Palaeogeography, Palaeoclimatology, Palaeoecology 411 (2014) 267–280

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Discrepancy between Sr isotope and biostratigraphic datings of the upper middle and upper Miocene successions (Eastern North Sea Basin, Denmark)

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ARTICLE INFO

Article history:
Received 6 February 2014
Received in revised form 19 June 2014
Accepted 6 July 2014
Available online 18 July 2014

Keywords:
Strontium isotope stratigraphy
Danish Upper Oligocene–Miocene succession

ABSTRACT

One hundred and fifty-six $^{87}Sr/^{86}Sr$ analyses have been performed on 129 samples from 18 outcrops and boreholes in Oligocene–Miocene deposits from Jylland, Denmark. These analyses were mainly conducted on mollusc shells but foraminiferal tests, *Bolboforma* and one shark tooth were also analysed.

The main purpose of the study is to compare the ages of the Danish succession suggested by the biostratigraphic zonation on dinoflagellate cysts (Dybkjær and Piasecki, 2010) with the ages based on analyses of the $^{87}Sr/^{86}Sr$ composition of marine calcareous fossils in the same succession.

Analyses of samples from the Danish Brejning, Vejle Fjord, Klintinghoved, Arnum, Odderup, Hodde, Ørnhøj and Gram formations gave ages between 25.7 My (late Oligocene) and 10.3 My (late Miocene). The Sr isotope ages from the lower part of the succession, i.e. Brejning to Odderup formations, agree with the age estimates based on biostratigraphy. However, the $^{87}Sr/^{86}Sr$ ratios of fossil carbonates from the middle–upper Miocene, Hodde to Gram succession consistently indicate ages older than those recorded by biostratigraphy. Post-depositional processes as an explanation for this offset are inconsistent with good preservation of shell material and little reworking. A palaeoenvironmental cause for the observed mismatch is therefore indicated.

Search for geological events that could explain the older ages obtained by Sr isotope compositions have not led to any conclusions and we had recognised the same problem in earlier reports and communications. We conclude that this is a general and possibly global, middle–late Miocene problem that has to be reconsidered and explained geologically.

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1. Introduction

In Jylland (Denmark), uppermost Paleogene and Neogene sediments occur below the glacial deposits over large areas (Fig. 1). Outcrops representing uppermost Oligocene and Miocene occur along the east coast of Jylland, in the Limfjorden area and in clay-, coal- and sandpits in the southern and middle part of Jylland. In 1999, a Danish national programme was initiated, aiming to map all major subsurface reservoirs for drinking water (aquifers). The most important aquifers in this part of Jylland are sand layers deposited in the early to middle Miocene (Dybkjær and Piasecki, 2010; Rasmussen et al., 2010) when global climatic variations and major sea-level changes (Zachos et al., 2001; Miller et al., 2005), combined with uplift of the southern part of the Fennoscandian Shield, led to increased sediment transport from the north (present-day Finland, Sweden and particularly Norway). This resulted in deposition of extensive, fluvio-deltaic sand systems intercalated with marine clay in the eastern North Sea Basin including the present day Jylland (Rasmussen, 2004; Rasmussen et al., 2010). A new drilling programme was initiated by the county authorities and the geology was re-interpreted by the Geological Survey of Denmark and Greenland (GEUS; e.g. Rasmussen et al., 2004; Rasmussen et al., 2010). It includes detailed sedimentological and log-interpretations of new stratigraphic boreholes and interpretation of high-resolution seismic data. More than 50 boreholes (including some offshore boreholes) and about twenty-five outcrops have been studied palynologically (Fig. 1). Fossil dinoflagellate cysts (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 and Piasecki, 2010).

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http://dx.doi.org/10.1016/j.palaeo.2014.07.005
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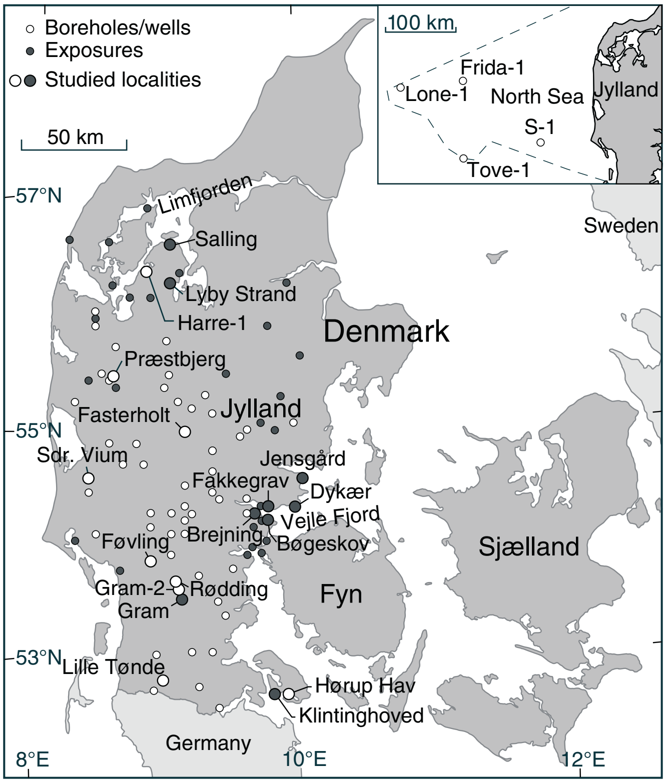

Fig. 1. Map of onshore and offshore Denmark showing wells, boreholes and outcrops analysed for dinoflagellate cysts (Dybkjær and Piasecki, 2010), *Bolboforma* and foraminifera (Eidvin et al., 2013d) and showing the sites where shell material has been Sr dated. Small circles: outcrops and boreholes which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

The succession is well dated by dinocyst biostratigraphy. Stratigraphic events in the Danish succession are correlated with corresponding events e.g. in DSDP/ODP/IODP cores from the North Atlantic region and integrated with biostratigraphy, palaeomagnetic stratigraphy, radiometric dating and Sr isotope stratigraphy. However, long distance correlation from the North Sea region to events in the North Atlantic region may introduce uncertainties in the precision. With the purpose of elucidating this uncertainty, Sr isotope dating on selected shell material from the Danish Miocene succession has been performed on the same well and outcrop samples as the dinocyst investigations. The results of these analyses form the basis of this contribution.

Strontium isotope stratigraphy (SIS) is a very useful tool for chronostratigraphic control. The $^{87}Sr/^{86}Sr$ ratio of seawater is very uniform on a global scale, which is a reflection of the long oceanic residence time of strontium (2–4 My), combined with a relatively short ($\leq$2000 years) oceanic mixing rate. The tool is particularly useful for the dating of Oligocene and Miocene sections. The resolution is best in sediments older than 15 Ma. The reason for this is that the Sr isotopic composition of seawater changed rapidly with time during this period (e.g. Koepnick et al., 1985).

The Norwegian Petroleum Directorate (NPD) has executed strontium isotope analyses on tests of calcareous foraminifera, *Bolboforma* and mollusc shells from a large number of wells and boreholes on the Norwegian continental shelf through the post-Eocene succession (see Eidvin et al., 1998a,b, 1999, 2007, 2010, 2013a,b,c,d; Eidvin and Rundberg, 2001, 2007; Eidvin and Riis, 2013). Unfortunately, thin-walled calcareous microfossils such as foraminifera and *Bolboforma* are generally absent in most areas with Danish onshore Neogene succession, either dissolved by humic acid in the pore water or not deposited in marginal marine environments. However, from the southern Jylland we were able to retrieve foraminifera, *Bolboforma* and mollusc shells from most parts of the sections of the stratigraphic borehole Rødding-1 (Fig. 1). From the North German Basin (also southern Jylland), Laursen and Kristoffersen (1999) have established a detailed foraminiferal biostratigraphy of the Miocene Ribe and Måde groups based on examination of the foraminiferal and *Bolboforma* contents in marine clay from 18 onshore boreholes.

2. Material and methods

2.1. Material

$^{87}Sr/^{86}Sr$ ratios of 143 samples from 18 localities were obtained (Fig. 1; Table 1); 54 of these samples were from the Rødding well, DGUnr. 141.1141. The analyses were carried out mainly on fragments of mollusc shells, tests of foraminifera and one sample was a shark tooth (Table 1). *Bolboforma* are a group of calcareous microscopic fossils of uncertain affinity, probably algae. They have stratigraphic value in the Eocene to Pliocene, but especially in the middle and upper Miocene. The recently 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, 1968).

2.2. Methods

The analytical work was executed by the Mass Spectrometry Laboratory at the University of Bergen, Norway. All Sr isotope ratios were normalised to $^{86}Sr/^{88}Sr = 0.1194$ and to the National Institute for Standard and Technology (NIST) SRM 987 = 0.710248 (McArthur et al., 2001). Reproducibility of the methodology is estimated to be 0.000023 (2 sd, n = 239) by multiple measurements of NIST SRM 987 between 2008 and 2012. Sr isotope values were converted to age estimates using the Strontium isotope stratigraphy Look-Up Table Version 4: 08/04 (Howarth and McArthur, 2004). See also Eidvin and Rundberg (2001, 2007) and Eidvin et al. (2013d) for more details about the method.

The correlative dinoflagellate stratigraphy in this study is based on the 2004 time-scale (Gradstein et al., 2004) and consequently the ages from Sr isotope values have been correlated with the Look-Up Table Version 4: 08/04.

3. Geological setting

The Norwegian–Danish Basin is confined by the Fennoscandian Shield in the north and the Fennoscandian Border Zone also known as the Sorgenfrei–Tornquist Zone in the northeast. In the south, the Ringkøbing-Fyn High separates the Norwegian–Danish Basin from the North German Basin. The deepest part of the basin is located in the west, bordering the Central Graben (Ziegler, 1990; Rasmussen et al., 2005). The basin was formed during a period of Permian rift tectonism (Ziegler, 1982, 1990; Berthelsen, 1992). Thick, coarse-grained, delta fan deposits were laid down during the rift event. Reactivation of different structural elements commenced in the Triassic to Early Cretaceous (Vejbæk and Andersen, 1987; Berthelsen, 1992; Thybo, 2001). The depositional environment was characterised by progradation and retrogradation of a coastal plain, resulting in alternating, sand-rich, shoreface deposits and mud-dominated marine sediments (Nielsen, 2003). The basin was inverted during the Late Cretaceous (Liboriussen et al., 1987; Mogensen and Korstgård, 1993) and again in the early Miocene (Rasmussen, 2009). Furthermore, fission track analysis and reactivation of salt structures indicate an Eocene–Oligocene tectonic phase. The Late Cretaceous–Paleogene period was dominated by a deep marine depositional environment characterised by pelagic and hemipelagic deposits (Heilmann-Clausen et al., 1985; Surlyk and Lykke-Andersen, 2007). The tectonic phase at the transition between the Eocene and Oligocene was accompanied by progradation of lower–upper Oligocene deltas off southern Norway (Schiøler et al., 2007). Coincident with early Miocene inversion tectonics, widespread delta progradation commenced in the eastern North Sea Basin. These deltas were sourced from central Sweden and southern Norway and major parts of the Norwegian–Danish

Table 1
Strontium isotope analyses (all samples were analysed at the University in Bergen, if not stated otherwise). All Sr ratios were corrected to NIST 987 = 0.710248. Numerical ages were derived from the SIS Look-up Table Version 4:08/04 of Howarth and McArthur (2004). NIST = National Institute for Standard and Technology. DC = ditch cuttings.

