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Age and palaeoenvironment of the Utsira Formation in the northern North Sea based on marine palynology

Stijn De Schepper[1,2] & Gunn Mangerud[1]

[1] *Department of Earth Science, University of Bergen, P.O. Box 7803, N–5020 Bergen, Norway.*
[2] *Uni Research Climate, Bjerknes Centre for Climate Research, Jahnebakken 5, N–5007 Bergen, Norway.*

E-mail corresponding author (Stijn De Schepper): stijn.deschepper@uni.no

The Utsira Formation is a major player in the carbon capture and storage on the Norwegian Shelf. Although this northern North Sea unit has been subjected to several geological and monitoring studies, its lateral distribution and stratigraphic position are still not fully understood. This unit was considered to be late Neogene and deposited in neritic environments on the Norwegian Shelf, in an area from the Viking Graben to the Tampen Spur. Here, we present marine palynomorph (dinoflagellate cysts, acritarchs) data extracted mainly from cutting samples of eight industry wells that cover the entire distribution area of the Utsira Formation to provide an age and palaeoenvironmental reconstruction for this unit. We conclude that deposits classified as Utsira Formation are Late Miocene/Early Pliocene to Early Pleistocene in age. Early Pliocene sediments are found mainly in the Viking Graben area, whereas sediments with an Early Pleistocene age occur over the entire distribution area of the Utsira Formation. All sediments were deposited in neritic environments that gradually became shallower from the Early Pliocene to the Pleistocene. At the same time, the dinoflagellate cysts also indicate a cooling that corresponds well with late Neogene global cooling. Precise dating of the Utsira Formation is difficult, but this can be improved by (1) using samples from cored section (in contrast to using cuttings), (2) a clear and unquestionable lithological definition of the Utsira Formation and (3) a continuous, calibrated reference section in the Neogene North Sea for comparison of the bioevents.

Keywords: Dinoflagellate cysts, biostratigraphy, palaeoenvironment, Pliocene, Utsira Formation, carbon dioxide storage

Electronic Supplement 1: Sample information and palynological raw data.
Electronic Supplement 2: Study sites (wells) information, sample position and dinoflagellate cyst and acritarch biostratigraphy.

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Introduction

Several geological units on the Norwegian Shelf have been identified as potential reservoirs for carbon dioxide storage. In particular, the late Neogene Utsira Formation saline aquifer in the northern North Sea is considered as an excellent reservoir (e.g., Halland et al., 2014). As part of a carbon sequestration programme of Statoil ASA, carbon dioxide from Jurassic and Tertiary gas reservoirs has been captured and stored in the Utsira Formation, a half-open to fully open storage system. Since the start of carbon dioxide injection, the Utsira Formation has been the centre of attention for detailed geological study (Halland et al., 2011, 2014), seismic characterisation (Gregersen & Johannessen, 2007), biostratigraphic (e.g., Eidvin & Rundberg, 2001) and sequence-stratigraphic investigations (Galloway, 2002), and carbon dioxide accumulation (Bickle et al., 2007) and monitoring studies (Hermanrud et al., 2009).

Although the Utsira Formation has been used for CCS since 1996, its stratigraphic position, lateral distribution and age remain a matter of debate (e.g., Eidvin et al., 2013). Originally, Isaksen & Tonstad (1989, p. 54–55) described the Utsira Formation in its type section (well 16/1–1, from 1064 to 644.5 m) as follows: "*The formation consists of marine sandstones and claystones.*

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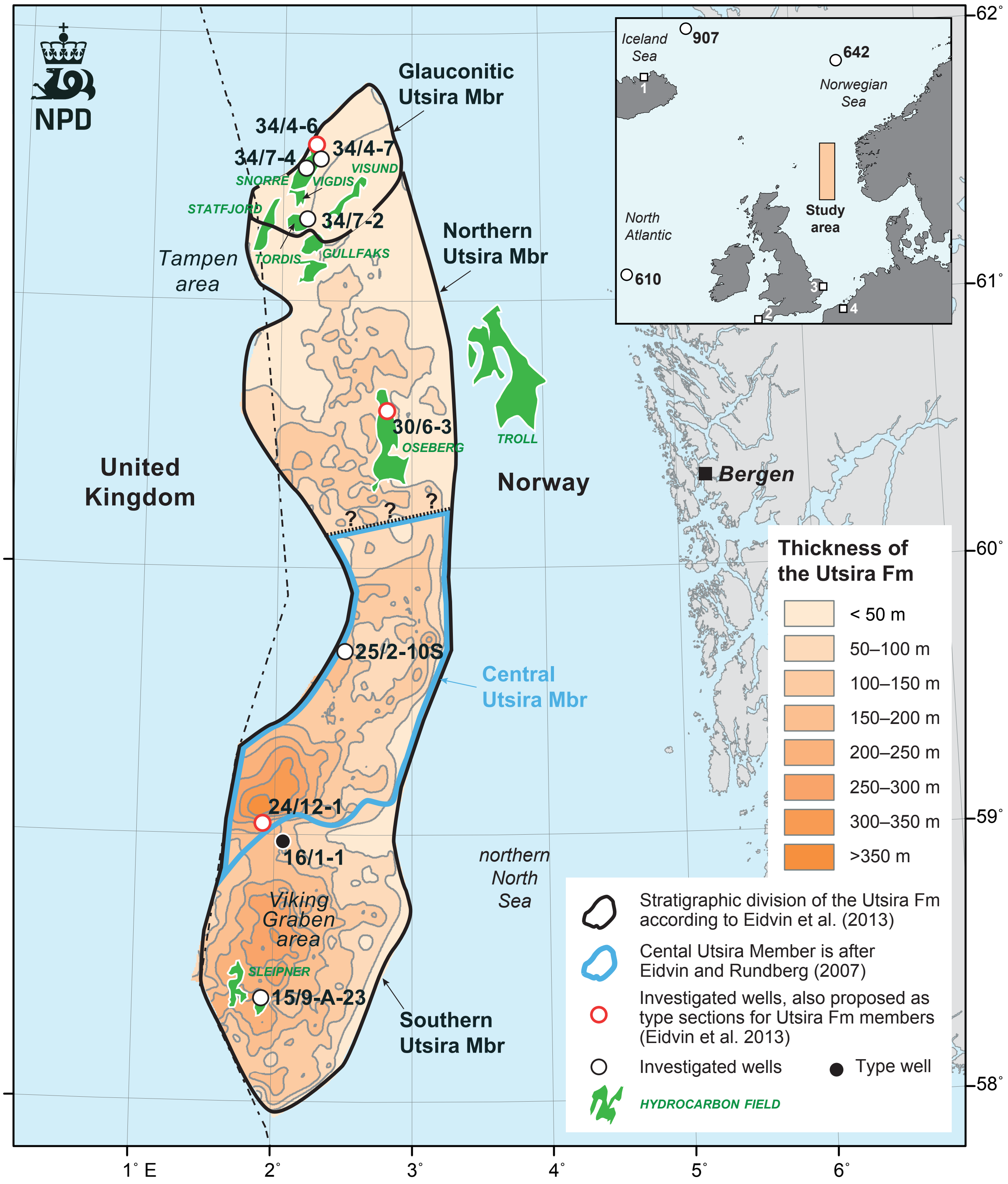

Figure 1. Thickness map of the Utsira Formation including the location of the studied sites in the northern North Sea. (based on fig. 4–080 in the CO_2 Storage Atlas of the Norwegian Petroleum Directorate at http://www.npd.no/Global/Norsk/3-Publikasjoner/Rapporter/Samleatlas/Figurer-Figures/Chapter-4/Fig-4-080.pdf and Eidvin et al. 2014a). Distribution of the different members is approximate and based on Rundberg & Eidvin (2005), Eidvin & Rundberg (2007), Gregersen & Johannessen (2007) and Eidvin et al. (2013, 2014a). The inset map shows locations of Ocean Drilling Program (Sites 642, 907), Deep Sea Drilling Project (Site 610) and onshore sites mentioned in the text. 1 – Tjörnes Section (Iceland), 2 – St Erth Beds (SW England), 3 – crag deposits in East England, 4 – Antwerp Harbour (northern Belgium).

The sandstones are clear to white, often light greenish and normally very fine to fine-grained, in places medium to very coarse grained. Occasionally rock fragments and lignite are found. The sandstones are separated by soft, plastic, light greenish claystones and minor siltstones. Glauconite and fossil fragments are common throughout.” In practice, the unit is generally identified in wells on the Norwegian Shelf based on gamma-ray logs. This follows the description by Isaksen & Tonstad (1989), who noted that the upper and lower boundaries can be identified based on, respectively, a decrease and an increase in the gamma-ray response in the type section. When the Skade Formation underlies the Utsira Formation, identification of the lower boundary of the Utsira Formation is more difficult, but is normally marked by a break on the velocity log (Isaksen & Tonstad, 1989, p. 55). However, Rundberg & Eidvin (2005) demonstrated an erroneous correlation between the Utsira and Skade formations between wells 16/1–1 and 24/12–1. This illustrates the difficulty in identifying the Utsira Formation using physical properties since diverse facies characterise the formation (Gregersen et al., 1997; Galloway, 2002; Rundberg & Eidvin, 2005). Notwithstanding, sandy units occurring within the Neogene to Quaternary on the Norwegian Shelf have been considered to belong to the Utsira Formation from the Viking Graben to the Tampen Spur (Fig. 1). Today, the Utsira Formation is considered to cover an area of at least 75 x 450 km^2 with its main, sandy depocentre reaching 250–300 m thickness in the Viking Graben. The depocentre stretches out northwards to the Tampen Spur, pinching out between the Oseberg and Troll Fields (Fig. 1); but recently, an incident near the Tordis and Visund oil fields (Tampen Spur area), following injections into sediments that were interpreted as the Utsira Formation, questioned the presence of this formation there (Eidvin, 2009; Eidvin & Øverland, 2009). It can be concluded that the use of geophysical properties alone for identifying this unit may lead to erroneous correlation and identification.

