though rarely) in both onshore and offshore areas (Chris King, personal communication). Planktonic foraminifera are represented throughout almost all this interval in some areas. A succession of pteropod zones is identified through the early Tortonian (Gürs & Jansen, 2002). Planktonic foraminifera are represented (quite commonly) through the Upper Miocene in the central North Sea Basin (e.g., well 2/4-C-11 (Eidvin et

Figure 8. Palaeogeographic reconstruction of the North Sea Basin and adjacent areas in the Miocene (after Knox et al., 2010; Rasmussen et al., 2008; Dybkjær & Piasecki, 2010). The extents of the Miocene deltas and fan deposits and possible drainage routes in Denmark are from figure 3. Hypothetical drainage routes for the Hutton sand and Skade Formation are modified from Halland et al. (2014) and Gjeldvik et al., (2011). The approximate positions of the wells and boreholes from the correlation diagrams in Figures 4–7 are indicated with red dots and numbers. Other wells and boreholes are indicated with black, green and blue dots.

Figure 9. General view of the Late Paleogene and Neogene lithostratigraphy modified after Rundberg & Eidvin (2008) and Eidvin et al. (2013). On the right-hand side of the diagram some palaeoclimatic data are added including a global deep-sea oxygen curve, bottom-water paleo-temperatures in the world's oceans, periods with ice-sheets in Antarctica and the northern hemisphere (after Zachos et al., 2001) and a global sea-level curve after Hardenbol et al. (1998). Periods with deposition of IRD at ODP Site 913 (off East Greenland; Eldrett et al., 2007) and on the Lomonosov Ridge (Arctic Ocean; Backman et al., 2006; Moran et al., 2006; St. John, 2008) are also indicated

Figure 10. Post-Eocene lithostratigraphy of the Norwegian North Sea including main results of the strontium isotope analyses based on fossil tests interpreted to be in situ (after Eidvin et al., 2013).

Figure 11. Curve showing strontium-isotope evolution of seawater from 25 to 5 Ma (from Howarth & McArthur, 1997). For clarity, the obtained $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (y-axis) and corresponding ages (x-axis; mean values) for the Norwegian Skade, Eir (informal) and Utsira formations, the Danish Brejning, Vejle Fjord, Klintinghoved, Arnum and Odderup formations and the British Hutton sand (informal; from Figs. 2, 6 & 10) are indicated with different colours.

al., 1999, 2013)). The late Tortonian (7.5 Ma) transition from dextral to sinistral *Neogloboquadrina atlantica* is also identified in the central North Sea (Spiegler & Jansen, 1989; King, 1989). Dinocyst assemblages also indicate continuing oceanic connections, and there is no stratigraphical break in the Miocene–Pliocene succession in Denmark (Dybkjær & Piasecki, 2010).

In the correlation chapter and Figures 4–7 we described the correlations of *Bolboforma* assemblages from the Ringkøbing–Fyn High, in the southeast, through the Central and Viking grabens to the Norwegian Sea shelf and Vøring Plateau (Norwegian Sea) in the north (see Fig. 8).

Figure 14 synthesises the *Bolboforma* correlation. The *Bolboforma badenensis*–*Bolboforma reticulata* assemblage, the oldest assemblage, is recorded from the Hodde Formation in the Gram-1 borehole (Larsen & Kristoffersen, 1999) and the Rødding borehole (both from the Ringkøbing–Fyn High). Larsen & Kristoffersen (1999) also recorded this assemblage farther south from the Borg-1 and Lille Tønde boreholes in the North German Basin (Fig. 8; not included in Fig. 14). The assemblage is not recorded in well 2/4-C-11 (Central Graben) since there is a local hiatus in the Middle Miocene in that area, possibly due to salt tectonics and polygonal faulting (Eidvin et al., 2013). In the Viking Graben, the *B. badenensis*–*B. reticulata* assemblage is recorded from the Nordland Group, including the lowermost part of the Utsira Formation, in wells 24/12-1 and 25/10-2 as well as