Localities	Lithostratigraphy/sample level	$^{87}Sr/^{86}Sr$	2 err	Sr age (Ma)	Comments	Analysed fossils	Dinocyst zone	Dinocyst zone age range (Ma)	
Brejning (outcrop)	Brejning Fm	0.708202	0.000009	23.99		One mollusc fragment	*D. phosphoritica*	24.40	23.03
Brejning (outcrop)	Brejning Fm	0.708193	0.000008	24.16	Same sample as above	One mollusc fragment	*D. phosphoritica*	24.40	23.03
Dykær (outcrop)	Brejning Fm	0.708272	0.000008	22.68		Two mollusc fragmentss	*D. phosphoritica*	24.40	23.03
Dykær (outcrop)	Brejning Fm	0.708273	0.000008	22.67	Same sample as above	Two mollusc fragmentss	*D. phosphoritica*	24.40	23.03
Fakkegrav (outcrop)	Brejning Fm	0.708163	0.000009	24.78		One mollusc fragment	*D. phosphoritica*	24.40	23.03
Fakkegrav (outcrop)	Brejning Fm	0.708161	0.000008	24.83	Same sample as above	One mollusc fragment	*D. phosphoritica*	24.40	23.03
Bøgeskov (outcrop)	Brejning Fm	0.708287	0.000008	22.43		One mollusc fragment	*D. phosphoritica*	24.40	23.03
Bøgeskov (outcrop)	Brejning Fm	0.708275	0.000008	22.63	Same sample as above	One mollusc fragment	*D. phosphoritica*	24.40	23.03
Jensgård (outcrop)	Brejning Fm	0.708164	0.000008	24.76		One mollusc fragment	*D. phosphoritica*	24.40	23.03
Jensgård (outcrop)	Brejning Fm	0.708155	0.000008	24.99	Same sample as above	One mollusc fragment	*D. phosphoritica*	24.40	23.03
Lyby Strand (outcrop)	Brejning Fm	0.708202	0.000008	23.99		One mollusc fragment	*D. phosphoritica*	24.40	23.03
Lyby Strand (outcrop)	Brejning Fm	0.708231	0.000008	23.93	Same sample as above	One mollusc fragment	*D. phosphoritica*	24.40	23.03
Hørup Hav (borehole)	Brejning Fm? 76.8–76.4 m (bucket)	0.708243	0.000009	23.2		One mollusc fragment	*C. galea*	23.03	22.36
Harre (borehole)	Brejning Fm, 44.25 m (core)	0.708174	0.000008	24.53		Two mollusc fragments	*D. phosphoritica*	24.40	23.03
Harre (borehole)	Brejning Fm, 44.25 m (core)	0.708212	0.000008	23.81		Three mollusc fragments	*D. phosphoritica*	24.40	23.03
Harre (borehole)	Brejning Fm, 37.25 m (core)	0.708202	0.000008	23.99		One mollusc fragment	*D. phosphoritica*	24.40	23.03
Harre (borehole)	Brejning Fm, 31.25 m (core)	0.70819	0.000009	24.22		One mollusc fragment	*D. phosphoritica*	24.40	23.03
Rødding (borehole)	Vejle Fjord Fm, 243 m (DC)	0.708265	0.000009	22.8		One mollusc fragment	*Homotryblium spp.*	22.36	21.60
Rødding (borehole)	Vejle Fjord Fm, 241 m (DC)	0.708199	0.000009	24.05		One mollusc fragment	*Homotryblium* spp.	22.36	21.60
Salling 1 (outcrop)	Vejle Fjord Fm	0.708313	0.000009	22.06		Three mollusc fragments	*C. galea*	23.03	22.36
Salling 1 (outcrop)	Vejle Fjord Fm	0.708297	0.000008	22.28		Six mollusc fragments	*C. galea*	23.03	22.36
Salling 1 (outcrop)	Vejle Fjord Fm	0.708318	0.000008	21.99	Same sample as the two above	One mollusc fragment	*C. galea*	23.03	22.36
Fasterholt (boreh.)	Vejle Fjord Fm, 170 m (core)	0.708259	0.000009	22.91		One mollusc fragment	*Homotryblium* spp.	22.36	21.60?
Fasterholt (boreh.)	Vejle Fjord Fm, 170 m (core)	0.708266	0.000008	22.79		One mollusc fragment	*Homotryblium* spp.	22.36	21.60?
Fasterholt (boreh.)	Vejle Fjord Fm, 170 m (core)	0.708284	0.000008	22.48		One mollusc fragment	*Homotryblium* spp.	22.36	21.60?
Hørup Hav (boreh.)	Vejle Fjord Fm, 68.8–68.4 m (bucket)	0.708302	0.000009	22.22		One mollusc fragment	*Homotryblium* spp.	22.36	21.60
Harre (borehole)	Vejle Fjord Fm, 19.75 m (core)	0.708252	0.000009	23.03		One mollusc fragment	*C. galea*	23.03	22.36
Rødding (borehole)	Vejle Fjord Fm, 238 m (DC)	0.708233	0.000008	23.39		One mollusc fragment	*Homotryblium* spp.	22.36	21.60
Rødding (borehole)	Vejle Fjord Fm, 236 m (DC)	0.708258	0.000008	22.93		Three mollusc fragments	*Homotryblium* spp.	22.36	21.60
Rødding (borehole)	Vejle Fjord Fm, 230 m (DC)	0.708232	0.000009	23.41		One mollusc fragment	*Homotryblium* spp.	22.36	21.60
Rødding (borehole)	Vejle Fjord Fm, 228 m (DC)	0.708262	0.000009	22.86		One mollusc fragment	*Homotryblium* spp.	22.36	21.60
Rødding (borehole)	Vejle Fjord Fm, 225 m (DC)	0.70823	0.000009	23.45		One mollusc fragment	*Homotryblium* spp.	22.36	21.60
Rødding (borehole)	Vejle Fjord Fm, 222 m (DC)	0.708276	0.000008	22.62		One mollusc fragment	*Homotryblium* spp.	22.36	21.60
Rødding (borehole)	Vejle Fjord Fm, 220 m (DC)	0.708263	0.000009	22.84		One mollusc fragment	*Homotryblium* spp.	22.36	21.60
Rødding (borehole)	Vejle Fjord Fm, 218 m (DC)	0.70838	0.000009	21.09		One mollusc fragment	*Homotryblium* spp.	22.36	21.60
Rødding (borehole)	Vejle Fjord Fm, 216 m (DC)	0.708387	0.000009	20.97		One mollusc fragment	*T. pelagica*	21.10	20.00
Salling 2 (outcrop)	Klintinghoved Fm	0.708462	0.000009	19.66		One mollusc fragment	*S. hamulatum*	20.00	19.00
Salling 2 (outcrop)	Klintinghoved Fm	0.708447	0.000007	19.87		One mollusc fragment	*S. hamulatum*	20.00	19.00
Salling 2 (outcrop)	Klintinghoved Fm	0.708439	0.000008	19.98	Same sample as the two above	Two mollusc fragments	*S. hamulatum*	20.00	19.00
Klintinghoved (outcrop)	Klintinghoved Fm	0.708389	0.000008	20.93		One mollusc fragment	*T. pelagica*	21.10	20.00
Klintinghoved (outcrop)	Klintinghoved Fm	0.708371	0.000008	21.24		One mollusc fragment	*T. pelagica*	21.10	20.00

(continued on next page)

Table 1 *(continued)*

Localities	Lithostratigraphy/sample level	$^{87}Sr/^{86}Sr$	2 err	Sr age (Ma)	Comments	Analysed fossils	Dinocyst zone	Dinocyst zone age range (Ma)	
					Same sample as above				
Klintinghoved (outcrop)	Klintinghoved Fm	0.70837	0.000009	21.25		One mollusc fragment	*T. pelagica*	21.10	20.00
Klintinghoved (outcrop)	Klintinghoved Fm	0.708398	0.000009	20.75		One mollusc fragment	*T. pelagica*	21.10	20.00
[a]Sønder Vium (borehole)	Klintinghoved Fm, 283.3 m (core)	0.708395[a]	0.000008	20.81		One mollusc fragment	*T. pelagica*	21.10	20.00
[a]Sønder Vium (borehole)	Klintinghoved Fm, 268.5 m (core)	0.708459[a]	0.000008	19.7		One mollusc fragment	*T. pelagica*	21.10	20.00
Præstbjerg (borehole)	Klintinghoved Fm, 155–154 m (core)	0.708351	0.000008	21.52		One fragment of a shark tooth	*S. hamulatum*	20.00	19.00
Præstbjerg (borehole)	Klintinghoved Fm, 155–154 m (core)	0.708349	0.000009	21.55		One fragment of a shark tooth	*S. hamulatum*	20.00	19.00
Præstbjerg (borehole)	Klintinghoved Fm, 155–154 m (core)	0.708374	0.000009	21.19		One fragment of a shark tooth	*S. hamulatum*	20.00	19.00
Hørup Hav (borehole)	Klintinghoved Fm, 62.75–62.3 m (bucket)	0.708331	0.000009	21.8		One mollusc fragment	*T. pelagica*	21.10	20.00
Hørup Hav (borehole)	Klintinghoved Fm, 54.8–54.3 m (bucket)	0.708323	0.000009	21.92		One mollusc fragment	*T. pelagica*	21.10	20.00
Hørup Hav (borehole)	Klintinghoved Fm, 52.0–51.35 m (bucket)	0.708265	0.000008	22.8		One mollusc fragment	*T. pelagica*	21.10	20.00
Hørup Hav (borehole)	Klintinghoved Fm, 50.9–50.45 m (bucket)	0.708365	0.000009	21.32		One mollusc fragment	*T. pelagica*	21.10	20.00
Hørup Hav (borehole)	Klintinghoved Fm, 49.3–49.1 m (bucket)	0.708348	0.000009	21.56		One mollusc fragment	*T. pelagica*	21.10	20.00
Hørup Hav (borehole)	Klintinghoved Fm, 43.0 m (bucket)	0.708438	0.000008	20		One mollusc fragment	*S. hamulatum*	20.00	19.00
Rødding (borehole)	Klintinghoved Fm, 185 m (DC)	0.709012	0.000008	5.67	Probably caved	One mollusc fragment	*T. pelagica*	21.10	20.00
[a]Sønder Vium (borehole)	Arnum Fm, 112 m (core)	0.708555[a]	0.000008	18.44		One mollusc fragment	*C. cantharellus*	19.00	18.40
[a]Sønder Vium (borehole)	Arnum Fm, 112 m (core)	0.70856[a]	0.000008	18.38		One mollusc fragment	*C. cantharellus*	19.00	18.40
[a]Sønder Vium (borehole)	Arnum Fm, 111.15 m (core)	0.70858[a]	0.000008	18.12		One mollusc fragment	*E. insigne*	18.40	17.80
[a]Sønder Vium (borehole)	Arnum Fm, 111.15 m (core)	0.708543[a]	0.000007	18.59		One mollusc fragment	*E. insigne*	18.40	17.80
[a]Sønder Vium (borehole)	Arnum Fm, 111.0–109.5 m (core)	0.708572[a]	0.000008	18.23		One mollusc fragment	*E. insigne*	18.40	17.80
[a]Sønder Vium (borehole)	Arnum Fm, 111.0–109.5 m (core)	0.708611[a]	0.000008	17.74		One mollusc fragment	*E. insigne*	18.40	17.80
[a]Sønder Vium (borehole)	Arnum Fm, 90.0–88.5 m (core)	0.708529[a]	0.000008	18.77		One mollusc fragment	*E. insigne*/ *C. aubryae*	17.80	17.80
[a]Sønder Vium (borehole)	Arnum Fm, 90.0–88.5 m (core)	0.708611[a]	0.000008	17.74		One mollusc fragment	*E. insigne*/ *C. aubryae*	17.80	17.80
[a]Sønder Vium (borehole)	Arnum Fm, 71.15 m (core)	0.708622[a]	0.000009	17.6		One mollusc fragment	*C. aubryae*	17.80	15.97
[a]Sønder Vium (borehole)	Arnum Fm, 71.15 m (core)	0.708545[a]	0.000009	18.56		One mollusc fragment	*C. aubryae*	17.80	15.97
Sønder Vium (borehole)	Arnum Fm, 51.80 m (core)	0.708717	0.000008	16.04		One mollusc fragment	*L. truncatum*	15.97	14.80
Sønder Vium (borehole)	Arnum Fm, 51.80 m (core)	0.708694	0.000007	16.43		Two mollusc fragments	*L. truncatum*	15.97	14.80
Sønder Vium (borehole)	Arnum Fm, 51.80 m (core)	0.708714	0.000009	16.09		Two mollusc fragments	*L. truncatum*	15.97	14.80
Sønder Vium (borehole)	Arnum Fm, 51.50 m (core)	0.708708	0.000008	16.19		One mollusc fragment	*L. truncatum*	15.97	14.80
Lille Tønde (borehole)	Arnum Fm, 87.6 m (DC)	0.708527	0.000009	18.8		One mollusc fragment	*C. aubryae*/ *L. truncatum*	17.80	17.80
Lille Tønde (borehole)	Arnum Fm, 82.85–82.35 m (DC)	0.708614	0.000009	17.7		One mollusc fragment	*L. truncatum*	15.97	14.80
Lille Tønde (borehole)	Arnum Fm, 81.35–80.8 m (DC)	0.708614	0.00001	17.7		One mollusc fragment	*L. truncatum*	15.97	14.80
Lille Tønde (borehole)	Arnum Fm, 67.9–67.45 m (DC)	0.708624	0.000009	17.57		One mollusc fragment	*U. aquaeductum*	14.80	13.20
Rødding (borehole)	Arnum Fm, 135 m (DC)	0.708558	0.000009	18.28		One mollusc fragment	*S. hamulatum*	20.00	19.00
Rødding (borehole)	Arnum Fm, 132 m (DC)	0.708424	0.000008	20.24		One mollusc fragment	*S. hamulatum*	20.00	19.00
Rødding (borehole)	Arnum Fm, 129 m (DC)	0.708527	0.000008	18.8		One mollusc fragment	*C. cantharellus*/ *E. insigne*	19.00	17.80
Rødding (borehole)	Arnum Fm, 127 m (DC)	0.708502	0.000009	19.12		One mollusc fragment	*C. cantharellus*/ *E. insigne*	19.00	17.80
Rødding (borehole)	Arnum Fm, 124 m (DC)	0.70844	0.000009	19.97		One mollusc fragment	*C. aubryae*	17.80	15.97
Rødding (borehole)	Arnum Fm, 120 m (DC)	0.708852	0.000009	11.14	Caved	One mollusc fragment	*C. aubryae*	17.80	15.97
Rødding (borehole)	Arnum Fm, 100 m (DC)	0.708846	0.000011	11.39	Caved	One mollusc fragment	*C. aubryae*	17.80	15.97
Rødding (borehole)	Arnum Fm, 99 m (DC)	0.708734	0.000008	15.78		One mollusc fragment	*L. truncatun*	15.97	14.80
Rødding (borehole)	Arnum Fm, 94 m (DC)	0.708746	0.000008	15.59		One mollusc fragment	*L. truncatun*	15.97	14.80
Rødding (borehole)	Arnum Fm, 92 m (DC)	0.708805	0.000008	13.59	Caved	One mollusc fragment	*L. truncatun*	15.97	14.80