It is thus fair to say that, even today, the Utsira Formation remains poorly characterised in terms of lithology, geophysical properties, stratigraphy and lateral distribution unit within the Late Neogene of the Norwegian Shelf. Considering this background, it is not surprising that sediments considered to belong to the Utsira Formation have been dated using different methods to the Mid Miocene and Early Pliocene (Fig. 2). Several investigations have been undertaken to understand the stratigraphy and age of the Utsira Formation, and disentangle it from sandy deposits with similar geophysical properties on the Norwegian Shelf (e.g., Galloway, 2002; Eidvin & Rundberg, 2007; Gregersen & Johannessen, 2007; Eidvin et al., 2013, 2014a). In this study, we follow the subdivision of the Utsira Formation by Eidvin et al. (2013). These authors proposed to subdivide the Utsira Formation into a Southern, Northern and Glauconitic Utsira Member and presented new type well sections for each member (Figs. 1, 3, 4; Table 1). This stratigraphic division largely overlaps with Eidvin

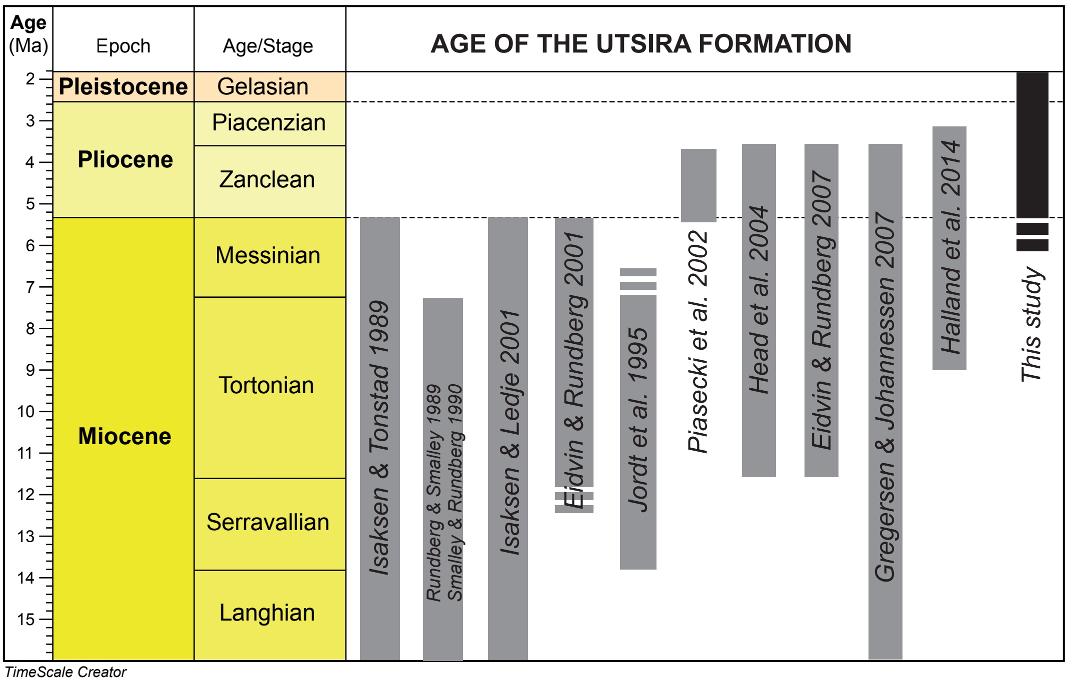

Figure 2. Age of the Utsira Formation as reported in the literature and in this study. This summary does not differentiate between the regions (Tampen area, Viking Graben), or between direct (Rundberg & Smalley, 1989; Smalley & Rundberg, 1990; Piasecki et al., 2002), indirect (Head et al., 2004) or inferred dating (Isaksen & Tonstad, 1989; Isaksen & Ledje, 2001; seismics study of Jordt et al., 1995; Halland et al., 2014), nor does it take into account whether the Utsira Formation was partially (cored section only in Piasecki et al., 2002) or entirely (e.g., Eidvin & Rundberg, 2001, 2007) dated.

Isaksen & Tonstad (1989)	Eidvin & Rundberg (2007)	Eidvin et al. (2013, 2014a)
Utsira Fm	**Utsira Fm** Glauconitic Utsira Member Northern Utsira Member Central Utsira Member Southern Utsira Member	**Utsira Fm** Glauconitic Utsira Member Northern Utsira Member Southern Utsira Member
No Formal Name	**Unnamed**	**Eir Fm**
Skade Fm	**Skade Fm**	**Skade Fm**

Figure 3. *Stratigraphic subdivision of late Neogene deposits according to Isaksen & Tonstad (1989) and Eidvin et al. (2013, 2014a).*

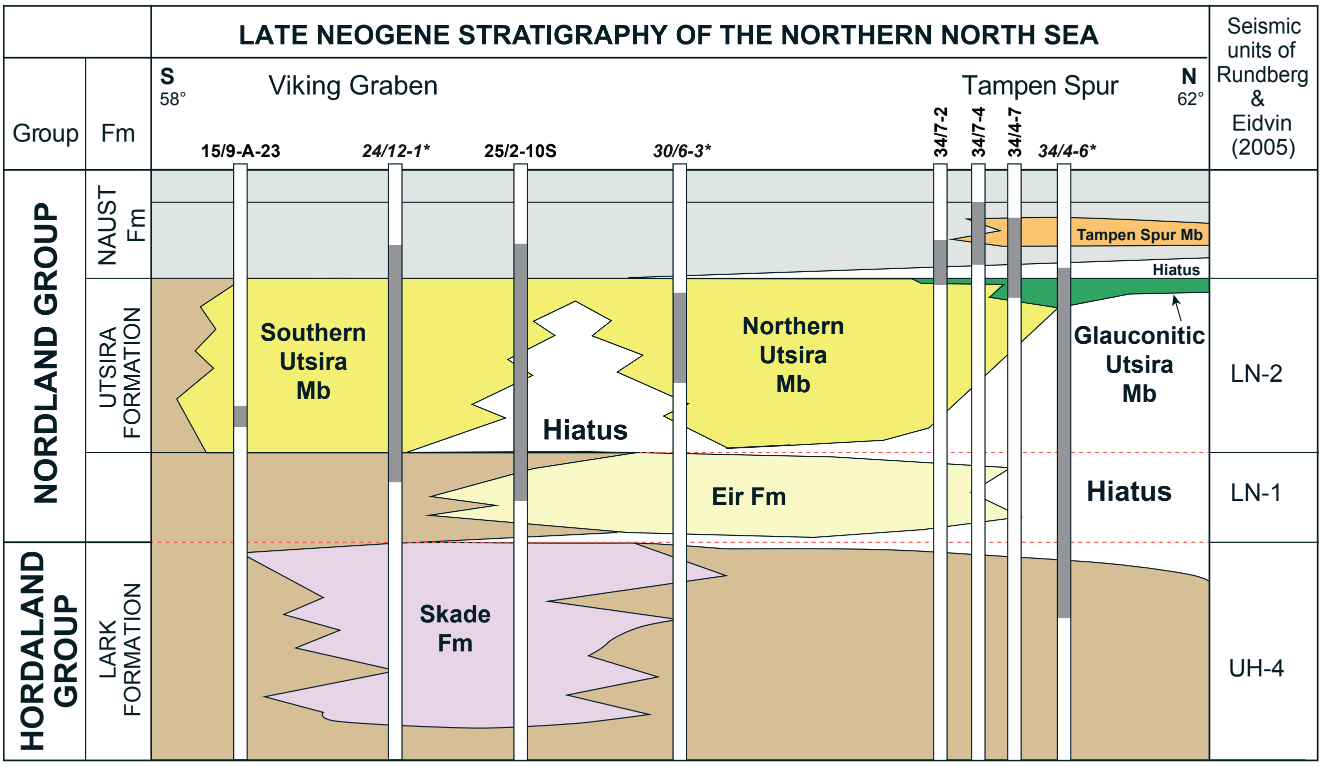

Figure 4. *Schematic representation of the late Neogene stratigraphy in the northern North Sea between 58° and 62°N (based on Eidvin & Rundberg, 2007; Eidvin et al., 2013, 2014a), including the approximate position of the wells investigated in this study. Grey shading in each well represents the interval analysed for palynology. Asterisk (*) indicates type wells for the different Utsira Formation lithological units according to Eidvin et al. (2013).*

& Rundberg (2007), where a Central Utsira Member was proposed in addition to a Southern, Northern and Glauconitic Utsira Member (Figs. 1 & 3). The Central Utsira Member of Eidvin & Rundberg (2007) separates a northern and a southern depocentre, and comprises an eastward-prograding sandy strandplain wedging out into mudstone-dominated facies to the east (Galloway, 2002; Rundberg & Eidvin, 2005). In the scheme of Eidvin et al. (2013), the Central Utsira Member is part of the Southern Utsira Member, meaning that well 24/12–1 belongs to the Southern Utsira Member. According to Eidvin & Rundberg (2007), this well would belong to the Central Utsira Member (Fig. 1). Eidvin et al. (2013, 2014a) also tentatively introduced the Eir Formation (Figs. 3 & 4), following the erroneous correlation between the Utsira and Skade formations between wells 16/1–1 and 24/12–1 (Isaksen & Tonstad, 1989; Rundberg & Eidvin, 2005). The Eir Formation represents sandy sections in the basal part of the Nordland Group and is found below the Utsira Formation and above the Skade Formation and the Mid Miocene unconformity. Finally, a potential type section for the Tampen Spur Member of the Naust Formation was suggested by Eidvin et al. (2013) (Fig. 4).