in the Nordland Group in well 25/2-10 S. The lack of the top of the assemblage in the latter well is probably due to a break in the stratigraphy. Towards the west, the *B. badenensis*–*B. reticulata* assemblage is recorded in the UK well 9/09a-A 23 on the East Shetland Platform. As seen in Figure 14, in the scientific boreholes at ODP Sites 642 and 644 on the Vøring Plateau the occurrence of *B. badenensis* and *B. reticulata* is estimated to be slightly older than 14 to c. 11.7 Ma (Middle Miocene; Spiegler & Müller, 1992; Müller & Spiegler, 1993).

Higher up in the sections at ODP Sites 642 and 644, Spiegler & Müller (1992) and Müller & Spiegler (1993) described a *B. fragori*–*B. subfragori* Zone from sediments with an age of approximately 11.7–10.3 Ma (earliest Late Miocene). Between the *B. badenensis*–*B. reticulata* Zone and the *B. fragori*–*B. subfragori* Zone they described a very thin *Bolboforma compressispinosa* Zone. Immediately above the *B. fragori*–*B. subfragori* Zone, Spiegler & Müller (1992) and Müller & Spiegler (1993) described a *Bolboforma laevis* Zone extending up to sediments estimated to c. 10 Ma in age. *B. laevis* and *B. clodiusi* are also common in the *B. fragori*–*B. subfragori* Zone (Quale & Spiegler, 1989; Müller & Spiegler, 1993).

Larsen & Kristoffersen (1999) recorded *B. clodiusi* assemblages from the Gram Formation in the Borg-1 and Lille Tønde boreholes (North German Basin) and the Gram-1 borehole (Ringkøbing–Fyn High; Fig. 8). Eidvin et al. (2013) recorded a *B. laevis* assemblage from the

Figure 12. Correlation panel of the Oligocene to Pliocene succession from central Jylland, Denmark, into the North Sea and northward to just west of Stadt, western Norway. The datum (horizontal blue line) is the base of the Hodde Formation in the Danish and southern Norwegian sector. North of 58°30' N the blue line corresponds to the so-called Middle Miocene unconformity (see also Fig. 3 for location, after Eidvin et al. (2010, 2013)).

Northern Viking Graben - 61°N

Figure 13. East-west transect of the northern North Sea at about 61°N illustrating the main sequences and sedimentary architecture of the post-Eocene strata (see Fig. 3 for location; modified after Eidvin & Rundberg, 2001, Rundberg & Eidvin, 2005 and Eidvin et al., 2013).

Ørnhøj and Gram formations in the Rødding borehole (Ringkøbing-Fyn High; Fig. 14). A *B. fragori*-*B. subfragori* assemblage is recorded from the Nordland Group in well 2/4-C-11 (Central Graben). *B. fragori* assemblages are recorded from the Utsira Formation in the wells 24/12-1 and 25/10-2 (Viking Graben; Fig. 14). In well 25/2-10 S (Viking Graben), sediments with a similar age as the *B. fragori* assemblage are eroded.

Above the *B. laevis* Zone in the boreholes at ODP Sites 642 and 644, Spiegler & Müller (1992) and Müller & Spiegler (1993) described a *B. metzmacheri* Zone from sediments with an age of c. 10–8.7 Ma (Late Miocene). *B. metzmacheri* assemblages are recorded in the Gram Formation from the Borg-1 and Lille Tønde boreholes (North German Basin; Laursen & Kristoffersen, 1999), from the Gram-1 and Rødding boreholes (Ringkøbing-Fyn High), from the Nordland Group in well 2/4-C-11 (Central Graben), from the Utsira Formation in well 25/10-2 (Viking Graben), from the lower part of the Molo Formation in well 6407/9-5 (Trøndelag Platform) and from the middle part of the Kai Formation in well 6508/5-1 (Helgeland Basin; Figs. 8 & 14).