Table 1 *(continued)*

Localities	Lithostratigraphy/sample level	^{87}Sr/^{86}Sr	2 err	Sr age (Ma)	Comments	Analysed fossils	Dinocyst zone	Dinocyst zone age range (Ma)	
Rødding (borehole)	Arnum Fm, 91 m (DC)	0.708718	0.000008	16.02		One mollusc fragment	*L. truncatun*	15.97	14.80
Føvling (borehole)	Odderup Fm, 69 m (core)	0.708688	0.000009	16.53		One mollusc fragment	*C. aubryae*	17.80	15.97
Føvling (borehole)	Odderup Fm, 69 m (core)	0.708696	0.000009	16.39		One mollusc fragment	*C. aubryae*	17.80	15.97
Føvling (borehole)	Odderup Fm, 69 m (core)	0.708655	0.000009	17.11		One mollusc fragment	*C. aubryae*	17.80	15.97
Rødding (borehole)	Odderup Fm, 81 m (DC)	0.707898	0.000009	32.37	Reworked	One bryozoan fragment	*L. truncatum*	15.97	14.80
Rødding (borehole)	Odderup Fm, 78 m (DC)	0.708752	0.000008	15.49		One mollusc fragment	*L. truncatum*	15.97	14.80
Rødding (borehole)	Odderup Fm, 72 m (DC)	0.708708	0.000009	16.19		One small gastropod	*L. truncatum*	15.97	14.80
Rødding (borehole)	Odderup Fm, 69 m (DC)	0.708746	0.000009	15.59		One small gastropod	*L. truncatum*	15.97	14.80
Rødding (borehole)	Odderup Fm, 65 m (DC)	0.70886	0.000009	10.84	Caved	One mollusc fragment	*L. truncatum*	15.97	14.80
Rødding (borehole)	Odderup Fm, 64 m (DC)	0.708764	0.000008	15.32		One mollusc fragment	*L. truncatum*	15.97	14.80
Rødding (borehole)	Odderup Fm, 41 m (DC)	0.708731	0.000008	15.82		One mollusc fragment	*L. truncatum*	15.97	14.80
Lille Tønde (borehole)	Hodde Fm, 67.45–66.9 m (DC)	0.708752	0.000009	15.49		One mollusc fragment	*U. aquaeductum*	14.80	13.20
Lille Tønde (borehole)	Hodde Fm, 64.4–63.6 m (DC)	0.708771	0.000008	15.2		One mollusc fragment	*A. andalousiense*	13.20	12.80
Gram brickwork (Gram II, borehole)	Hodde Fm, 38.5–38.0 (bucket)	0.708681	0.000007	16.66		One mollusc fragment	*L. truncatum*	15.97	14.80
Gram brickwork (Gram II, borehole)	Hodde Fm, 37.0–36.5 (bucket)	0.708714	0.000008	16.09		One mollusc fragment	*L. truncatum*	15.97	14.80
Rødding (borehole)	Hodde Fm, 40 m (DC)	0.7087	0.000008	16.33		One mollusc fragment	*L. truncatum*	15.97	14.80
Rødding (borehole)	Hodde Fm, 40 m (DC)	0.708741	0.000008	15.67		20 tests of *U. semiornata semiornata*	*L. truncatum*	15.97	14.80
Rødding (borehole)	Hodde Fm, 39 m (DC)	0.708754	0.000008	15.46		24 tests of *A. guerichi staeschei*	*U. aquaeductum*	14.80	13.20
Rødding (borehole)	Hodde Fm, 39 m (DC)	0.708747	0.000008	15.57		20 tests of *A. guerichi staeschei*	*U. aquaeductum*	14.80	13.20
Rødding (borehole)	Hodde Fm, 38 m (DC)	0.708715	0.000008	16.07		One mollusc fragment	*U. aquaeductum*	14.80	13.20
Rødding (borehole)	Hodde Fm, 38 m (DC)	0.708589	0.000009	18.01		One mollusc fragment	*U. aquaeductum*	14.80	13.20
Rødding (borehole)	Hodde Fm, 37 m (DC)	0.708715	0.000008	16.07		One mollusc fragment	*U. aquaeductum*	14.80	13.20
Rødding (borehole)	Hodde Fm, 37 m (DC)	0.708704	0.000009	16.26		One mollusc fragment	*U. aquaeductum*	14.80	13.20
Rødding (borehole)	Hodde Fm, 36 m (DC)	0.708672	0.000008	16.82		12 tests of *C. contraria*	*U. aquaeductum*	14.80	13.20
Rødding (borehole)	Hodde Fm, 36 m (DC)	0.708836	0.000009	12.02	Caved	One mollusc fragment	*U. aquaeductum*	14.80	13.20
Rødding (borehole)	Hodde Fm, 35 m (DC)	0.708707	0.000008	16.21		One mollusc fragment	*U. aquaeductum*	14.80	13.20
Rødding (borehole)	Hodde Fm, 35 m (DC)	0.708767	0.000009	15.27		One mollusc fragment	*U. aquaeductum*	14.80	13.20
Rødding (borehole)	Hodde Fm, 34 m (DC)	0.708713	0.000008	16.1		One mollusc fragment	*U. aquaeductum*	14.80	13.20
Rødding (borehole)	Hodde Fm, 34 m (DC)	0.708727	0.000009	15.88		One mollusc fragment	*U. aquaeductum*	14.80	13.20
Rødding (borehole)	Ørnhøj Fm, 33 m (DC)	0.708742	0.000008	15.65		One mollusc fragment	*A. andalousiense*	13.20	12.80
Rødding (borehole)	Ørnhøj Fm, 32 m (DC)	0.708766	0.000008	15.29		One mollusc fragment	*A. andalousiense*	13.20	12.80
Rødding (borehole)	Ørnhøj Fm, 32 m (DC)	0.708633	0.000009	17.45		One mollusc fragment	*A. andalousiense*	13.20	12.80
Rødding (borehole)	Ørnhøj Fm, 30 m (DC)	0.708655	0.000009	17.11		One mollusc fragment	*A. andalousiense*	13.20	12.80
Rødding (borehole)	Ørnhøj Fm, 30 m (DC)	0.708624	0.000008	17.57		One mollusc fragment	*A. andalousiense*	13.20	12.80
Rødding (borehole)	Ørnhøj Fm, 29 m (DC)	0.708706	0.000008	16.22		One mollusc fragment	*A. andalousiense*	13.20	12.80
Gram clay pit (outcrop)	Gram Fm	0.70876	0.000007	15.37		One mollusc fragment	*H. obscura*	8.80	7.60
Gram clay pit (outcrop)	Gram Fm	0.7087777	0.000008	15.08		One mollusc fragment	*H. obscura*	8.80	7.60
Gram clay pit (outcrop)	Gram Fm	0.708856	0.000007	10.98	Same sample as the above	One mollusc fragment	*H. obscura*	8.80	7.60
Gram clay pit (outcrop)	Gram Fm	0.708873	0.000007	10.41		One mollusc fragment	*H. obscura*	8.80	7.60
Gram clay pit (outcrop)	Gram Fm	0.708787	0.000008	14.85	Same sample as the above	One mollusc fragment	*H. obscura*	8.80	7.60
Gram clay pit (outcrop)	Gram Fm	0.708778	0.000009	15.06		One mollusc fragment	*H. obscura*	8.80	7.60
Gram clay pit (outcrop)	Gram Fm	0.708852	0.000008	11.14		One mollusc fragment	*H. obscura*	8.80	7.60
Gram clay pit (outcrop)	Gram Fm	0.708857	0.000008	10.95	Same sample as the above	One mollusc fragment	*H. obscura*	8.80	7.60
Gram clay pit (outcrop)	Gram Fm	0.708875	0.000009	10.34		25 tests of *Hoeglundina elegans*	*H. obscura*	8.80	7.60
Gram clay pit (outcrop)	Gram Fm	0.708859	0.000008	10.87		30 tests of *U. venusta saxonica*	*H. obscura*	8.80	7.60
Gram brickwork (Gram II, borehole)	Gram Fm, 34.5–34.0 m (bucket)	0.708719	0.000009	16.01		One mollusc fragment	*U. aquaeductum*	14.80	13.20
Gram brickwork (Gram II, borehole)	Gram Fm, 32.5–32.0 m (bucket)	0.708688	0.000008	16.53		One mollusc fragment	*G. verricula*	14.80	13.20
Gram brickwork (Gram II, borehole)	Gram Fm, 24.5–24.0 m (bucket)	0.70878	0.000009	15.01		One mollusc fragment	*A. umbracula*	12.80	11.40
Gram brickwork (Gram II, borehole)	Gram Fm, 20.5–20.0 m (bucket)	0.708758	0.000009	15.4		One mollusc fragment	*A. umbracula*	11.40	8.80
Gram brickwork (Gram II, borehole)	Gram Fm, 11.5–14.5 m (bucket)	0.708784	0.000008	14.92		One mollusc fragment	*H. obscura*	8.80	7.60
Gram brickwork (Gram II, borehole)	Gram Fm, 11.5–11.0 m (bucket)	0.708854	0.00001	11.06		One mollusc fragment	*H. obscura*	8.80	7.60
Gram brickwork (Gram II, borehole)	Gram Fm, 9.5–9.0 m (bucket)	0.708816	0.000009	12.93		One mollusc fragment	*H. obscura*	8.80	7.60
Gram brickwork (Gram II, borehole)	Gram Fm, 32.5–32.0 m (bucket)	0.708824	0.000008	12,58		One mollusc fragment	*H. obscura*	8.80	7.60

(continued on next page)

Table 1 *(continued)*

Localities	Lithostratigraphy/sample level	$^{87}Sr/^{86}Sr$	2 err	Sr age (Ma)	Comments	Analysed fossils	Dinocyst zone	Dinocyst zone age range (Ma)	
Lille Tønde (borehole)	Gram Fm, 60.0–59.05 m (DC)	0.708669	0.000009	16.87		One mollusc fragment	*G. verricula*	12.80	11.40
Lille Tønde (borehole)	Gram Fm, 45.7–44.3 m (DC)	0.708814	0.000008	13.02		One mollusc fragment	*H. obscura*	8.80	7.60
Lille Tønde (borehole)	Gram Fm, 17.0–16.55 m (DC)	0.708851	0.000008	11.18		One mollusc fragment	*H. obscura* or younger?	8.80	0
Lille Tønde (borehole)	Gram Fm, 11.2–10.2 m (DC)	0.70888	0.000009	10.18		One mollusc fragment	*H. obscura* or younger?	8.80	0
Rødding (borehole)	Gram Fm, 28 m (DC)	0.708713	0.000009	16.1		One mollusc fragment	*A. andalousiense*	13.20	12.80
Rødding (borehole)	Gram Fm, 28 m (DC)	0.708733	0.000009	15.79		One mollusc fragment	*A. andalousiense*	13.20	12.80
Rødding (borehole)	Gram Fm, 27 m (DC)	0.708805	0.000009	13.59		One mollusc fragment	*G. verricula*/ *H. obscura*	12.80	11.40
Rødding (borehole)	Gram Fm, 26 m (DC)	0.708811	0.000008	13.18		One mollusc fragment	*G. verricula*/ *H. obscura*	12.80	11.40
Rødding (borehole)	Gram Fm, 26 m (DC)	0.708768	0.000009	15.25		One mollusc fragment	*G. verricula*/ *H. obscura*	12.80	11.40
Rødding (borehole)	Gram Fm, 25 m (DC)	0.7088	0.000009	14.33		One mollusc fragment	*G. verricula*/ *H. obscura*	12.80	11.40
Rødding (borehole)	Gram Fm, 25 m (DC)	0.708782	0.00001	14.97		One mollusc fragment	*G. verricula*/ *H. obscura*	12.80	11.40
Rødding (borehole)	Gram Fm, 24 m (DC)	0.708851	0.000008	11.18		One mollusc fragment	*G. verricula*/ *H. obscura*	12.80	11.40
Rødding (borehole)	Gram Fm, 24 m (DC)	0.708798	0.000009	14.44		Two mollusc fragments	*G. verricula*/ *H. obscura*	12.80	11.40
Rødding (borehole)	Gram Fm, 23 m (DC)	0.708749	0.000008	15.54		One mollusc fragment	*G. verricula*/ *H. obscura*	12.80	11.40
Rødding (borehole)	Gram Fm, 23 m (DC)	0.70883	0.000009	12.32		One mollusc fragment	*G. verricula*/ *H. obscura*	12.80	11.40
Rødding (borehole)	Gram Fm, 22 m (DC)	0.708837	0.000009	11.97		One mollusc fragment	*G. verricula*/ *H. obscura*	12.80	11.40
Rødding (borehole)	Gram Fm, 21 m (DC)	0.708792	0.0000008	14.71		One mollusc fragment	*G. verricula*/ *H. obscura*	12.80	11.40
Rødding (borehole)	Gram Fm, 21 m (DC)	0.708817	0.0000008	12.88		One mollusc fragment	*G. verricula*/ *H. obscura*	12.80	11.40

[a] Data from Dybkjær and Piasecki (2010).