In this study, we investigated the marine palynology (dinoflagellate cysts and acritarchs) in eight wells

Table 1. Lithostratigraphy, type well, depth and estimated age for the units investigated in this study (following Eidvin et al., 2013). Depth: m RKB – metres below rig floor.

Formation	*Member*	*Type well*	*Depth (m RKB)*
Naust Fm.	Tampen Spur Mbr.	34/4–7	1050–1090
Utsira Fm.	Glauconitic Utsira Mbr.	34/4–6	1210–1250
	Northern Utsira Mbr.	30/6–3	680–750
	Southern Utsira Mbr.	24/12–1	495–730
Eir Fm.		25/2–10S	520–630

to better understand the time of deposition and palaeoenvironment of Late Neogene sandy deposits on the Norwegian Shelf, including the Utsira Formation. The wells were specifically chosen to have a good spatial coverage of sediments belonging to the different members of the Utsira Formation as well as the Eir Formation and Tampen Spur Member (Table 1). Dinoflagellate cysts and acritarchs can provide detailed age control and palaeoenvironmental insights for sediments that have limited or coarse biostratigraphic control in the North Sea to sub-Arctic North Atlantic (e.g., Head, 1997; Louwye et al., 2004; De Schepper et al., 2009; Verhoeven et al., 2011; Grøsfjeld et al., 2014). For dating, we can rely on relatively high-resolution, late Neogene, biozonation schemes and/or calibrated stratigraphic ranges of dinoflagellate cysts and acritarchs for the Norwegian Sea (De Schepper et al., 2017), the North Sea (Munsterman & Brinkhuis, 2004; Dybkjær & Piasecki, 2010), the eastern North Atlantic (De Schepper & Head, 2008a, 2009) and the Iceland Sea (Schreck et al., 2012). Additionally, because the late Neogene dinoflagellate cyst record still contains several extant components, the modern (Marret & Zonneveld, 2003) as well as Pliocene (De Schepper et al., 2011) understanding of dinoflagellate cyst palaeoecology can be applied in the case of the Utsira Formation deposits.

Methods

Studied wells and samples

Cuttings, side-wall core and core samples were collected from eight industry wells to investigate the Eir Formation, the different Utsira Formation members and the Tampen Spur Member (Naust Formation) at their proposed type wells (Table 2). Samples from well 25/2–10S (Southern Utsira Member) and from Tampen area wells 34/7–2 (Glauconitic Utsira Member) and 34/7–4 ('Utsira Formation') were also analysed for palynology. Three samples from well 15/9–A–23 were reinvestigated

Table 2. Location of the eight industry wells investigated in this study with indicated the studied interval, number and type of samples. Samples were investigated from the Utsira Formation and its bounding lithological units. Depth: m RKB – metres below rig floor. SWC – sidewall core. Source: Norwegian Petroleum Directorate, factpages.npd.no. Asterisk (*) indicates type wells for the different Utsira Formation lithological units according to Eidvin et al. (2013).

Well	*Field/Location*	*Coordinates*	*Total depth* (m RKB)	*Water depth* (m)	*Utsira Formation depth* (m RKB)	*Investigated interval* (depth m)	*Samples* Number, type
15/9–A–23	Sleipner Øst	58° 22' 2.05" N- 1° 54' 32.06" E	5590	86	950–1350	1084.13–1084.99	3 Core
24/12–1*	Gudrun Terrace	59° 2' 29.8" N 1° 52' 57.93" E	3966	113	497–732	440–750	11 Cutting
25/2–10S	East of Øst Frigg	59° 53' 11.8" N 2° 30' 8.33" E	2967	120	475–520	470–570	6 Cutting
30/6–3*	Oseberg	60° 34' 52.9" N 2° 47' 1.41" E	2940	102	656–892	710–740	3 Cutting
34/4–6*	Snorre	61° 34' 14.1" N 2° 13' 19.9" E	3282	373.5	1128–1149	1220–1260	4 Cutting
34/4–7	Snorre	61° 31' 9.8" N 2° 15' 15.5" E	2950	354	1062–1097	1063–1190	8 Cutting & SWC
34/7–2	/	61° 17' 57.2" N 2° 9' 40.9" E	2475	245	1026–1035	990–1030	3 SWC
34/7–4	/	61° 29' 4.4" N 2° 8' 0.3" E	3115	319	1034–1115	980–1180	6

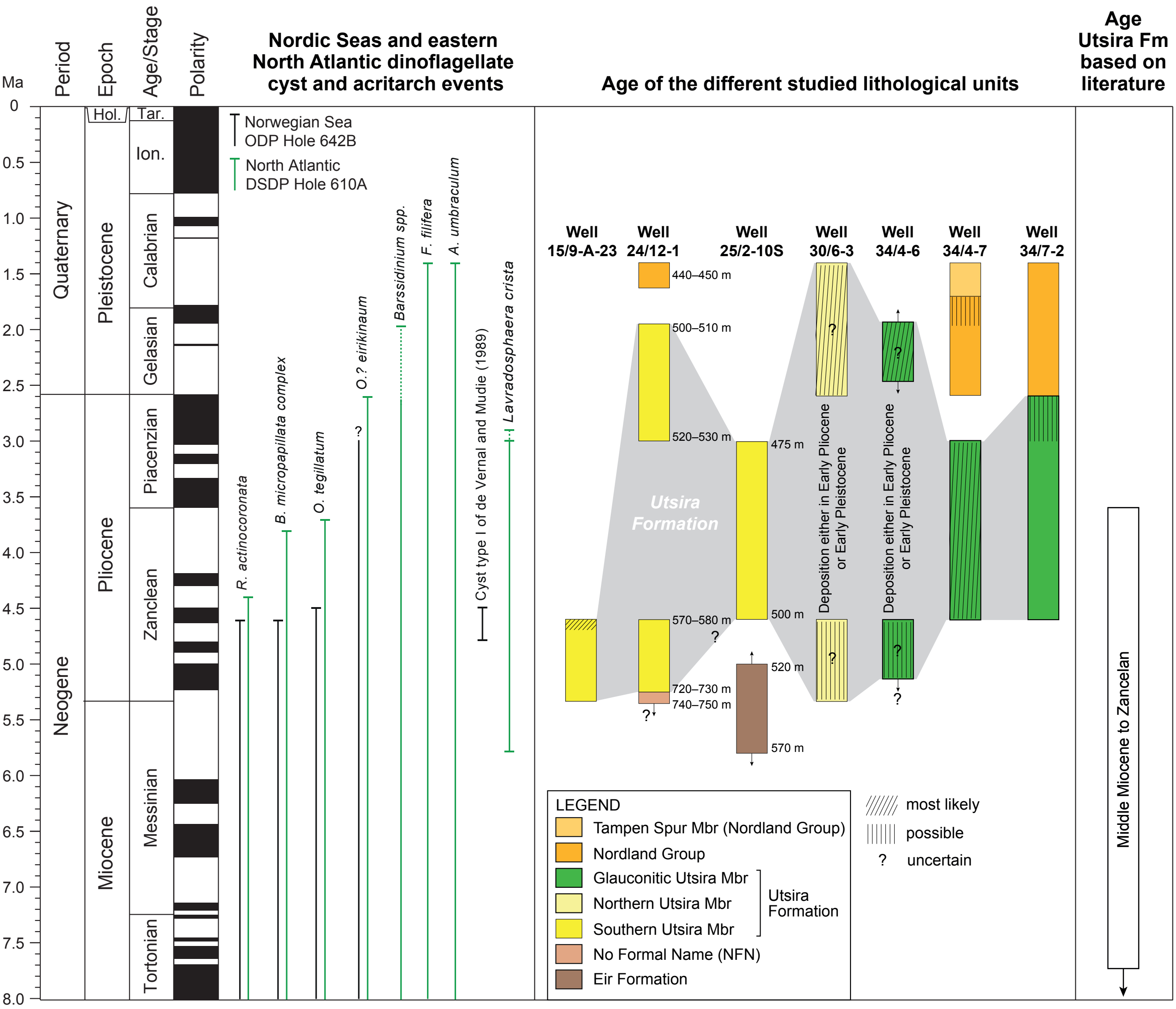

Figure 5. Age estimate of the Utsira Formation, Eir Formation and Tampen Spur Member based on dinoflagellate cyst and acritarch stratigraphy. For comparison, the entire age range of the Utsira Formation as mentioned in the literature is also presented (see Fig. 2 for details).

to identify additional stratigraphic markers not reported in Piasecki et al. (2002). The sample depth of cutting samples in the wells must be considered as an approximate depth since they can represent an interval of up to 10 m of sediment (i.e., 740–750 m).