Planktonic foraminifera of Late Miocene age (Spiegler & Jansen, 1989; Figs. 4–7), as sinistral and dextral coiled *N. atlantica*, *Globigerina bulloides* and *Globorotalia puncticulata*, occur in the upper part of the Utsira Formation in the wells we have investigated in the Viking Graben and in the Nordland Group in the Central Graben (Eidvin et al., 2013).

All these observations clearly show that planktonic deep-sea forms, which have their origin in the North Atlantic and the Norwegian Sea, have been brought by ocean currents through an open strait into the northern and central North Sea during the entire Serravallian, Tortonian, Messinian and Zanclean time interval (approximately 14.5–3.5 Ma).

Deposited in a shelf setting, the sandy Utsira Formation (about 12.5–3.5 Ma; Eidvin et al., 2013) overlies Middle Miocene shales (about 15–12.5 Ma; Eidvin et al., 2013) in a large area in the Norwegian sector of the North Sea. The Utsira Formation thins and appears to be condensed towards the west, shaling out towards the south, east and north. It appears to consist of a lower unit (approximately 12.5–6 Ma), which is mainly restricted to the depo-centres and being commonly strongly affected by soft-sediment deformation, and an upper unit (approximately 5–3.5 Ma) which is less deformed and has a wider distribution (Riis & Eidvin, 2015, 2016). In the northernmost part of the Norwegian North Sea (Tampen area) there is a 10–50 m-thick sheet of glauconite sand (approximately 5.7–4.2 Ma; Fig. 15; Eidvin & Rundberg, 2001; Eidvin, 2009; Eidvin & Øverland, 2009; Eidvin et al., 2013). The glauconite sand overlies an erosional unconformity. Løseth & Henriksen (2005) suggested that the erosion was related to Middle Miocene uplift and they correlated it to the uplift of southern Scandinavia. Our alternative interpretation is that there was Early–Middle Miocene uplift along the margin of the Møre Basin which created a submarine

CORRELATION OF BOLBOFORMA ASSEMBLAGES

Figure 14. Correlation of Middle and Upper Miocene Bolboforma assemblages from the wells in Figures 4–7 and from other selected wells and boreholes to the Bolboforma zonation of the ODP Sites 642 and 643 on the Vøring Plateau (Müller & Spiegler, 1993). The IRD curve is after Jansen & Sjøholm (1991) and Frøndal & Jansen (1996).

Figure 15. (A) Log correlation diagram of wells from the Visund area (block 34/8), wells from the Snorre area (blocks 34/4 and 34/7) and well 34/2-4 on the northern Tampen Spur (northernmost North Sea; modified after Eidvin & Rundberg, 2001). (B) Distribution of Utsira Formation sands in the Snorre and Visund Field areas at Tampen. Light and dark yellow areas show the outlines of the main Utsira quartzose sands. Hatched area (with green stars) shows the assumed outline of the thin glauconitic member extending beyond the main Utsira sand. Red lines indicate top Oligocene truncation, whereas red arrows show sediment transport directions (note also well 34/7-2 in the Tordis Field area; modified after Eidvin & Rundberg, 2001; Rundberg & Eidvin, 2005). (C) Global sea-level curves of Hardenbol et al. (1998; light-grey shading) and Miller et al. (2005; black line), as well as the 4th-order eustatic cycles of Esteban et al. (1996; dark-grey shading; modified after Pérez-Asensio, 2013). Please note that the glauconitic Utsira Formation sand was deposited coevally with the period of transgression after the Messinian lowstand.

topographic high where probably only small amounts of Miocene sediments accumulated. The erosion that gave rise to the unconformity could have been mainly related to a sea-level drop in the Late Miocene, concurrent with the Messinian salinity crises (Fig. 15). This interpretation is consistent with our view that there was an open seaway in the North Sea throughout the Middle Miocene. It is noted that the unconformity itself is affected by soft-sediment deformation. The pre-deformational tectonic structure is not easy to reconstruct in the seismic data.