Basin became a land area in the early Miocene (Rasmussen, 2004; Rasmussen et al., 2010). During the early and early middle Miocene (about 23–15 Ma) the northwest-southeast trending coastline was situated across the present-day Jylland (Fig. 2B–G). Mainly due to eustatic changes, the position of the coastline changed resulting in three overall periods with delta progradation followed by transgressions (Figs. 2 and 3). The two oldest delta systems, deposited in the early Miocene, were sourced from the north, from the western part of the Fennoscandian Shield, and prograded southwards (Fig. 2C and E), while the source area for the third delta system, deposited in the latest early Miocene to early middle Miocene, seems to have changed to the northeastern and eastern parts of the Fennoscandian Shield (Fig. 2G). Due to accelerated subsidence of the North Sea area in the Langhian and Serravallian (middle Miocene), a distinct overall transgression occurred and marine clay was deposited far towards eastern Denmark and possibly Sweden. In the latest Tortonian (late Miocene), resumed progradation resulted in deposition of deltaic and coastal plain deposits (Fig. 2I). The overall progradation continued until the late Pliocene, when the shoreline prograded as far as the Central Graben (Rasmussen et al., 2010). Distinct tilting of the Norwegian–Danish Basin and uplift of the Scandinavian region commenced in the late Neogene (Jensen and Schmidt, 1992; Japsen, 1993; Japsen et al., 2010). This was succeeded by marked erosion of the marginal areas of the Norwegian–Danish Basin.

4. Lithostratigraphy

The lithostratigraphy of the upper Oligocene and Neogene succession onshore Denmark has recently been revised by Rasmussen et al. (2010) (Fig. 3). The uppermost Oligocene (upper Chattian) to lowermost Miocene (lower Aquitanian) Brejning Formation comprises shallow-marine, glaucony-rich, silty clays and shows a shallowing upwards trend in the upper part.

The sand-rich deltaic deposits above (Fig. 2B,C) are referred to as the Billund Formation, while the clayey deposits are referred to as the Vejle Fjord Formation. Minor hiatuses are indicated in the sandy deposits east of the investigated localities. These deposits were formed in the proximal area of the delta complex during the late Aquitanian and the earliest Burdigalian (Dybkjær and Rasmussen, 2000; Dybkjær and Piasecki, 2010; Rasmussen et al., 2010).

The transgression in the earliest Burdigalian resulted in the regional deposition of marine clay and silt, referred to as the Klintinghoved Formation (Fig. 2D). Time-equivalent sediments deposited within barrier complexes associated with the transgression are referred to as the Kolding Fjord Member. In the early to middle Burdigalian, a sand system of fluvio-deltaic deposits, referred to as the Bastrup Formation, prograded far southwards (Fig. 2E). These deposits are overlain by the middle to upper Burdigalian marine clay, referred to as the Arnum Formation (Fig. 2F). Another prograding system of fluvio-deltaic sand, the Odderup Formation, was deposited in the late Burdigalian to Langhian (Fig. 2G, Rasmussen et al., 2010; Dybkjær and Piasecki, 2010).

The major transgression in the late Langhian–Tortonian (middle to early late Miocene) resulted in deposition of marine clay, referred to as the Hodde, Ørnhøj and Gram formations, throughout the region (Fig. 2H). Reworked glauconite and goethite in the upper part of the Ørnhøj Formation indicated a minor sea-level fall at the Serravallian–Tortonian transition. Sand-rich deposits from a prograding coastline occur in the uppermost Tortonian and are referred to as the Marbæk Formation (Fig. 2I).

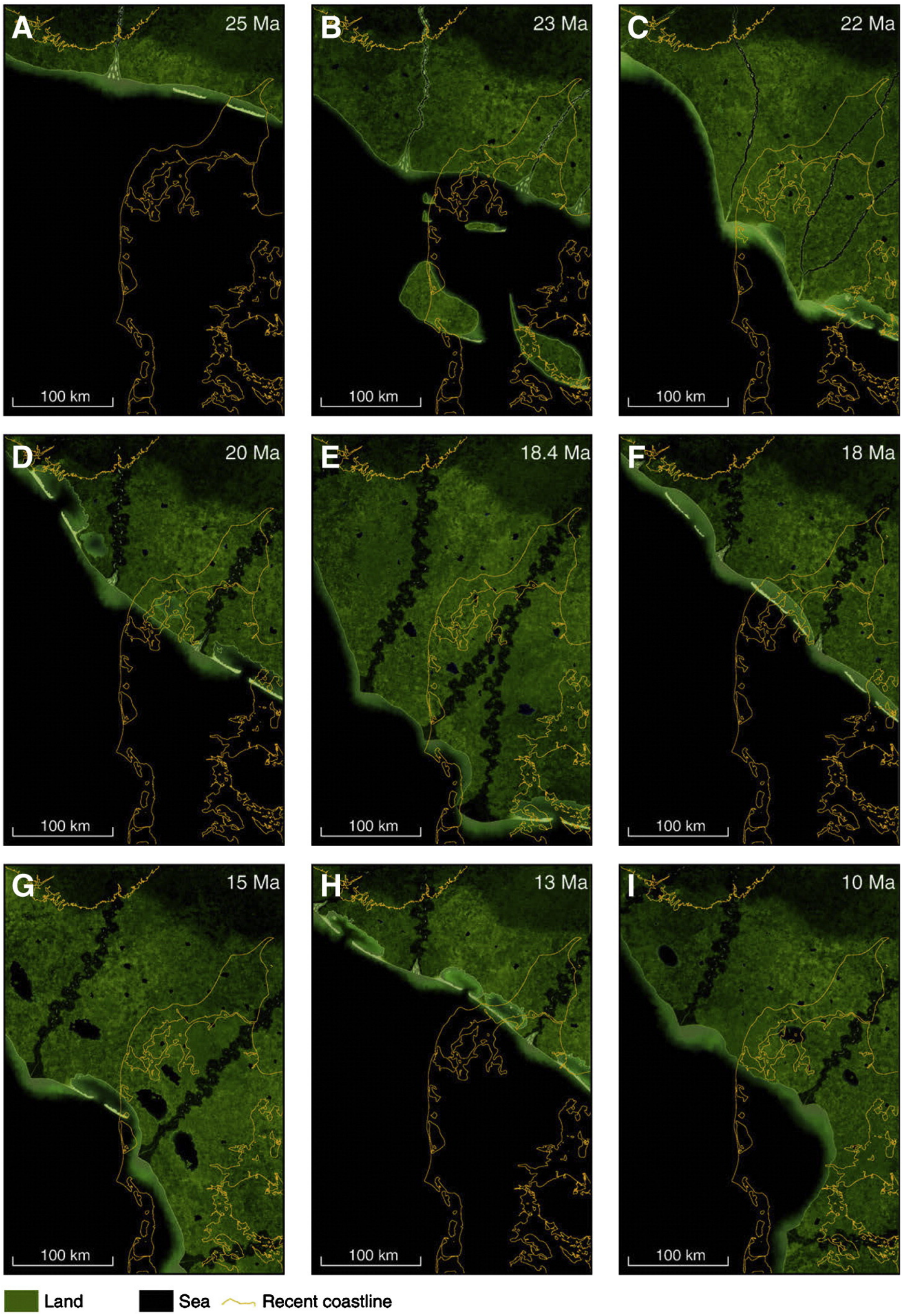

Fig. 2. A to I: Paleogeographic maps showing the changing position of the coastline, resulting from changes in eustatic and large-scale tectonic events (after Rasmussen et al., 2010; Dybkjær and Piasecki, 2010).

5. Strontium isotope stratigraphy, analytical results

5.1. Brejning Formation

The Brejning Formation was sampled from outcrops at Brejning, Dykær, Fakkegrav, Bøgeskov, Jensgård and Lyby Strand and from boreholes at Hørup Hav and Harre (Fig. 1). Two analyses were carried out on different material from each of the sampled outcrops. The analyses of each outcrop sample show similar results. The analyses from Brejning gave 24.0 and 24.2 Ma (Table 1), the two analyses of the Dykær sample both gave 22.7 Ma, the analyses of the Fakkegrav sample both gave 24.8 Ma, the Bøgeskov sample gave 22.6 and 22.4 Ma, the Jensgård sample gave 25.0 and 24.8 Ma and the Lyby Strand sample gave 24.0 and 23.9 Ma. One analysis was carried out on a sample from 76.8–76.4 m in the Hørup Hav borehole suggesting an age of 23.2 Ma. Four analyses on samples from the section 44.25–31.25 m in the Harre borehole gave ages from 24.5 to 23.8 Ma. The inferred age range of the Brejning Formation is then 25.0 to 22.4 Ma.

5.2. Vejle Fjord Formation

This formation was analysed from an outcrop at Salling ('Salling 1') and from boreholes at Fasterholt (170 m), Hørup Hav (68.8–68.4 m), Harre (19.75 m) and Rødding (243–216 m) (Fig. 1 and Table 1). Two analyses were carried out on the sample 'Salling 1'. The obtained $^{87}Sr/^{86}Sr$ ratios gave similar ages of 22.3 to 22.0 Ma (Table 1). Three analyses were

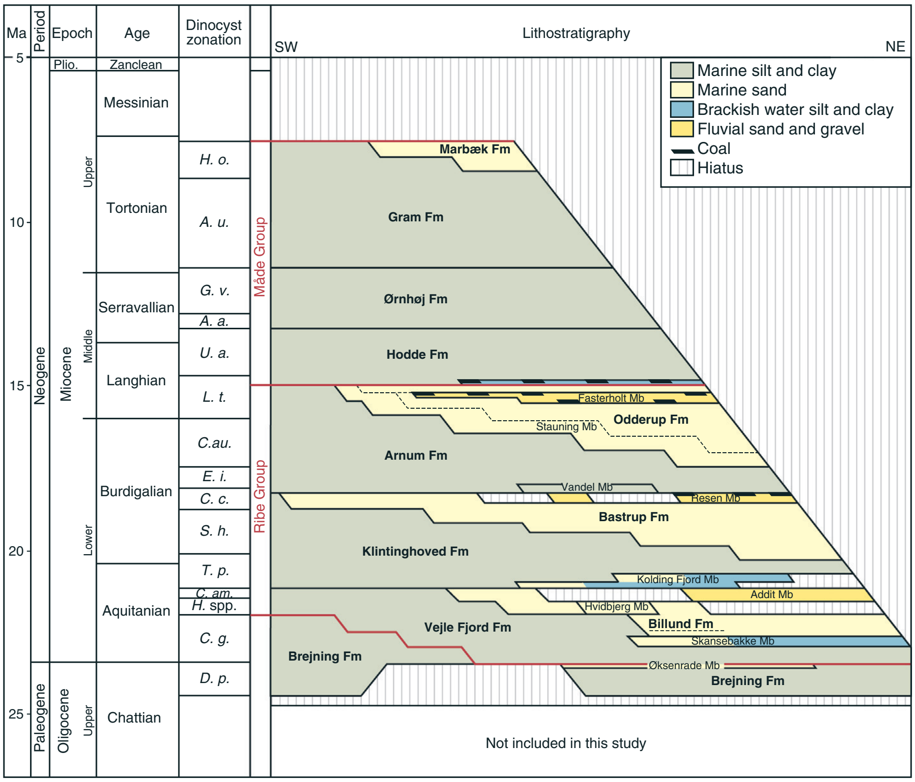

Fig. 3. Lithostratigraphy of the Danish Miocene and latest Oligocene (from Rasmussen et al., 2010). The dinocyst zonation is after Dybkjær and Piasecki (2010).

carried out on the sample taken at 170 m from the Fasterholt borehole, and these gave very similar ages of 22.3 to 22.0 Ma. One analysis was carried on the sample taken at 68.8–68.4 m from the Hørup Hav borehole giving an age of 22.2 Ma, and one analysis was carried out on the sample at 19.75 m from the Harre borehole giving an age of 23.0 Ma. One analysis from each of eight samples from the interval 238–216 m in the Rødding borehole gave ages from 24.1–21.0 Ma. All samples from Vejle Fjord Formation gave ages between 24.1 and 21.0 Ma.