Palynological laboratory procedure and microscopy

Samples were processed by Palynological Laboratory Services Ltd (Holyhead, UK). One *Lycopodium clavatum* spore tablet (Batch no. 483.216, n = 18583 ± 1708 spores per tablet) was added to a specified weight of each sample prior to chemical degradation. Calcium carbonate and silica were removed by adding 50% hydrochloric acid (HCl) and 60% hydrofluoric acid (HF). In between and after the acid treatments, the sample was sieved through a 10-µm sieve cloth and collected. Oxidation using 50% cold nitric acid (HNO_3) and/or a short ultrasonic treatment was carried out on some samples (see Electronic Supplement 1). Before mounting, the residue was mixed with a 1% solution of polyvinyl alcohol (PVA) to prevent clotting, and stained with Safranin-O. It was then pipetted onto a 32 x 22 mm cover slip, which was mounted onto the glass microscope slide using glycerine jelly optical adhesive.

Dinoflagellate cysts and acritarchs were counted using a Zeiss AxioImager.A2 transmitted light microscope at the University of Bergen. Each slide was scanned at 400x magnification until about 200 or more dinoflagellate cyst specimens were counted or the entire slide was analysed. During this regular count, all encountered acritarchs, spores, pollen and freshwater algae were also enumerated. Consequently, at least five traverses were scanned at 200x magnification to look for rare taxa not seen during the regular count.

Data storage

All raw data are presented in Electronic Supplement 1.

Biostratigraphic ranges of selected dinoflagellate cysts and acritarchs

Because there is no calibrated reference section in the North Sea, we used ranges of stratigraphic markers from independently calibrated (magnetostratigraphy, marine isotope stratigraphy) sections from nearby sites in the North Atlantic and Nordic Seas. It is important to make a comparison with both regions, because recent investigation has revealed the diachroneity of several stratigraphic markers between the North Atlantic, Iceland Sea and Norwegian Sea (Fig. 5; De Schepper et al., 2015, 2017). The location of the Utsira Formation, roughly midway between the Norwegian Sea ODP Site 642 and eastern North Atlantic Site 610, makes the application of Nordic Seas and/or North Atlantic stratigraphic marker events sometimes difficult (see further).

Dinoflagellate cyst ranges in the Nordic Seas and North Atlantic

In this chapter and Table 3, we compile the stratigraphic ranges of several markers from the eastern North Atlantic Deep Sea Drilling Project (DSDP) Site 610, the Ocean Drilling Program (ODP) Site 907 in the Iceland Sea and Site 642 in the Norwegian Sea.

Table 3. *Compilation of the stratigraphic range of selected markers from the eastern North Atlantic Deep Sea Drilling Project (DSDP) Site 610, the Ocean Drilling Program (ODP) Site 907 in the Iceland Sea and Site 642 in the Norwegian Sea. Abbreviations: FA – first appearance, LA – last appearance*

Biostratigraphic event	*Norwegian Sea ODP Site 642[1]*	*Iceland Sea ODP Site 907[2]*	*eastern North Atlantic DSDP Site 610[3,4]*	*North Atlantic region compilation*
Dinoflagellate cysts				
LA *Amiculosphaera umbraculum*			1.44 Ma	
FA *Ataxiodinium zevenboomii*	5.3 Ma	Not recorded		
LA *Barssidinium pliocenicum/ Barssidinium graminosum*	≤ 3 Ma	4.5 Ma	2.74 Ma	2.1–1.95 Ma in eastern England[5]
LA *Batiacasphaera hirsuta*	5.0 Ma (5.5 Ma?)	8.4 Ma	/	
LA *Batiacasphaera micropapillata* complex	4.6 Ma	4.6 Ma	3.83 Ma	
LA *Filisphaera filifera*			1.44 Ma	
LA *Invertocysta lacrymosa*	3.27 Ma	4.5 Ma	2.74 Ma	2.7–2.8 Ma[3]
LA *Operculodinium*? *eirikianum eirikianum*	≤ 3 Ma	4.5 Ma	2.62 Ma	
LA *Operculodinium tegillatum*	4.6 Ma	4.5 Ma	3.71 Ma	
FA *Operculodinium tegillatum*	5.3 Ma	8.9 Ma continuously from 5.1 Ma		>7.5 Ma in Belgium[6]
LA *Reticulatosphaera actinocoronata*	4.6 Ma	4.5 Ma		4.4 Ma[7]
LA *Selenopemphix brevispinosa*	4.6 Ma			Late Pliocene [e.g. 7,8]
Acritarchs				
LA *Cymatiosphaera*? *icenorum*	≤3 Ma	/	2.14 Ma	1.7 Ma at DSDP Site 603[9]
LA *Lavradosphaera crista*	≤3 Ma		HO: 2.67 Ma,0 HCO: 3.00 Ma	2.9–3.0 Ma[9]
LA *Leiosphaeridium rockhallensis*			3.83 Ma	
Range Cyst type I of de Vernal & Mudie (1989)	4.7–4.6 Ma			4.7–4.2 Ma at DSDP Site 603[10]
LA *"Veriplicidium franklinii"* of Anstey (1992)	5.3 Ma			?5.3 Ma at ODP Site 982[11]

References: [1] – De Schepper et al. (2015, 2017), [2] – Schreck et al. (2012), [3] – De Schepper & Head (2008a), [4] – De Schepper & Head (2009), [5] – Head (1993), [6] – Louwye et al.)2007), [7] – Louwye et al. (2004), [8] – Louwye & De Schepper (2010), [9] – De Schepper & Head (2008b, 2014), [10] – M.J. Head, unpublished data, [11] – Van Ranst (2015).

Amiculosphaera umbraculum ranges up to c. 1.4 Ma in the eastern North Atlantic (De Schepper & Head, 2008a). A range top in the Nordic Seas is not available.

Ataxiodinium zevenboomii ranges from the Upper Miocene into the Pleistocene, but is recovered mainly from Pliocene deposits (*e.g.,* Head, 1997; Louwye & Laga, 2008; De Schepper & Head, 2009). Its range in the Norwegian Sea starts at c. 5.3 Ma near the Miocene–Pliocene boundary (De Schepper et al., 2017).

Barssidinium graminosum and *Barssidinium pliocenicum* disappear from the eastern North Atlantic record at around 2.6 Ma (De Schepper & Head, 2008a, 2009), but have been reported from shallow deposits as young as 1.95 Ma in southern England (Head, 1993).

Batiacasphaera hirsuta has a last appearance (LA) in the Iceland Sea at c. 8.4 Ma in the upper Tortonian (Schreck et al., 2012), but in the Norwegian Sea it has a persistent range up to 5.5 Ma, with spot occurrences up to 5.0 Ma (De Schepper et al., 2017).

Batiacasphaera micropapillata complex has a highest common occurrence (HCO) at 4.6 Ma in the Norwegian Sea, with occasional younger occurrences considered to be reworked (De Schepper et al., 2015, 2017). It has a HCO at 4.6 Ma in the Iceland Sea (Schreck et al., 2012), and a LA at 3.8 Ma in the North Atlantic (De Schepper & Head, 2008a).

Filisphaera filifera ranges up to c. 1.4 Ma in the eastern North Atlantic (De Schepper & Head, 2008a).

Invertocysta lacrymosa has a relatively synchronous LA in the North Atlantic region at around 2.74 Ma (De Schepper & Head, 2008a). Its range top in the Nordic Seas is less well defined: in the Iceland Sea it ranges up to 4.5 Ma (Schreck et al., 2012), in the Norwegian Sea ODP Hole 642B up to 3.27 Ma (De Schepper et al., 2017) or possibly up to ~2.8 Ma (M. Smelror, unpublished data).

Operculodinium? *eirikianum eirikianum* occurs well into the Upper Pliocene (≤ ~3 Ma) on the Vøring Plateau (De Schepper et al., 2017) and in the eastern North Atlantic (up to 2.6 Ma; De Schepper & Head, 2008a), but in the Iceland Sea it disappears already at c. 4.5 Ma (Schreck et al., 2012).

Operculodinium tegillatum has a LA at 4.6 Ma in the Norwegian Sea (De Schepper et al., 2017), at 4.5 Ma in the Iceland Sea (Schreck et al., 2012), and at 3.7 Ma in the eastern North Atlantic (De Schepper & Head, 2008a). It first appears in the Norwegian Sea at around 5.3 Ma, but was recorded occasionally from c. 8.9 Ma and continuously from 5.1 Ma in the Iceland Sea (Schreck et al., 2012). It is also present in the southern North Sea Basin as *Operculodinium antwerpensis* in the Upper Miocene Diest Formation (>7.5 Ma; Louwye et al., 2007).