Based on the marine palynomorphs in two ditch-cutting samples at 1190 and 1180 m in well 34/4-6 in the glauconitic Utsira Formation, De Schepper & Mangerud (2017) assigned a maximum age of 3.0 Ma for the upper part of this formation and a minimum age of 4.6 Ma for the lowermost part. However, as the sediments represent ditch-cutting samples and it was difficult to differentiate between reworked, in situ and caved specimens, they considered this age to be uncertain.

Strontium-isotope ages based on tests of foraminifera which have their last occurrence in the Late Miocene to Early Pliocene in the North Sea (King, 1989), picked from ditch-cutting samples and a sidewall core in wells from the Snorre and Visund fields, gave ages of 5.7–5.2 Ma. Records from a sidewall core from the Tordis Field gave ages of 4.7 and 4.2 Ma (Fig. 15). These ages are substantiated by the fact that glauconite was precipitated, most commonly, during periods with transgression on outer shelves at 200–300 metres water depths (Odin & Matter, 1981 and Van Houten & Purucker, 1984). According to Hardenbol et al. (1998) a global transgression started in the middle of the Messinian and a regression in the middle Zanclean.

According to Løseth & Henriksen (2005) and Løseth et al. (2016a, 2017), the Molo Formation postdates the Kai Formation. The occurrences of the *Bolboforma metzmacheri* assemblage in the lower part of the Molo Formation in well 6407/9-5, in the middle part of the

Kai Formation in well 6508/5-1 (Fig. 14), in the lower middle part of the Kai Formation in well 6607/5-1 and in the middle to upper part of the Kai Formation in well 6609/5-1 (Eidvin et al., 2013 and unpublished data) suggest that the Molo Formation, in its southern distribution area, correlates with the middle/upper part of the Kai Formation.

Conclusions

Strontium-isotope data ($^{87}\text{Sr}/^{86}\text{Sr}$ ratios) from the Upper Oligocene–Lower Miocene succession in Jylland, Denmark (94 samples from 18 localities; Eidvin et al., 2014a), were utilised for correlation with Norwegian wells and boreholes (Eidvin, 2016 and Eidvin et al., 2013, 2014b) together with foraminiferal and pyritised diatom data. Dinocyst correlation is also used in some areas. For the Middle–Upper Miocene parts of the succession the correlations are based mainly on *Bolboforma* data from a stratigraphic borehole at Rødding in southern Jylland.

The Sr isotope investigations of samples from the Danish, Brejning, Vejle Fjord, Klintinghoved, Arnum and Odderup formations gave ages between 25.7 and 15.5 Ma. These sediments can be correlated with deposits from a number of sedimentological units in the Norwegian North Sea, Norwegian Sea shelf and one well on the East Shetland Platform in UK waters. These include clay-rich deposits of the Hordaland Group (central, southeastern and northern North Sea), Hutton sand (informal; East Shetland Platform), the sandy Skade Formation (northern North Sea) and the Brygge Formation (Norwegian Sea shelf). A *Bolboforma* assemblage in the Hodde Formation in the Rødding borehole was correlated with sandy and fine-grained deposits in the lower part of the Nordland Group, situated between the Skade and Utsira formations, in the Viking Graben and the upper part of the Hutton sand (informal) on the East Shetland Platform. *Bolboforma* assemblages in the Ørnhøj and Gram formations in the Rødding borehole were correlated with the lower part of the sandy Utsira Formation (northern North Sea), the lower part of the Molo Formation (in its southern distribution area), middle/upper part of the Kai Formation (Norwegian Sea shelf) and with the ODP boreholes on the Vøring Plateau (Norwegian Sea; Figs. 2, 4–7, 10, 11 & 14). This demonstrates that there must have existed a seaway between the North Sea and the Norwegian Sea during the Middle, Late Miocene and Early Pliocene.

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