5.3. Klintinghoved Formation

Deposits from the Klintinghoved Formation were sampled from outcrops at Salling ('Salling 2') and Klintinghoved (main profile) and from boreholes at Sønder Vium, Præstbjerg, Hørup Hav and Rødding (Fig. 1). Three analyses were carried out on the sample 'Salling 2' and gave ages of 20.0 to 19.7 Ma (Table 1). Four analyses were carried out on three samples from Klintinghoved, giving ages of 21.3 and 20.9 Ma. Two analyses from the Sønder Vium borehole (283.3 and 268.5 m) gave 20.8 and 19.7 Ma, respectively (Table 1). Three analyses were carried out on a shark tooth taken at 155–154 m from the Præstbjerg borehole, giving very uniform ages of 21.6 to 21.2 Ma. Analyses of six samples from a section at 62.75–43.0 m in the Hørup Hav borehole gave ages ranging from 22.8 to 20.0 Ma (generally increasing downhole, Table 1). One analysis based on a sample taken from 185 m in the Rødding borehole gave an age of 5.7 Ma, indicating that the sample is obviously caved (Table 1). All the analyses of the *in situ* samples from the Klintinghoved Formation gave ages between 22.8 and 19.7 Ma.

5.4. Arnum Formation

The Arnum Formation was sampled from boreholes at Sønder Vium, Lille Tønde and Rødding. Analyses of 14 samples from the section 112–51.5 m in the Sønder Vium borehole gave ages from 18.8 to 16.0 Ma (generally increasing downhole, Table 1). Analyses of four samples from the section 87.6–67.45 m in the Lille Tønde borehole gave ages of 18.8 to 17.6 Ma. In the Rødding borehole, eight samples from the section at 135–91 m gave ages from 20.2 to 15.8 Ma (generally increasing downhole). Three samples contain obvious caved material (120, 100 and 92 m, Table 1). All the samples of *in situ* material from the Arnum Formation gave ages between 20.2 and 15.8 Ma.

5.5. Odderup Formation

The Odderup Formation was sampled from the Rødding borehole and from a borehole at Føvling. In the Rødding borehole, five samples from the section at 78–41 m gave ages from 16.2 to 15.3 Ma. One sample (81 m) contains obvious reworked material and one sample contains obvious caved material (65 m, Table 1). Three analyses were carried out on one sample taken at 69 m in the Føvling borehole giving ages of 17.2 to 16.4 Ma. All the samples of *in situ* material from the Odderup Formation gave ages between 17.4 and 15.3 Ma.

5.6. Hodde Formation

The Hodde Formation was sampled from the boreholes at Rødding, Gram brickworks (Gram II borehole) and Lille Tønde. Thirteen samples from the section at 40–34 m in the Rødding borehole gave ages from 16.8 to 15.3 Ma. One sample (one of two samples from 36 m) contains obvious caved material (Table 1). The analyses from two samples of the Gram II borehole (38.5–38.0 and 37.0–36.5 m) gave 16.7 and 16.1 Ma, respectively (Table 1), and analyses of two samples from Lille Tønde (67.45–66.9 and 64.4–63.6 m) gave 15.5 and 15.2 Ma respectively (Table 1). Except for the obvious caved sample, the analyses of the Hodde Formation gave ages between 18.1 and 15.3 Ma, but there is a discrepancy between some of these ages and the ages obtained by dinoflagellate cyst stratigraphy (see discussion).

5.7. Ørnhøj Formation

Six samples from the Ørnhøj Formation in the Rødding borehole (33–29 m) gave ages of 17.6 to 15.3 Ma. There is a discrepancy between these ages and the ages obtained by dinoflagellate cyst stratigraphy (see discussion).

5.8. Gram Formation

The Gram Formation was sampled from an outcrop at Gram Clay Pit (whale discovery site), the borehole at Gram brickworks (Gram II borehole), the Lille Tønde borehole (near the German border, Fig. 1) and the Rødding borehole. Six samples were taken from the Gram Clay Pit and four of the samples were analysed twice. The analyses gave ages varying between 15.4 and 10.3 Ma (Table 1). Analyses of eight samples from the section 34.5–7.5 m in the Gram II borehole gave ages from 16.5 to 10.9 Ma (generally increasing downhole, Table 1). Analyses of four samples from 60.0 to 10.2 m in the Lille Tønde borehole gave ages from 16.9 to 10.2 Ma (also generally increasing downhole). Fourteen samples from the Gram Formation in the Rødding borehole (28–21 m) gave ages of 16.1 to 11.2 Ma. All the samples of the Gram Formation gave ages between 16.9 and 10.2 Ma, but there is a major discrepancy between most of these ages and ages obtained by dinoflagellate biostratigraphic correlation (see discussion).

6. Discussion

For most of the investigated lithological units there is generally good agreement between the ages derived from the obtained $^{87}Sr/^{86}Sr$ ratios and the ages derived from the dinoflagellate stratigraphy, e.g. in uppermost Oligocene–lower Miocene (Figs. 4 and 5).

All samples have been dated using dinocyst stratigraphy. In some cases the ages of the dinocyst zonal boundaries were refined using Sr analysis, e.g. the top of the *Thalassiphora pelagica*, *Sumatradinum hamulatum* and *Cordosphaeridum cantharellus* zones (Dybkjær and Piasecki, 2010; Fig. 4, Table 1).

In contrast, there is discrepancy between the Sr ages and the ages derived from dinoflagellate stratigraphy for most samples from middle

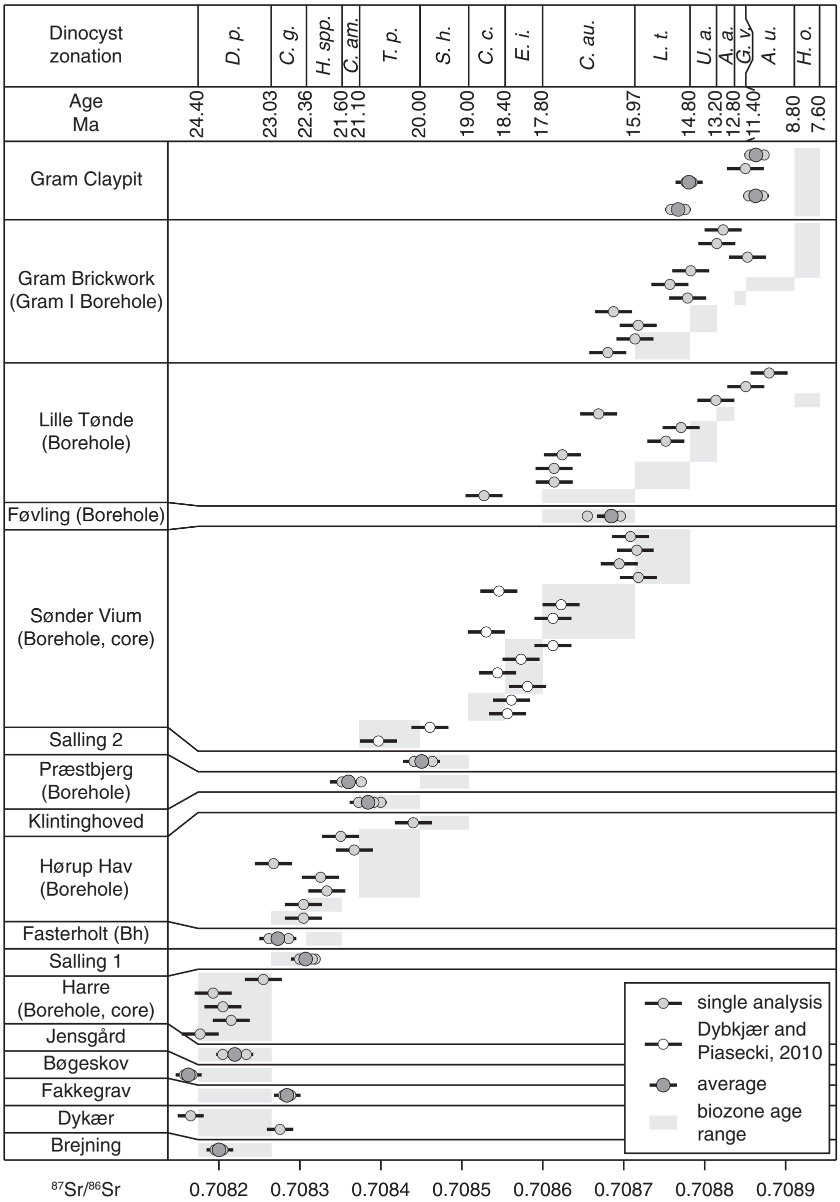

Fig. 4. Plot of strontium isotope ages of samples dated by dinoflagellate stratigraphy in wells and outcrops from Jylland, Denmark. White circles: Data from Dybkjær and Piasecki (2010).

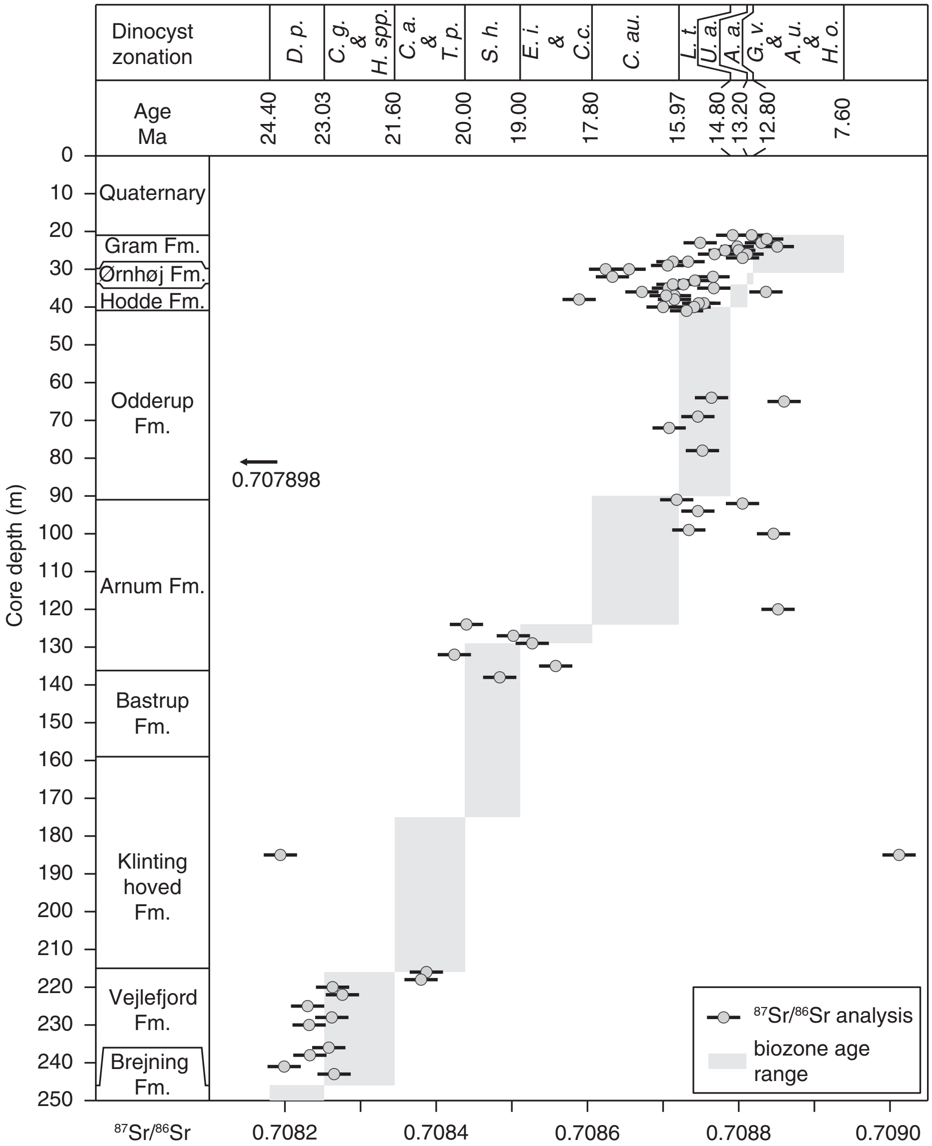

Fig. 5. Plot of strontium isotope ages of samples dated by dinoflagellate and *Bolboforma* stratigraphy in the Rødding borehole (DGUnr 141.1141) in western Jylland, Denmark.

and upper Miocene deposits (Figs. 4 and 5). As an example, the basal part of the Hodde Formation was deposited during a major, regional transgression and rich dinoflagellate assemblages within the marine clay of this formation indicate an age of approximately 15–13.2 Ma, and refers the formation to the upper Langhian to lower Serravallian. The $^{87}Sr/^{86}Sr$ ratio results, on the other hand, indicate ages between 18.1 and 15.3 Ma for the Hodde Formation (Table 1; Figs. 4 and 5). These large age differences are due to increasing deviations from values expected from biostratigraphic age estimates, reaching an average of ~0.00011 in the the *Hystrichosphaeropsis obscura* Zone (8.8–7.6 Ma, Fig. 6). In the Rødding borehole, the trend towards more unradiogenic $^{87}Sr/^{86}Sr$ ratios with time is less systematic (Fig. 7), but also here discrepancies averaging ~0.00008 are observed for the Hodde formation.