Reticulatosphaera actinocoronata has a LA at 4.6 Ma in the Norwegian Sea (De Schepper et al., 2017) and at 4.5 Ma in the Iceland Sea (Schreck et al., 2012), consistent with its estimated range up to ~4.4 Ma in the North Atlantic (Louwye et al., 2004). Although this species can occur as reworked in Lower to Upper Pliocene deposits (e.g., Louwye & De Schepper, 2010), it can be considered as a relatively contemporaneous Nordic Seas–North Atlantic event (De Schepper et al., 2017).

Selenopemphix armageddonensis is known from the Upper Miocene (de Verteuil & Norris, 1996; Louwye, 2002; Dybkjær & Piasecki, 2010) and may be reworked, but has been recorded in places in the Lower Pliocene of the North Sea (e.g., Louwye et al., 2004).

Selenopemphix brevispinosa is a rare to common, persistent component of the palynological assemblage in the Norwegian Sea prior to the 4.6 Ma event (De Schepper et al., 2017). It also occurs in the Upper Pliocene of the North Sea (Louwye et al., 2004, 2007).

Acritarch ranges in the Nordic Seas and North Atlantic Ocean

Cymatiosphaera? *icenorum* has a LA in the eastern North Atlantic at around 2.14 Ma and in the western North Atlantic at around 1.7 Ma (De Schepper & Head, 2014).

Lavradosphaera crista has been recorded from the latest Messinian (c. 5.8 Ma) up to the Late Pliocene around 2.9–3.0 Ma (De Schepper & Head, 2014).

Cyst type I of de Vernal & Mudie (1989) has a narrow stratigraphic range within the Zanclean of the Labrador Sea (de Vernal & Mudie, 1989) and in the Zanclean of the Norwegian Sea (4.6–4.7 Ma; De Schepper et al., 2017). In the western North Atlantic it occurs from 4.7 to 4.2 Ma (M.J. Head, unpublished data).

"Veriplicidium franklinii" of Anstey (1992) was described for the first time from the Upper Miocene through possibly Lower Pliocene of Baffin Bay (Anstey, 1992). It is known from the Norwegian Sea ODP Hole 642B, where it occurs from the base of the studied interval at 5.9 Ma to near the Miocene–Pliocene boundary at 5.3 Ma (De Schepper et al., 2017). A single occurrence at 4.81 Ma can be considered as reworking. It is also possibly recorded between 8.2 and 5.3 Ma in the eastern North Atlantic ODP Site 982 (as *Platycysta spp. in* Van Ranst, 2015).

Results and interpretation

General considerations and limitations

Downhole contamination or caving

Because most investigated samples were (ditch) cutting samples from industry wells, downhole caving of younger sediments and their included palynomorphs presents a problem for dating the Utsira Formation deposits. Caving is the process where the *in situ* fossil assemblage is contaminated by stratigraphically younger fossils during the drilling operation. Especially the identification of first appearances (or lowest occurrences) can be hampered by downhole contamination. As a consequence, we have based our age estimates of the Utsira Formation on the extinctions or highest occurrences (known as first downhole occurrences in the industry) identified in the different wells. Using uncontaminated side-wall cores (e.g., in well 34/4–7, 34/7–2) or cored sections (well 15/9–A–23) has served as a quality control for the studied cuttings.

Age estimate limitations due to asynchrony of nearby extinction events

We have compared the biostratigraphic events in the studied wells mainly with the Nordic Seas extinction events (ODP Sites 642 and 907) to estimate the ages in the studied wells. This conservative approach results in older age estimates than when North Atlantic extinctions (DSDP Site 610) would have been used, due to the diachroneity of the North Atlantic and Nordic Seas extinction events (De Schepper et al., 2015, 2017). When calibrated extinction events were not available from the Nordic Seas (e.g., *Amiculosphaera umbraculum, Filisphaera filifera)*, we had to rely on the North Atlantic bioevents.

The Southern Utsira Member in well 15/9–A–23: a reinvestigation of Piasecki et al. (2002)

We reinvestigated three of the eight samples from the study by Piasecki et al. (2002) to look for previously unidentified stratigraphic markers. It is important to note that this was a cored section, implying that the palynological assemblages are not affected by caving.

1.1.1 Palynological assemblage

The palynological assemblage is diverse, recording minimally 29 dinoflagellate cyst taxa as well as eight to eleven acritarch taxa per sample. Terrestrial palynomorphs (bisaccates, small pollen and spores) are as abundant, or even more abundant than marine palynomorphs. Concentrations could not be determined. The dominant dinoflagellate cyst species are *Barssidinium pliocenicum, Barssidinium graminosum, Operculodinium tegillatum* and *Spiniferites/ Achomosphaera* spp. indet. In places, common species are *Filisphaera filifera, Habibacysta tectata, Operculodinium israelianum/centrocarpum* s.s. and *Operculodinium*? *eirikianum eirikianum. Ataxiodinium zevenboomii* and *Selenopemphix brevispinosa* were recorded in two samples, as well as several species of *Batiacasphaera.* One specimen of *Selenopemphix armageddonensis* in the lowermost investigated sample could be in situ, but may also be reworked. Reworking is proven by the presence of other Miocene taxa such as *Cerebrocysta poulsenii, Hystrichosphaera obscura, Labyrinthodinium truncatum* and *Palaeocystodinium* sp.

Biostratigraphy and age assessment

The dinoflagellate cysts and acritarch assemblage is most consistent with a Zanclean age for the studied interval, as Piasecki et al. (2002) also concluded. Nevertheless, our reinvestigation of three samples revealed previously unidentified stratigraphic markers including *Batiacasphaera micropapillata* complex, *Operculodinium tegillatum, Operculodinium*? *eirikianum* and *Lavradosphaera* spp. Together with *Reticulatosphaera actinocoronata* and the acritarch Cyst type I of de Vernal & Mudie (1989), this suggests an Early Pliocene age, older than 4.6 Ma when using the Nordic Seas bioevents. The range of *Ataxiodinium zevenboomii* in the Norwegian Sea starts at c. 5.3 Ma near the Miocene–Pliocene boundary, which provides a tentative maximum for the age of deposition. This is consistent with the first appearance of *Operculodinium tegillatum* in the Norwegian Sea at around 5.3 Ma. However, it must be noted that *Operculodinium tegillatum* is also known from the Upper Miocene in the North Atlantic realm (>7.5 Ma; Louwye et al., 2007; Schreck et al., 2012). Our study thus confirms and provides further detail on the Early Pliocene age proposed by Piasecki et al. (2002). We estimate the sediment to have been deposited between 5.3 and 4.6 Ma, possibly even entirely at around 4.7–4.6 Ma (Fig. 5).

Limited reworking of Miocene taxa such as *Cerebrocysta poulsenii, Hystrichosphaera obscura, Labyrinthodinium truncatum* and *Palaeocystodinium* is observed. The occurrence of *Selenopemphix armageddonensis*, known from the Late Miocene but also recorded in the Early Pliocene of the North Sea (Louwye et al., 2004), can either be part of the in situ assemblage or reworked, as Piasecki et al. (2002) interpreted it.

Palaeoenvironment

The sediments were most likely deposited on an open shelf, at some distance from the coast with almost no influence of riverine and open ocean waters. The dominance of *Spiniferites/Achomosphaera* and high numbers of *Barssidinium* and *Operculodinium tegillatum* in each sample suggest a neritic environment. High abundances of *Operculodinium tegillatum* are recorded from water depths of 30–50 m (Kattendijk Sands, southern North Sea Basin; Louwye et al., 2004; De Schepper et al., 2009), the outer shelf (ODP 642B, Vøring Plateau, water depth 1286 m; De Schepper et al., 2015, 2017) to the open ocean settings of the North Atlantic (ODP Hole 610A, water depth 2417 m; De Schepper & Head, 2008a) and Iceland Sea (ODP Hole 907A, water depth 2036 m; Schreck et al., 2012). The high abundance of terrestrial palynomorphs indicates a proximal coastline, but the (near-)absence of freshwater algae indicates no freshwater inflow via rivers. The single occurrence of *Impagidinium patulum* is the only evidence for an influence of warm, open ocean waters. Similarly, Piasecki et al. (2002) concluded with a deposition on the outer shelf, probably during a transgression, with limited influence of oceanic water.

Sea surface conditions were most likely temperate and warmer than at present. The dinoflagellate cyst assemblage is characterised mainly by extinct thermophilic taxa (e.g., *Ataxiodinium zevenboomii, Bitectatodinium raedwaldii, Hystrichokolpoma rigaudiae*), although cool-water tolerant taxa like *Bitectatodinium tepikiense, Habibacysta tectata, Filisphaera filifera* and *Pyxidinopsis braboi* also occur. The presence of *Tuberculodinium vancampoae, Impagidinium patulum* and *Melitasphaeridium choanophorum* indicate a sea surface temperature (SST) higher than present. *Tuberculodinium vancampoae* is today a (sub)tropical coastal species that is usually found in areas with winter SST higher than c. 13°C and summer SST above 14.5°C (Marret & Zonneveld, 2003). However, Piasecki et al. (2002) suggested that this species could be reworked. We cannot prove or disprove this suggestion, but the presence of *Melitasphaeridium choanophorum* is consistent with warmer conditions than at present. This species was continuously present in the eastern North Atlantic until ~3 Ma (De Schepper & Head, 2009) and until ~3.3 Ma in the Norwegian Sea (De Schepper et al., 2015, 2017). It has been discovered recently in surface sediments from the Gulf of Mexico, where summer SSTs are between 26 and 30°C, and winter SSTs are 18 to 25°C (Limoges et al., 2013).