The overlying Ørnhøj Formation is approximately 13.2–11.6 Ma old, i.e. of late Serravallian age based on dinoflagellate stratigraphy. The Ørnhøj Formation is rich in glaucony which provided radiometric dating between approximately 13 and 9 Ma (Koch, 1989). The glaucony of the Ørnhøj Formation is not ideal for dating due to poor crystallinity, but the recovered age interval of Serravallian to early Tortonian is well in accord with the dinoflagellate correlations. The $^{87}Sr/^{86}Sr$ ratio results indicate ages between 17.6 and 15.3 Ma for the Ørnhøj Formation in the Rødding borehole (Table 1).

The Gram Formation is Tortonian, 11.6–7.12 Ma, according to the dinoflagellate stratigraphy, whereas the Sr isotope analyses indicate ages between 16.9 and 10.2 Ma (Table 1, Figs. 4 and 5), i.e. more than 2 My too old and with a significant variation of the results.

Below, we discuss possible explanations for the discrepancies concerning the ages of the Hodde, Ørnhøj and Gram formations.

6.1. Ages interpreted on the basis of long-distance, dinoflagellate biostratigraphic correlation could be wrong

The dinoflagellate biostratigraphy is mainly based on correlations within the North Sea Basin, but especially with respect to absolute dating of the bioevents, long-distance correlations with North Atlantic deep sea drillings have been used (Dybkjær and Piasecki, 2010) such that uncertainties and errors could have been introduced due to the distances involved.

Therefore, assemblages of *Bolboforma* have been studied together with the dinoflagellate assemblages from the Hodde, Ørnhøj and Gram formations in the Rødding Borehole in the Ringkøbing-Fyn High

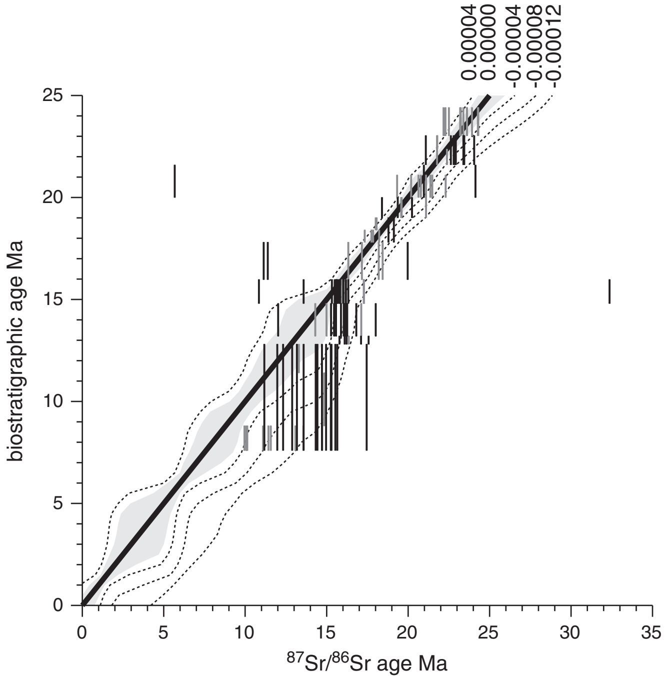

Fig. 6. Measured ^{87}Sr/^{86}Sr ages plotted against biostratigraphic age estimates. Dark grey lines represent materials from the Rødding borehole, medium grey lines represent other core materials and samples from outcrops. The length of the lines is defined by the age range estimated for the associated biozones (Dybkjær and Piasecki, 2010). The line of 1:1 correspondence is shown in black. The grey band illustrates the analytical uncertainties (2 sd reproducibility) and uncertainties in the Sr curve. Sample lines that partly overlap with the grey band are compatible with the Sr curve. Stippled lines are isolines for different offsets of ^{87}Sr/^{86}Sr from the coeval seawater ^{87}Sr/^{86}Sr (McArthur et al., 2001). Most samples showing disagreement with the Sr-curve have biostratigraphic ages < 15 Ma and are too un-radiogenic. Note the decreasing precision of the age estimates at ages younger than 15 Ma, which is indicated by a widening of the uncertainty band and is related to a decreasing gradient of the Sr isotope curve.

area in southern Denmark (Fig. 1). The recorded *Bolboforma* assemblages can be correlated with *Bolboforma* zones described from the DSDP/ODP boreholes from the North Atlantic and the Norwegian Sea (Spiegler and Müller, 1992; Müller and Spiegler, 1993). These zones have very short ranges and are calibrated with nannoplankton and palaeomagnetic stratigraphic data. The *Bolboforma* assemblages indicate an age slightly older than 14–11.7 Ma for most of the Hodde Formation, 10.3–10 Ma for the Ørnhøj Formation and approximately 10.3–8.7 Ma for the Gram Formation (see also Eidvin et al., 2013d). This is in accord with the dating of the Rødding Borehole based on dinocyst zonation (Dybkjær and Piasecki, 2010) and with dating of the regional Hodde and Gram formations based on dinoflagellate cysts (Rasmussen et al., 2010). The ages obtained by the dinoflagellate biostratigraphy are therefore supported by the *Bolboforma* assemblages.

In the Hodde Formation, *Bolboforma* of the *Bolboforma badenensis*–*Bolboforma reticulata* assemblage are recorded. The *B. badenensis* Zone and *B. reticulata* Zone are dated to slightly older than 14 to 11.7 Ma in North Atlantic deposits (Spiegler and Müller, 1992) and therefore confirm the age based on dinoflagellate stratigraphy (Dybkjær and Piasecki, 2010). Thus, both dinoflagellate and *Bolboforma* stratigraphy indicate a common age for the Hodde Formation in contrast to the consistently older age (> 15 Ma) indicated by the Sr isotope analyses. Similarly, in the Rødding well, a precise age from 10.3 to 8.7 Ma (Spiegler and Müller, 1992; Müller and Spiegler, 1993) has been demonstrated for the Gram Formation based on the content of *Bolboforma* (Eidvin et al., 2013d). Also, the mollusc zonation of the Gram Formation (Banke-Rasmussen, 1966; Hinsch, 1990) support the ages indicated by the dinoflagellate stratigraphy (Piasecki, 2005). The biostratigraphy and the derived ages of the sediments are therefore confirmed by three independent fossil groups. The recorded foraminferal species have longer stratigraphical ranges than the *Bolboforma* and dinoflagellate species.

6.2. A low gradient for the middle and upper Miocene part of the global strontium isotope seawater curve after about 15 Ma may give less accurate age calculations

The global strontium seawater curve (Strontium Isotope Stratigraphy Look-up Table Version 4: 08/04 of Howarth and McArthur, 2004) shows a high gradient for the Oligocene and the lower part of the Miocene, i.e. the part older than approximately 15 Ma. For the younger part of the Miocene, the gradient is lower (Howarth and McArthur, 1997, 2004), indicating that the seawater Sr isotopic composition changed more rapidly during the early Miocene before approximately 15 Ma

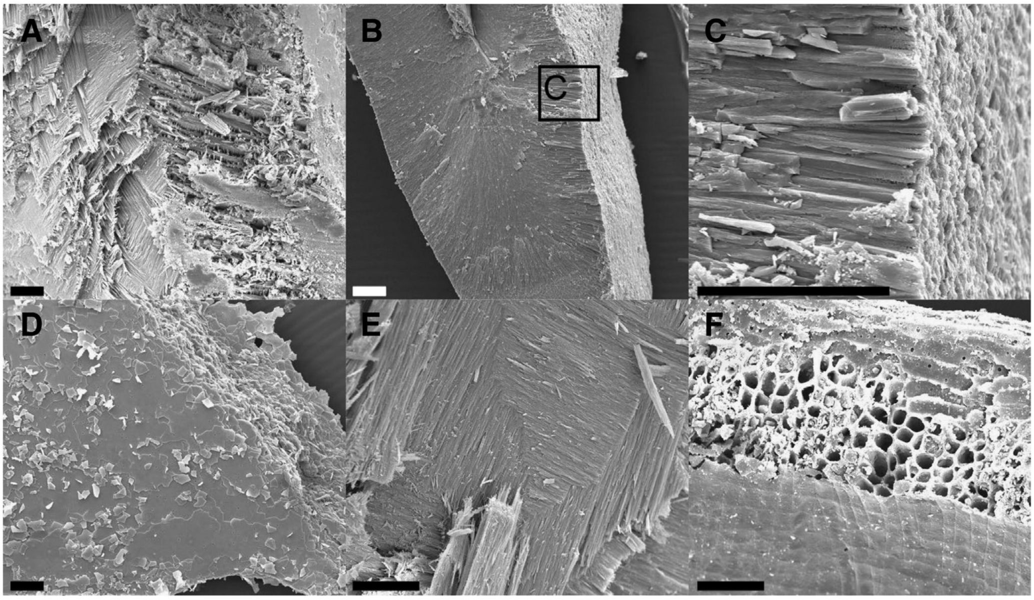

Fig. 7. SEM photos of mollusc shells from the Rødding borehole illustrating good preservation and very limited dissolution of biogenic carbonate. Scale bars are 50 μm. A: mollusc fragment from 21 m depth. B: mollusc fragment from 22 m depth. C: detail from B showing minimal dissolution of the shell in a zone of ~10 μm from the surface. D: mollusc fragment from 29 m depth. E: mollusc fragment from 32 m depth. F: mollusc fragment from 35 m depth.

than after. This change of slope in the Sr isotope curve coincides with our change in precision of the Sr isotope age results (Fig. 6). While our analytical precision for the interval from 25 Ma to 15 Ma equates to a dating precision of ~0.4 Ma, much larger uncertainties of ~0.9 Ma arise in the interval from 15 Ma to 5 Ma, due to the lower gradient in the marine Sr isotope curve. Small errors in the $^{87}Sr/^{86}Sr$ isotopic composition due to minor impurities in the calcareous tests, recrystallisation of the shells, errors introduced during sample preparation and the mass spectroscopy analysis process, etc., have less impact when calculating ages from the high gradient part of the strontium isotope seawater curve than from the low gradient part. $^{87}Sr/^{86}Sr$ ages derived for upper Miocene sections from the Norwegian North Sea and Norwegian Sea and shelf, however, did not show any significant effect of such impurity-related biases. Furthermore, the absolute difference of the measured $^{87}Sr/^{86}Sr$ ratios from the expected ratios increases with decreasing age (Fig. 6), so that a uniform, offset from expected values can confidently be excluded. This implies that the low gradient for the middle and upper Miocene part of the global strontium isotope seawater curve cannot be the reason for the discrepancy between the Sr ages and the ages derived from biostratigraphy on dinoflagellates and *Bolboforma* in the Danish succession.

6.3. Middle to upper Miocene mollusc faunas could be reworked

The middle to upper Miocene in the Rødding borehole with *Bolboforma* and foraminiferal assemblages (See 6.1) is also rich in mollusc shells. A large number of these were analysed for $^{87}Sr/^{86}Sr$ isotope composition. The recovered Sr ages are older than the ages obtained by the *Bolboforma* and dinoflagellate biostratigraphic correlations. In addition, some Sr analyses were made on foraminifera from the same samples and these Sr ages are in accordance with the Sr ages recorded from molluscs and are therefore also too old compared to the *Bolboforma* and dinoflagellate stratigraphy.

The disagreements of Sr isotope and biostratigraphic ages in the Rødding borehole could be due to the presence of reworked material in the mollusc fragments. However, the Sr analyses of foraminifera, which most likely are stratigraphically, *in situ* give the same age offset as the molluscs. Furthermore, the comprehensive mollusc studies of the Hodde and Gram formations (Rasmussen, 1966, 1968) have no records of sub-contemporaneous reworking of Miocene fossils. Hypothetical reworking of faunas reflecting the age offset by the Sr isotope analyses would require erosion of 60–100 m of sediments and should consequently be reflected by the sedimentology of the succession. The depositional environments of the Hodde and Gram formations were dominantly quiescent with the deposition of undisturbed muddy sediments throughout the studied region; the exceptions being the basal Hodde Formation transgressional gravel bed and the prograding shore deposits of uppermost Gram Formation (Rasmussen et al., 2010). In the latter case, frequent storm-derived silt and sand layers were deposited on the sea floor.

The precise biostratigraphic accordance of the *Bolboforma* and dinoflagellate assemblages most definitively rejects reworking of calcareous microfossils as being the cause of the too old Sr isotope ages.

Analysis of caved shell material can generally be discounted because the Sr ages recorded here are, in general, too old rather than too young and offsets from the expected age range are also seen in analyses of outcrop material (e.g., the Gram clay pit).