Comparison with foraminifers and Sr-isotopic data

The marine palynology suggests a time of deposition during the Early Pliocene, overlapping partly with Late Miocene to Early Pliocene ages based on foraminifers (Wilkinson, 1999; Eidvin & Rundberg, 2007). Comparable to the outer-shelf environment concluded from the dinoflagellate cysts, foraminifers also indicate a middle- to outer-shelf environment with limited oceanic influence (Wilkinson, 1999).

Strontium isotopic data were obtained from mollusc fragments, benthic foraminifera, and benthic and planktonic foraminifera in a core sample at 1080 m (Eidvin & Rundberg, 2007). Five $^{87/86}$Sr ages reported from in situ specimens exhibit a range between 1.35 and 6.46 Ma for the time of deposition. The oldest age appears too old for the Early Pliocene age assignment based on dinoflagellate cysts, whereas other $^{87/86}$Sr ages are much younger at <2.7 Ma. This wide range may be explained by high-frequency variation in seawater $^{87/86}$Sr, analytical noise, caving and/or reworking. It crucially illustrates the difficulty of using this dating method in the North Sea region (Eidvin et al., 2014b).

The Southern Utsira Member in well 24/12–1

Palynological assemblage

Nine samples were studied from the Southern Utsira Member (= Central Utsira Member according to Eidvin & Rundberg, 2007), which likely correspond to the upper part of the Utsira Formation (Eidvin & Rundberg, 2007). One sample was studied from the underlying No Formal Name (NFN) unit and one from the overlying Nordland Group. The dinoflagellate cyst assemblage of the Central Utsira Member is moderately diverse, recording between 18 and 34 taxa per sample. The NFN unit recorded 22 dinoflagellate cyst taxa and the Nordland Group sample only 11 taxa. Dinoflagellate cysts and acritarchs are usually dominant, but terrestrial palynomorphs outnumber the marine palynomorphs in the upper part of the Utsira Formation. Also, four taxa of freshwater algae occur commonly throughout the studied section.

The dominant dinoflagellate cyst species in the Southern Utsira Member are *Habibacysta tectata, Filisphaera filifera, Operculodinium centrocarpum sensu* Wall & Dale (1966), *Operculodinium*? *eirikianum, Operculodinium tegillatum* and *Spiniferites/Achomosphaera* spp. Also, *Barssidinium* spp., *Batiacasphaera* spp., *Nematosphaeropsis labyrinthus, Operculodinium centrocarpum/israelianum* and *Reticulatosphaera actinocoronata* are common constituents of the assemblage.

Reworked dinoflagellate cysts occur in every sample, but these were not identified further.

Biostratigraphy and age assessment

The assemblage in the single sample (740 m) from the NFN unit consists mainly of taxa that also occur in the overlying Southern Utsira Member. Because this sample was taken close to the boundary between the NFN and the Southern Utsira Member (730 m), caving could be responsible for the presence of *Barssidinium pliocenicum, Batiacasphaera micropapillata complex, Operculodinium*? *eirikianum eirikianum* and *Reticulatosphaera actinocoronata* in the NFN. If these species are nevertheless in situ, they are consistent with an Early Pliocene (older than 4.6 Ma) to Late Miocene age. The single specimen of *Pentadinium laticinctum* could be consistent with a Late Miocene to earliest Early Pliocene age, because this species has a highest occurrence (HO) in the *Selenopemphix armageddonensis* Zone (7.6–5.0 Ma) of Dybkjær & Piasecki (2010). *Labyrinthodinium truncatum*, with a HO in late Tortonian (Schreck et al., 2012), likely occurs as reworked. The nature of the samples and cuttings does allow the possibility that both *Labyrinthodinium truncatum* and *Pentadinium laticinctum* are in place, and thus imply a Miocene age.

Since these samples correspond to the upper part of the Utsira Formation (Rundberg & Eidvin, 2005; Eidvin et al., 2014a), the lower succession of the Utsira Formation in this southern part of the basin must be older.

The dinoflagellate cyst and acritarch assemblage of the Southern Utsira Member suggests that deposition occurred in two phases (Fig. 5; Electronic Supplements 1 & 2): a first depositional phase (720 to 570 m) took place in the Late Miocene to Early Pliocene (>4.6 Ma), followed by a second depositional phase between 3.0 and 1.4 Ma (520 to 500 m). The palynomorph assemblage in the Southern Utsira Member between 720 and 570 m differs from the assemblage in the overlying samples. A maximum age for the deposits between 720 m and 570 m can be proposed based on the presence of *Operculodinium tegillatum*. This indicates a maximum age as young as 5.3 Ma if only its Norwegian Sea range is considered. However, considering the entire known range of *Operculodinium tegillatum*, this lowermost part of the Southern Utsira Member could also be Late Miocene. A Late Miocene age is also supported by the occurrence of "*Veriplicidium franklinii*" of Anstey (1992) between 730 and 640 m, which in the Norwegian Sea ranges from >5.9 Ma to 5.3 Ma (De Schepper et al., 2015, 2017) and from 8.2 to 5.3 Ma in the eastern North Atlantic ODP Site 982 (as *Platycysta* spp. in Van Ranst, 2015).

Stratigraphic dinoflagellate cyst markers such as *Batiacasphaera micropapillata complex, Operculodinium tegillatum* and *Reticulatosphaera actinocoronata* disappear from the record at 570 m. While the LA of the first two taxa in the eastern North Atlantic is recorded at around 3.7–3.8 Ma, all three taxa disappear simultaneously from the Nordic Seas at around 4.6 Ma. The range of the acritarch Cyst Type I of de Vernal & Mudie (1989) between 670 m and 570 m corroborates an Early Pliocene age, which may be close to 4.7–4.6 Ma. In the Nordic Seas, these taxa disappear as a consequence of changed oceanography in the Early Pliocene (De Schepper et al., 2015). In this well, we recorded also the HO of *Operculodinium*? *eirikianum eirikianum* and the acritarch *Lavradosphaera crista* at 570 m. Because both taxa occur well into the Upper Pliocene in the North Atlantic and Norwegian Sea, a hiatus and/or non-deposition due to a major shoaling environment is interpreted between 570 and 530 m in this well. Sample 550 m (not shown) is dominated by terrestrial palynomorphs and plant material in various stages of degradation but also records *Spiniferites, Bitectatodinium, Filisphaera filifera, Habibacysta tectata* and *O. israelianum*, together suggesting a shallow-marine environment. Stratigraphic markers were absent in this sample.

The assemblage in the upper two samples of the southern Utsira Member (520 and 500 m) and the Nordland Group sample does not contain any Lower Pliocene markers. As mentioned, also *Operculodinium*? *eirikianum eirikianum* and the *acritarch Lavradosphaera crista* are absent. This indicates an age younger than ~3.0 Ma for the sediments above 520 m. Using the North Atlantic LA of *Barssidinium graminosum* and *Barssidinium pliocenicum*, a latest Pliocene to Early Pleistocene age of around 2.6 Ma, but possibly also as young as 1.95 Ma (Head, 1993), can be proposed for sample 520 m. The presence of *Amiculosphaera umbraculum* and *Filisphaera filifera* at 500 m and 440 m suggests that these samples are older than 1.4 Ma (De Schepper & Head, 2008a, 2009). Considering the single occurrences of *Reticulatosphaera actinocoronata* and *Operculodinium*? *eirikianum* as reworked, the sediment between 520 and 440 m was likely deposited between 3.0 and 1.4 Ma.

Palaeoenvironment

The palynological assemblages indicate a neritic (shelf) environment with low to moderate influence of fresh water (via rivers) and limited open ocean influence. The neritic environment is indicated by the dominance of autotrophic, spiniferate, dinoflagellate cysts. Several heterotrophic species were recorded, but never in high abundance. Marine palynomorphs (dinoflagellate cysts and acritarchs) are more abundant than the terrestrial palynomorphs in the lower part, while this is reversed in the upper part. Freshwater algae increase in abundance, and together with the high amount of pollen and spores indicate a closer proximity to the coast and a riverine influence in the upper part. The low occurrence of *Impagidinium* demonstrates a very limited influence of oceanic waters. The sample at 540 m (not shown) contains few dinoflagellate cysts and a major amount of pollen and spores, suggesting a shoaling of the environment to a very shallow, near-coastal environment.

The dinoflagellate cyst assemblage is characterised by typical Early Pliocene thermophilic species (e.g., *Melitasphaeridium choanophorum, Operculodinium*? *eirikianum eirikianum, Operculodinium tegillatum*) reflecting temperate conditions. Cool-water tolerant taxa *Habibacysta tectata* and *Filisphaera filifera* (Head, 1994; De Schepper et al., 2011) are also abundant and both show opposing trends: *Habibacysta tectata* is abundant at the base and decreases upward, whereas *Filisphaera filifera* only becomes very abundant in the upper three samples. These upper three samples furthermore do not contain extinct, warm-water Pliocene species (e.g., *Melitasphaeridium choanophorum, Invertocysta lacrymosa*) and record a decrease in species numbers compared to the other samples, suggesting a cooler environment.

Comparison with foraminifer data and Strontium isotopic data

The age estimates based on benthic foraminifer assemblages (Eidvin & Rundberg, 2007) partly overlap, but generally suggest an older age than the dinoflagellate cyst estimates. The benthic foraminifer assemblages between 750 and 550 m indicate a Mid Miocene to Early

Pliocene age, whereas we conclude with a Late Miocene to Early Pliocene (>4.6 Ma) age. The uppermost part of the Southern Utsira Member between 500 and 520 m is Early Pliocene according to the benthic foraminifer assemblages. The dinoflagellate cysts here indicate a Late Pliocene (<3.0 Ma) to Pleistocene age. The Early Pleistocene benthic foraminifers in the lowermost part of the Nordland Group (480–500 m) correspond favourably with the dinoflagellate cysts, which indicate an Early Pleistocene age between 2.6–1.95 and 1.4 Ma.

The comparison between strontium isotopic ages (table 2 in Eidvin & Rundberg, 2007) and dinoflagellate cyst biostratigraphy is problematic. The problem lies in the large scatter of the strontium isotope measurements in subsequent samples or even within the same sample. Hence, it is impossible to objectively determine whether the Sr-derived ages are accurate or affected by reworking or caving. For example, mollusc fragments in the sample at 650 m depth yield an age range between 2.41 and 8.96 Ma. Another example is the sample at 500 m, for which the Sr-isotope age (2.1 Ma) was considered too young and interpreted to be due to caving of the mollusc fragment (Eidvin & Rundberg, 2007). Compared to the Late Pliocene to Pleistocene age based on dinoflagellate cysts for the sediments above 520 m, a Sr-isotope age of 2.1 Ma at 500 m may, in hindsight, be an accurate age estimate.

The Eir Formation and Utsira Formation in Well 25/2–10S

Palynological assemblage

Six cutting samples between 570 and 470 m were studied. The samples at 570 and 540 m belong to the Eir Formation (Eidvin et al., 2013). The sample at 520 m is taken at the boundary of the Eir and Utsira formations. Because this is a cutting sample and the palynological assemblage is mostly similar to the Eir Formation assemblages (see Electronic Supplement 1), we consider the palynological assemblage to reflect the Eir Formation. The samples at 500 and 490 m are from the Utsira Formation and are likely part of the eastward prograding, sandy, strandplain facies (Galloway, 2002; Rundberg & Eidvin, 2005). Following Eidvin et al. (2013), we consider these samples to belong to the Southern Utsira Member (= Central Utsira Member according to Eidvin & Rundberg, 2007). The sample at 470 m is located within the basal Nordland Group.

The dominant dinoflagellate cyst species in all samples of well 25/2–10S are *Operculodinium centrocarpum sensu* Wall & Dale (1966) and *Spiniferites/Achomosphaera* spp. indet. *Barssidinium* spp. and *Habibacysta tectata* are common taxa in all samples, whereas *Batiacasphaera hirsuta* is common only in the Eir Formation.

Biostratigraphy and age assessment

The samples in the Eir Formation (570–520 m) may be Early Pliocene, older than 5.0 Ma, but can also be Late Miocene (Fig. 5; Electronic Supplements 1 & 2). *Batiacasphaera hirsuta* and *Operculodinium tegillatum* range up to 520 m. Although *Batiacasphaera hirsuta* has a LA of around 8.5 Ma in the Iceland Sea, its LA in the Norwegian Sea (Table 3) suggests an age older than 5.0 Ma. This is in correspondence with the known range of *Operculodinium tegillatum* in the Nordic Seas up to 4.6 Ma. When the Norwegian Sea range of *Operculodinium tegillatum* is considered, an Early Pliocene age can be inferred since this species has a lowest occurrence around 5.3 Ma. However, considering the entire known range of *Operculodinium tegillatum* (Table 3) and the fact that the samples are cuttings, the age could also be Late Miocene. In fact, if *Labyrinthodinium truncatum truncatum* is in situ, the age of the Eir Formation would be >7.5 Ma.

Samples investigated from the Southern Utsira Member (520–475 m) indicate an age between 4.6 and 3.0 Ma (Fig. 5). The HOs of *Operculodinium tegillatum* and *Batiacasphaera hirsuta* at 520 m suggest an age younger than 5.0 Ma and 4.6 Ma, respectively. The minimum age for this unit is not younger than c. 2.9–3.0 Ma based on the presence of the acritarch *Lavradosphaera crista* in all samples and occurrences of *Operculodinium*? *eirikianum, Barssidinium* spp. and *Invertocysta lacrymosa*. The Nordland Group sample (470 m) contains the same markers as the sediments below, and thus cannot be distinguished from the underlying Southern Utsira Member.

Palaeoenvironment

The palynological assemblages in all samples indicate deposition in a shallow shelf environment at some distance from the coast during temperate conditions. The marine and terrestrial palynomorphs suggest conditions comparable to the shallow-water Pliocene deposits that were deposited in proximity to the coast of the southern North Sea Basin (Louwye et al., 2004; De Schepper et al., 2009). In addition, *Batiacasphaera hirsuta* suggests a neritic environment with increased nutrients (Quaijtaal et al., 2014). Oceanic (*Impagidinium*) and freshwater algae are only occasionally recorded, indicating a very limited influence of oceanic waters and riverine input. Cool tolerant taxa (*Filisphaera filifera, Habibacysta tectata*) are a minor component of the assemblage, which is dominated by thermophilic, extinct taxa (e.g., *Operculodinium tegillatum, Barssidinium* spp.).

Comparison with published age estimates

In Eidvin et al. (2013), the interval between 520 and 475 m (Utsira Formation) is considered to be the Lower Pliocene and Eidvin et al. (2014a, fig. 22) place this interval in the Upper Miocene to Lower Pliocene, which is considerably older than our interpretation (4.6 to 3.0 Ma). Also, most $^{87/86}$Sr ages (5.41–4.09 Ma; (Eidvin et al., 2013) are slightly older than in our interpretation, although some overlap exists.

The Northern Utsira Member in well 30/6–3

Palynological assemblage

The three investigated cutting samples from the Northern Utsira Member are dominated by *Filisphaera filifera, Habibacysta tectata* and *Spiniferites/Achomosphaera* spp. indet.

Biostratigraphy and age assessment

An age assessment based on the dinoflagellate cyst assemblage is open for interpretation (Fig. 5): the sediments could have been deposited in the Early Pliocene or Early Pleistocene (2.6–1.4 Ma). In each sample, Cyst Type I of de Vernal & Mudie (1989) is recorded (Electronic Supplement 2), which would favour an Early Pliocene age at around 4.6–4.7 Ma for this interval. This is consistent with the presence of other Early Pliocene palynomorphs *Operculodinium tegillatum, Reticulatosphaera actinocoronata, Lavradosphaera crista,* Cyst Type I of de Vernal & Mudie, 1989), but to arrive at this age the Late Miocene–earliest Pliocene *Batiacasphaera hirsuta* must be interpreted as reworked.

An alternative interpretation that explains the presence of a mixture of markers is that all Upper Miocene to Lower Pliocene markers were reworked. This can be supported by the relatively high amounts of reworked palynomorphs in the samples. The high proportions of *F. filifera* and *H. tectata* (together 39–56%), could indicate that these are in situ and would be consistent with cooler conditions in the Early Pleistocene (compared to the generally warmer Early Pliocene). Using the stratigraphic ranges of those two species the deposits are older than 1.4 Ma. Finally, caving may also be responsible for the problematic interpretation.

Palaeoenvironment

Given the amount of reworking, potentially affecting the entire assemblage, palaeoenvironmental interpretations are speculative. Nevertheless, cool-water taxa *F. filifera* and *H. tectata* are dominant in the samples suggesting that these occur in situ. High concentrations of terrestrial palynomorphs and records of freshwater algae suggest that the coast was nearby. Most likely, cool conditions in shallow-water environments prevailed during deposition of the Northern Utsira Formation.

Comparison with published age estimates

Our age assessment could not conclude on an Early Pliocene or Pleistocene age for the interval between 710 and 740 m, although we favour the Early Pleistocene age. Eidvin et al. (2013) indicated an Early Pliocene age for the Utsira Formation between 740 and 680 m based on foraminifers. Sr-isotope ages (table 1 in Eidvin et al., 2013) indicate Quaternary (interpreted as caved) or Miocene ages (interpreted as reworked). Late Miocene ages of 6.99 Ma and 8.69 Ma were considered to be good estimates for the deposits between 710 and 740 m. Miocene ages are not supported by the dinoflagellate cysts.