6.4. Mollusc and foraminifer Sr isotope ages versus biostratigraphy

Biostratigraphy based on three independent fossil groups has been applied to the Rødding borehole and corresponding strata throughout the region and has dated the Hodde and Gram formations precisely. Sr isotope analyses of mollusc shells and foraminifer tests from these formations correspond quite well but generally indicate ages 2 to 5 My older than those recorded by biostratigraphy in the same strata. This significant and consistent deviation of Sr isotope ages in the Hodde and Gram formations, in contrast to all other stratigraphic data, clearly suggests that the Sr isotope compositions recorded in the calcareous fossils are not reliable for age estimates in this region. Apparently, the Sr isotope composition of calcareous fossils in the eastern North Sea area is not following the expected development of the oceanic $^{87}Sr/^{86}Sr$ ratio from approximately 15 Ma and at least to the top of the Tortonian (uppermost Gram Formation). Logically, this implies that the $^{87}Sr/^{86}Sr$ isotope ratio of the seawater of the mollusc habitat (i.e., the inner/eastern part of the North Sea Basin) is off-scale, but it is difficult to point to processes or events that could convincingly explain this change in the Sr isotope composition of seawater in parts of the North Sea Basin in lowermost Langhian, middle Miocene.

6.5. Diagenetic overprint of the $^{87}Sr/^{86}Sr$ ratio

Post-depositional, diagenetic alteration of the $^{87}Sr/^{86}Sr$ ratios of the fossil shell material selected for Sr isotope analysis could affect the analytical results significantly. The ratio can be shifted towards higher or lower values depending on the source of the strontium in the diagenetic fluid (Brand, 1991; McArthur, 1994). Clearly, some of the age misfits are generated by effects other than mass-spectrometric uncertainty because their offset from the general trend is much larger than what could be justified with the given quality control parameters. In the investigated upper Miocene deposits the $^{87}Sr/^{86}Sr$ ratios are on average too low.

The area from where these samples were derived is characterised by relatively high $^{87}Sr/^{86}Sr$ ratios in surface waters (Frei and Frei, 2011) and also the groundwater seems to be comparatively high in $^{87}Sr/^{86}Sr$ (Jørgensen et al., 1999). We suspect that the silicate matter comprising the matrix to the fossils is also more radiogenic than the fossils themselves, because it is the weathering product of basement rocks of the Fennoscandian Shield so that leaching of silicates and recrystallisation of the fossils cannot produce offsets to lower values. The only possible solution would be recrystallisation of the fossil shell material during interaction with fluids that contain strontium derived either from young volcanic material or from older carbonates with low Sr ratios.

Scanning Electronic Microscope (SEM) studies of shell material from the Hodde and Gram formations were performed to determine potential diagenetic alterations as a source of error. The calcareous shells were found to be basically unaffected by diagenesis and except for rare and small superficial traces of dissolution or cracks the shells are very well preserved. Furthermore, it appears unlikely that only molluscs from the Hodde and Gram formations were affected by post-depositional alteration, while the lower Miocene molluscs in similar lithologies were not.

6.6. Limited oceanic exchange with the inner North Sea Basin environment may have affected the Sr isotope ratio in the marine fauna

Major geological events occurred near 15 Ma in the region of the North Sea Basin. The so-called middle Miocene unconformity is due to major flooding far across the basin margins contemporaneous with the middle Miocene thermal maximum (17–15 Ma). Palynologically, this is just preceded by a maximum basin influx of gymnosperm pollen of cool, high-altitude affinity, suggesting that the uplift of Scandinavia had already commenced (pers. comm. E. S. Rasmussen, 2012). The uplift is reflected in a strong sediment influx into the North Sea Basin and explains the progradation of the uppermost Odderup Formation contemporaneous with a relative rise in sea level. These events occurred coevally with the apparent shift to low Sr isotope ratios in the middle and upper Miocene. However, the depositional system is very similar to the setting in the lower Miocene. Uplift and erosion of strongly weathered crystalline basement and extensive lower Paleozoic shales and carbonates in Scandinavia. Furthermore, the significant increased run-off to the eastern North Sea Basin from distant sources like the

Rhenish Massif and Carpathian Mountains in the Tortonian, main source for the so-called Eriocanos delta, may be responsible for the marked changes in freshwater influx.

The immense freshwater run-off from the rising mountains into the North Sea Basin certainly affected the environment, and both the dinoflagellate assemblages and the organic content in the Hodde and Gram Formations reflect this influx of freshwater. A significant freshwater plume in the eastern basin may have prevented or limited a full exchange of oceanic seawater from the North Atlantic Ocean and thereby delayed the changes in Sr isotope composition for at least some of the inner parts of the North Sea Basin and consequently also for the benthic fauna, especially since the North Sea Basin was open to the ocean only through a narrow strait between Shetland Islands and Norway (Rasmussen et al., 2010).

Nevertheless, this cannot explain the low Sr ratios of the analytical results throughout middle–late Miocene. The bulk of the lower Miocene sediments was deposited in much more marginal marine settings, in brackish environments and with a massive influx of freshwater and terrestrial organic matter from the same drainage area. This has apparently affected neither the Sr ratios nor the variation in the analytical results.

6.7. Volcanic rocks and meteorites

Strontium from young volcanic rocks could have affected the isotope ratio in Miocene shells but volcanic rocks are rare in the North Sea drainage area; thin ash layers have been reported only from the Serravallian in the S1 well in the Danish North Sea (S-1 well completion report, 1975).

The middle Miocene impact craters at Steinheim (15 Ma) and Nördlinger Ries (14.3–5 Ma) in southern Germany, e.g. into Jurassic limestone, created tectite strewn fields from 200 to 450 km towards the east–northeast (Artemieva et al., 2002). The timing with the onset of low Sr isotope ratios in the Danish North Sea faunas and plankton is interesting, but freshwater drainage from these German–East European areas is towards the east or south (Kuhlemann, 2007). Therefore, no significant Sr isotope source or fingerprint from these rocks should be expected to have reached into the North Sea Basin.

6.8. Sr isotope ratio in the middle to upper Miocene

The discussion above leads to no clear explanation of the low ^{87}Sr/^{86}Sr ratios and the data variability in the middle to upper Miocene (Hodde, Ørnhøj and Gram formations) in contrast to the Lower Miocene in Denmark. We cannot explain these too old, middle–upper Miocene Sr isotope results on the basis of local geology alone, and we have not seen any published reports on this subject. However, Browning et al. (2013) have calculated the theoretical maximum resolution of Sr isotope ratios in the Miocene based on the Sr isotope data from McArthur et al. (2001). The calculation shows a significant drop in resolution from 16 to 15 Ma and is much lower in the middle and upper Miocene than below. A low resolution is not the problem in our data but in the middle–upper Miocene analyses we see a clear offset from the expected values of Sr isotope composition (Figs. 4 and 5). A reduced age resolution, however, cannot account for the systematic deviation from the strontium isotope curve observed in our study (Figs. 4 and 5). We note that there are significant offsets between reported data from ODP sites remaining even after correction for inter-lab biases by normalisation to a common ^{87}Sr/^{86}Sr ratio for NIST SRM 987 (see Miller et al., 1991 and Martin et al., 1999 for examples). Our data fit the published values of ODP site 588 (Hodell and Woodruff, 1994) better than those of sites 608 and 747 (Miller et al., 1991; Oslick et al., 1994). Further investigations might show if these offsets between the studied sites are reproducible and are also found in other localities.

The original papers that were used to construct the upper Miocene Sr isotope curve illustrate some of the problems with the data (e.g. Martin et al., 1999). There are offsets between ODP sites amounting to ~0.00006 and if these differences can be generated in fully marine sections it would be easy to produce larger offsets in marginal marine settings. We therefore suspect that this problem with Sr isotope ages is not restricted to the Danish North Sea region but is of much wider geographic extent and therefore a general problem in the middle and upper Miocene successions.

7. Conclusions

The Danish uppermost Oligocene–Miocene succession is well dated biostratigraphically and now also with ^{87}Sr/^{86}Sr isotope ratio analyses of calcareous fossils. The analyses from the uppermost Oligocene–lower Miocene show a good correlation between new Sr isotope ages and earlier dinoflagellate stratigraphic ages. In contrast, the Sr isotope ages of middle and upper Miocene strata are 2–5 My older than the dinoflagellate biostratigraphic ages. Agreement between biostratigraphic ages derived from different fossil groups underlines the robustness of ages derived from fossil assemblages.

Of the possible scenarios leading to the observed mismatch between biostratigraphic and ^{87}Sr/^{86}Sr ages, a palaeoenvironmental cause is found to be the most likely. A conclusive scenario explaining this offset in the context of the geological evolution of the Danish North Sea, however, cannot be proposed based on our current state of knowledge.

Offsets from the expected average marine ^{87}Sr/^{86}Sr ratios are also recorded in publications on IODP material. Further studies addressing the evolution of ^{87}Sr/^{86}Sr ratios in the Miocene in a local context could potentially help to resolve this problem.

Acknowledgements

The authors extend their thanks to Rune Goa (Norwegian Petroleum Directorate, NPD) and Eva Melskens (Geological Survey of Denmark and Greenland, GEUS) for drawing of figures, David Roberts (Geological Survey of Norway) for improving the language and Yuval Ronen (University of Bergen) for carrying out the strontium isotope analyses. We acknowledge Chris King (private consultant, Bridgeport, UK) and Ken Miller (Rutger University, New Jersey, USA) for reviewing the manuscript and providing many valuable comments and suggestions. Sten Lennart Jakobsen (Geological Museum, Copenhagen (SNM)), is acknowledged for locating the mollusc collections of Leif B. Rasmussen and making the material accessible; and the NPD and GEUS are acknowledged for permission to publish.

References

Artemieva, N., Pierrazzo, E., Stöffler, D., 2002. Numerical modelling of tektite origin in oblique impacts: implication to Ries-Moldavites strewn fields. Bull. Czech Geol. Surv. 77, 303–311.

Berthelsen, A., 1992. Mobil Europe. In: Blundell, D.J., Mueller, St, Freeman, R. (Eds.), A Continent Revealed: The Eropean Geotraverse Project. Cambridge University Press, Cambridge, pp. 153–164.

Brand, U., 1991. Strontium isotope diagenesis of biogenic aragonite and low-Mg calcite. Geochim. Cosmochim. Acta 55, 505–513.

Browning, J.V., Kenneth, G.M., Sugarman, P.J., Barron, J., McCarthy, F.M.G., Kulhanek, D.K., Katz, M.E., Feigenson, M.D., 2013. Chronology of Eocene–Miocene sequences on the New Jersey shallow shelf: implications for regional, interregional, and global correlations. Geosphere 9 (6), 1434–1456. http://dx.doi.org/10.1130/GES00857.1.

Dybkjær, K., Piasecki, S., 2010. Neogene dinocyst zonation in the eastern North Sea Basin, Denmark. Rev. Palaeobot. Palynol. 161, 1–29.

Dybkjær, K., Rasmussen, E.S., 2000. Palynological dating of the Oligocene–Miocene successions in the Lille Bælt area, Denmark. Bull. Geol. Soc. Den. 47, 87–103.

Eidvin, T., Riis, F., 2013. The Lower Oligocene–Lower Pliocene Molo Formation on the inner Norwegian Sea continental shelf (extent and thickness, age from fossil and Sr isotope correlations, lithology, paleobathymetry and regional correlation). NGF Abstracts and Proceedings, 1, p. 31 (Poster available from the internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Presentasjoner/NGF-Vinterkonferanse-2013/Poster-4-til-NGF-vintermotet-nett.pdf. Accessed June 5, 2014).

Eidvin, T., Rundberg, Y., 2001. Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the northern North Sea, with emphasis on the chronology of early Neogene sands. Nor. Geol. Tidsskr. 81, 119–160 (Available from the internet: http://www.npd.no/Global/Norsk/3%20-%20Publikasjoner/Forskningsartikler/Eidvin_and_Rundberg_2001.pdf. Accessed June 5, 2014).

Eidvin, T., Rundberg, Y., 2007. Post-Eocene strata of the southern Viking Graben, northern North Sea; integrated biostratigraphic, strontium isotopic and lithostratigraphic study. Nor. J. Geol. 87, 391–450 (Available from the internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Forskningsartikler/Eidvin_and_Rundberg_2007.pdf. Accessed June 5, 2014).

Eidvin, T., Brekke, H., Riis, F., Renshaw, D.K., 1998a. Cenozoic Stratigraphy of the Norwegian Sea continental shelf, 64° N–68° N. Nor. Geol. Tidsskr. 78, 125–151 (Available from the internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Forskningsartikler/Eidvin-et-al.,-1998a.pdf. Accessed June 5, 2014).

Eidvin, T., Goll, R.M., Grogan, P., Smelror, M., Ulleberg, K., 1998b. The Pleistocene to Middle Eocene stratigraphy and geological evolution of the western Barents Sea continental margin at well site 7316/5-1 (Bjørnøya West area). Nor. Geol. Tidsskr. 78, 99–123 (Available from the internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Forskningsartikler/Eidvin_et_al_1998b.pdf. Accessed June 5, 2014).

Eidvin, T., Riis, F., Rundberg, Y., 1999. Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields). Nor. Geol. Tidsskr. 79, 97–127 (Available from the internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Forskningsartikler/Eidvin-et-al-1999-(2).pdf. Accessed June 5, 2014).

Eidvin, T., Bugge, T., Smelror, M., 2007. The Molo Formation, deposited by coastal progradation on the inner Mid-Norwegian continental shelf, coeval with the Kai Formation to the west and the Utsira Formation in the North Sea. Nor. J. Geol. 87, 75–142 (Available from the internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Forskningsartikler/Eidvin_et_al_2007.pdf. Accessed June 5, 2014).

Eidvin, T., Rasmussen, E.S., Riis, F., Rundberg, Y., 2010. Oligocene to Lower Pliocene deposits of the Norwegian continental shelf, with correlation to the Norwegian Sea, Greenland, Svalbard, Denmark and their relation to the uplift of Fennoscandia (poster). NGF Abstracts and Proceedings of the 29th Nordic Geological Winter Meeting (11–13 January. Oslo, 43–44. Available from the internet: http://www.npd.no/Global/Engelsk/3%20-%20Publications/Presentations/NGF-2010-Poster.pdf. Accessed June 5, 2014).

Eidvin, T., Riis, F., Gjeldvik, I.T., 2013a. The Lower Miocene Skade Formation in the northern North Sea (extent and thickness, age from fossil and Sr isotope correlations, lithology, paleobathymetry and regional correlation). NGF Abstracts and Proceedings, 1, pp. 28–29 (Poster available from the internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Presentasjoner/NGF-Vinterkonferanse-2013/Poster-1-til-NGF-vintermotet-nett.pdf. Accessed June 5, 2014).

Eidvin, T., Riis, F., Gjeldvik, I.T., 2013b. Middle Miocene sandy deposits of the Nordland Group, northern North Sea (Suggested called Eir Formation, extent and thickness, age from fossil and Sr isotope correlations, lithology, paleobathymetry and regional correlation). NGF Abstracts and Proceedings, 1, pp. 30–31 (Poster available from the internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Presentasjoner/NGF-Vinterkonferanse-2013/Poster-2-til-NGF-vintermotet-nett.pdf. Accessed June 5, 2014).

Eidvin, T., Riis, F., Gjeldvik, I.T., 2013c. The Upper Miocene–Lower Pliocene Utsira Formation in the northern North Sea (extent and thickness, age from fossil and Sr isotope correlations, lithology, paleobathymetry and regional correlation). NGF Abstracts and Proceedings, 1, pp. 29–30 (Poster available from the internet: http://www.npd.no/Global/Norsk/3-Publikasjoner/Presentasjoner/NGF-Vinterkonferanse-2013/Poster-3-til-NGF-vintermotet-nett.pdf. Accessed June 5, 2014).

Eidvin, T., Riis, F., Rasmussen, E.S., Rundberg, Y., 2013d. Investigation of Oligocene to Lower Pliocene deposits in the Nordic offshore area and onshore Denmark. NPD Bulletin No. 10Available from the internet http://www.npd.no/engelsk/cwi/pbl/NPD_papers/Hyperlink-NPD-Bulletin-10.pdf (Accessed June 5, 2014).

Frei, K.M., Frei, R., 2011. The geographic distribution of strontium isotopes in Danish surface waters — a base for provenance studies in archaeology, hydrology and agriculture. Appl. Geochem. 26, 326–340.

Gradstein, F., Ogg, J., Smith, A., 2004. A Geological Time Scale. Cambridge University Press, Cambridge, U.K.(589 pp.).

Heilmann-Clausen, C., Nielsen, O.B., Gersner, F., 1985. Lithostratigraphy and depositional environments in the Upper Paleocene and Eocene of Denmark. Geol. Soc. Den. Bull. 33, 287–323.

Hinsch, W., 1990. Subdivision and palaeogeography of the Gramian and Syltian stages (Late Miocene) in Schleswig-Holstein and Wursten (NW Germany). Tertiary Res. 11, 159–177.

Hodell, D.A., Woodruff, F., 1994. Variation in the strontium isotopic ratio of seawater during the Miocene: Stratigraphic and geochemical implications. Paleoceanography 9 (3), 405–426.

Howarth, R.J., McArthur, J.M., 1997. Statistics for strontium isotope stratigraphy: a robust LOWESS fit to marine Sr-isotope curve for 0 to 206 Ma, with look-up table for derivation of numeric age. J. Geol. 105, 441–456.

Howarth, R.J., McArthur, J.M., 2004. Strontium isotope stratigraphy. In: Gradstein, F.M., Ogg, J.G. (Eds.), A Geological Time Scale, with Look-up Table Version 4: 08/04. Cambridge University Press, Cambridge, U.K., pp. 96–105.

Japsen, P., 1993. Influence of lithology and Neogene uplift on seismic velocities in Denmark: implications for depth conversion of maps. Bull. Am. Assoc. Pet. Geol. 77, 194–211.

Japsen, P., Green, P.F., Bonow, J.M., Rasmussen, E.S., Chalmers, J.A., Kjennerud, T., 2010. Episodic uplift and exhumation along North Atlantic passive margins: implications for hydrocarbon prospectivity. In: Vining, B.A., Pickering, S.C. (Eds.), Petroleum Geology: From Mature Basins to New Frontiers — Proceedings of the 7th Petroleum Geology Conference, pp. 979–1004.

Jensen, L.N., Schmidt, B.J., 1992. Late Tertiary uplift and erosion in the Skagerrak area: magnitude and consequences. Nor. Geol. Tidsskr. 72, 275–279.

Jørgensen, N.O., Morthorst, J., Holm, P.M., 1999. Strontium-isotope studies of “brown water” (organic-rich groundwater) from Denmark. Hydrogeol. J. 7, 533–539.

Koch, B.E., 1989. Geology of the Søby-Fasterholt AreaWith contributions by E. Fjeldsø Christensen and E. Thomsen Danmarks Geologiske Undersøgelse (A 22, Text and Atlas, 170 pp. and 121 pp.).

Koepnick, R.B., Burke, W.H., Dension, R.E., Hetherington, E.A., Nelson, H.F., Otto, J.B., Waite, L.E., 1985. Construction of the seawater ^{87}Sr/^{86}Sr — curve for the Cenozoic and Cretaceous: supporting data. Chem. Geol. 58, 55–81.

Kuhlemann, J., 2007. Paleogeographic and paleotopographic evolution of the Swiss and Eastern Alps since the Oligocene. Glob. Planet. Chang. 58, 224–236.

Laursen, G.V., Kristoffersen, F.N., 1999. Detailed foraminiferal biostratigraphy of the Miocene formations in Denmark. Contrib. Quat. Geol. 36, 73–107.

Liboriussen, J., Aston, P., Tygesen, T., 1987. The tectonic evolution of the Fennoscandian Border Zone in Denmark. Tectonophysics 137, 21–29.

Martin, E.E., Shackleton, N.J., Zachos, J.C., Flower, B.P., 1999. Orbitally-tuned Sr isotope chemostratigraphy for the late Middle to Late Miocene. Palaeoceanography 14 (1), 74–83.

McArthur, J.M., 1994. Recent trends in strontium isotope stratigraphy. Terra Nova 6 (4), 331–358.

McArthur, J.M., Howarth, R.J., Bailey, T.R., 2001. Strontium isotope stratigraphy: LOWESS version 3: best fit to the marine Sr-isotope curve for 0–509 Ma and accompanying look-up table for deriving numerical age. J. Geol. 109, 155–169.

Miller, K.G., Kominz, J.V., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., Pekar, S.F., 2005. The Phanerozoic record of global sea-level changes. Science 310, 1293–1298.

Miller, K.G., Wright, J.D., Fairbanks, R.G., 1991. Unlocking the ice house: Oligocene-Miocene oxygen isotopes, eustasy, and margin erosion. Journal of Geophysical Research 96, 6,829–6,848.

Mogensen, T.E., Korstgård, J., 1993. Structural development and trap formation along the Børglum Fault, Tornquist Zone, Denmark, and a comparison with the Painted Canyon Fault, San Andreas Zone, USA. In: Spencer, A.M. (Ed.), Generation. Accumulation and Production of Europe's Hydrocarbons III. Springer Verlag, Berlin, pp. 89–97.

Müller, C., Spiegler, D., 1993. Revision of the Late/Middle Miocene boundary on the Voering Plateau (ODP Leg 104). Newsl. Stratigr. 28 (2/3), 171–178.

Nielsen, L.H., 2003. Late Triassic–Jurassic development of the Danish Basin and the Fennoscandian Border Zone, southern Scandinavia. In: Ineson, I., Surlyk, F. (Eds.), The Jurassic of Denmark and Greenland. Geology Survey of Denmark and Greenland Bulletin, 1, pp. 459–526.

Oslick, J.S., Miller, K.G., Feigenson, M.D., Wright, J.D., 1994. Oligocene-Miocene strontium isotopes: Stratigraphic revisions and correlation to an inferred glacioeustatic record. Paleoceanography 9, 427–444.

Piasecki, S., 2005. Dinoflagellate cysts of the Middle–Upper Miocene Gram Formation, Denmark. In: Roth, F., Hoedemarkers, H. (Eds.), The Gram Book. Palaeontos, 7, pp. 29–45.

Rasmussen, L.B., 1966. Biostratigraphical studies of the marine younger Miocene of Denmark. Based on the molluscan faunas. Danmarks Geologiske Undersøgelse, II Række, 88 (358 pp.).

Rasmussen, L.B., 1968. Molluscan faunas and biostratigraphy of the marine younger Miocene in Denmark. Part II: palaeontology. Danmarks Geologiske Undersøgelse, II Række, 92 (265 pp.).

Rasmussen, E.S., 2004. The interplay between true eustatic sea-level changes, tectonics, and climate changes: what is the dominating factor in sequence formation of the Upper Oligocene–Miocene succession in the eastern North Sea Basin, Denmark? Glob. Planet. Chang. 41, 15–30.

Rasmussen, E.S., 2009. Neogene inversion of the north-eastern North Sea. Tectonophysics 465, 84–97.

Rasmussen, E.S., Dybkjær, K., Piasecki, S., 2004. The Billund delta: a possible new giant aquifer in central and western Jutland. Geol. Surv. Den. Greenl. Bull. 4, 21–24.

Rasmussen, E.S., Vejbæk, O.V., Bidstrup, T., Piasecki, S., Dybkjær, K., 2005. Late Cenozoic depositional history of the Danish North Sea Basin: implications for the petroleum systems in the Kraka, Halfdan, Siri and Nini fields. In: Doré, A.G., Vinding, B.A. (Eds.), Petroleum Geology: North-West Europe and Global Perspectives. Proceedings of the 6th Petroleum Geology Conference. Geological Society, London, pp. 1347–1358.

Rasmussen, E.S., Dybkjær, K., Piasecki, S., 2010. Lithostratigraphy of the Upper Oligocene–Miocene succession of Denmark. Geol. Surv. Den. Greenl. Bull. 22 (92 pp., 9 plates).

S-1 completion report 1975. Chevron Petroleum Co. of Denmark, Copenhagen, Denmark 59 pp.

Schiøler, P., Andsbjerg, J., Clausen, O.R., Dam, G., Dybkjær, K., Hamberg, L., Heilmann-Clausen, C., Johannesen, P., Kristensen, L.E., Prince, I., Rasmussen, J.A., 2007. Lithostratigraphy of the Palaeogene–Lower Neogene succession of the Danish North Sea. Geol. Surv. Den. Greenl. Bull. 12, 77.

Spiegler, D., Müller, C., 1992. Correlation of *Bolboforma* zonation and nannoplankton stratigraphy in the Neogene of the North Atlantic: DSDP sites 12–116, 49–408, 81–555 and 94–608. Mar. Micropaleontol. 20, 45–58.

Surlyk, F., Lykke-Andersen, H., 2007. Contourite drifts, moats and channels in the Upper Cretaceous chalk of the Danish Basin. Sedimentology 54, 405–422.

Thybo, H., 2001. Crustal structure along the EGT profile across the Tornquist Fan interpreted from seismic, gravity and magnetic data. Tectonophysics 334, 155–190.

Vejbæk, O.V., Andersen, C., 1987. Cretaceous–early Tertiary inversion tectonism in the Danish Central Trough. Tectonophysics 137, 221–238.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to Present. Science 292, 686–693.

Ziegler, P.A., 1982. Geological Atlas of Western and Central Europe. Elsevier, Amsterdam (130 pp.).

Ziegler, P.A., 1990. Geological Atlas of Western and Central Europe. Geological Society, Geol. Soc. Publ. House Bath. London (239 pp., 56 encl.).