The Glauconitic Utsira Member in well 34/4–6

The reference well section for the Glauconitic Utsira Member is in well 34/4–6 from 1250 to 1210 m (Eidvin et al., 2013). In this interval, we analysed four samples and collected presence–absence data for three samples (1250, 1240 and 1230 m) and counted one sample at 1220 m.

Palynological assemblage

Sample 1220 m showed a dominance of *Habibacysta tectata, Bitectatodinium* spp. and *Spiniferites* spp. In total, 15 dinoflagellate cyst and 5 acritarch taxa were recorded. Terrestrial palynomorphs outnumber the dinoflagellate cysts, and also freshwater algae (*Botryococcus, Pediastrum*) were recorded.

Biostratigraphy and age assessment

The lower two samples (1250 and 1240 m) likely demonstrate a diverse Miocene dinoflagellate cyst assemblage (including *Apteodinium spiridoides, Cleistosphaeridium placacantha, Cordosphaeridium cantharellus, Distatodinium* spp., *Ennaedocysta* spp., *Glaphyrocysta* spp.).

A substantial hiatus is apparent between the lower and upper two samples: the samples 1230 m and 1220 m yielded the Lower Pliocene markers *Operculodinium tegillatum, Reticulatosphaera actinocoronata* and Cyst Type I of de Vernal & Mudie (1989). If in situ, these taxa suggest a time of deposition during the Early Pliocene before 4.6 Ma. However, it is not unthinkable that these taxa were also reworked and that deposition took place during the Late Pliocene to Early Pleistocene between 3.0 and 1.4 Ma (Fig. 5). Evidence supporting a Pleistocene age is the dominance of cool-water taxa *Filisphaera filifera* and *Habibacysta tectata*, the absence of the acritarch genus *Lavradosphaera* and the low number (n = 15) of taxa recorded. This is almost half of the on average 29 taxa in the Early Pliocene Central and Southern Utsira Member of wells 24/12–1 and 15/9–A–23, and could correspond to the climatically cooler conditions during the Pleistocene.

Palaeoenvironment

Cool-temperate conditions, in a shallow-water environment near the coast prevailed during deposition of the Glauconitic Utsira Member. Cool-water taxa *Habibacysta tectata* and *Filisphaera filifera* are abundant in the samples. High concentrations of terrestrial palynomorphs and records of freshwater algae indicate a proximity to the coast. Glauconitic deposits are commonly associated with transgressive phases (Sturrock, 1996). A high number of reworked dinoflagellate cysts from Miocene or older sediments is consistent with a transgression that may have eroded the Hordaland Group as well as Pliocene (Utsira Formation) sediments.

Comparison with published age estimates
Foraminifers and Sr isotope ages indicate a Late Miocene to earliest Early Pliocene age according to Eidvin et al. (2013). Our analysis of the palynomorphs indicates a Miocene age for the interval 1250–1240 m and an Early Pliocene or a Pleistocene age for 1230–1220 m.

The Glauconitic Utsira and Tampen Spur members in well 34/4–7

Palynological assemblage
Two samples (1190 and 1180 m) were investigated in the Utsira Formation. As the sediment is characterised as glauconitic sand (Eidvin & Rundberg, 2001), these samples can most likely be assigned to the Glauconitic Utsira Member. Two more samples were investigated from the immediately overlying Nordland Group sediments (1160 and 1140 m). In addition, three cuttings and one sidewall-core sample were investigated from the type section of the Tampen Spur Member of the Naust Formation (1090–1050 m; Eidvin et al., 2013).

The palynological assemblage is more diverse in the Utsira Formation than in the overlying deposits. *Habibacysta tectata* is common (5–16% of total assemblage) in the Utsira Formation and the basal Nordland Group, but is largely absent from the Tampen Spur Member (<1% of total assemblage in two samples). *Filisphaera filifera, Operculodinium centrocarpum* sensu Wall & Dale (1966) and *Spiniferites/Achomosphaera* spp. are dominant throughout.

Biostratigraphy and age assessment
The Utsira Formation (likely Glauconitic Utsira Member) in this well is older than 3.0 Ma, and the lowermost part may even be older than 4.6 Ma (Fig. 5; Electronic Supplement 2). The sample at 1190 m may be older than 4.6 Ma based on the presence of *Reticulatosphaera actinocoronata* and *Operculodinium tegillatum*. However, reworking of these specimens cannot be excluded which would suggest an age <4.6 Ma. The HO of *Operculodinium*? *eirikianum, Melitasphaeridium choanophorum, Invertocysta lacrymosa, Heteraulacacysta* sp. A of Costa & Downie (1979), *Barssidinium* spp. and the acritarch *Lavradosphaera crista* at 1180 m is consistent with an age older than 3.0 Ma.

Sediments of the Nordland Group underlying the Tampen Spur Member are younger than 2.6 Ma, possibly younger than 1.95 Ma. This is inferred from the absence of the Upper Pliocene markers *Barssidinium* spp., *Operculodinium*? *eirikianum* and *Invertocysta lacrymosa* (HOs at top Utsira Formation; Electronic Supplement 2). These species disappear from the North Atlantic at around 2.6–2.7 Ma, but *Barssidinium* spp. has been recorded up to 1.95–2.1 Ma in England (Head, 1993).

The Tampen Spur Member is older than 1.4 Ma based on the presence of *Amiculosphaera umbraculum* and *Filisphaera filifera* (Electronic Supplement 2).

Palaeoenvironment
The dinoflagellate cyst assemblages are dominated by *Habibacysta tectata, Filisphaera filifera, Operculodinium centrocarpum* sensu Wall & Dale (1966) and *Spiniferites* spp. indet. which points towards a shelf environment under cool-temperate conditions. Influence from the open ocean is minimal throughout, as shown by the occurrence of only a few specimens of *Impagidinium.* Continuous riverine input (presence of *Botryococcus* and *Pediastrum*) indicates the proximity of the coast during deposition of the Utsira Formation. The Tampen Spur Member was deposited even closer to the coast and near a strong riverine influence, since freshwater algae and terrestrial palynomorphs are more abundant.

Comparison with published age estimates
Eidvin et al. (2013) used planktonic and benthic foraminifera to estimate a Late Miocene to Early Pliocene age for the Utsira Formation, corroborating the Sr-isotope ages of 5.1 and 5.4 Ma (Eidvin & Rundberg, 2001). The dinoflagellate cysts indicate younger ages (4.6–3.0 Ma) for the upper sample (1180 m) in the Utsira Formation compared to the lower sample (1190 m, >4.6 Ma). The age for the lower sample is in agreement with the estimates of Eidvin et al. (2013), but the upper sample is thus considerably younger.

The Glauconitic Utsira Member in well 34/7–2 in the Tampen area

Palynological assemblage
Three sidewall core samples were investigated from this well. One sample was from the Utsira Formation, and two from the overlying sediments of the Nordland Group. The assemblage in the Utsira Formation is dominated by *Operculodinium*? *eirikianum, Bitectatodinium raedwaldii* and *Operculodinium centrocarpum* sensu Wall & Dale (1966). The Nordland Group samples are dominated by *Habibacysta tectata*. Considerable reworking is identified in these samples with the occurrence of *Cleistosphaeridium placacanthum, Hystrichosphaera obscura* and *Reticulatosphaera actinocoronata.*

Biostratigraphy and age assessment
The Utsira Formation (1030 m) is likely older than 2.6 Ma (Fig. 5; Electronic Supplement 2) based on the abundant presence of *Operculodinium*? *eirikianum* in sample 1030 m. If *Reticulatosphaera actinocoronata* is in situ in this sample, the age could be older than 4.6 Ma. However, there is strong evidence for reworking in this sample, given the occurrence of several Miocene dinoflagellate cysts, even in high abundance (*Cleistosphaeridium placacanthum*) in the same sample. Most likely, *Reticulatosphaera actinocoronata*

is reworked implying an age younger than 4.6 Ma. This is corroborated by the absence of other Lower Pliocene markers (e.g., *Operculodinium tegillatum*). Given the absence of *Lavradosphaera crista* it may even be that the sample is younger than 3.0 Ma, although this is speculative and needs confirmation from analysing more samples.

The overlying Nordland Group sediments are younger than 2.6 Ma, but older than 1.4 Ma given the presence of *Amiculosphaera umbraculum* and *Filisphaera filifera.*

Palaeoenvironment

The Utsira Formation sample indicates outer shelf and warm temperate conditions. The overlying samples were deposited closer to the coast, in shallower environments, and during cool temperate conditions.

Comparison with published age estimates

Eidvin (2009) and Eidvin et al. (2013) estimated these deposits to be Late Miocene to Early Pliocene based on foraminifer assemblages. Two Sr-isotope ages of benthic foraminifers from sidewall core 1030 m (listed as 1130 m in table 1 on p. 4 in Eidvin, 2009 and in Eidvin et al., 2013) gave ages of 4.7 and 4.2 Ma. The Nordland Group sediments were dated to the Late Pliocene. For both the Utsira Formation and the Nordland Group sediments, our dinoflagellate cysts analysis suggests younger ages.

Well 34/7–4 in the Tampen area

Palynological assemblage

In the completion log from well 34/7–4 (www.npd.no), the sandy sediments between 1034 and 1115 m were assigned to the Utsira Sands. According to Løseth et al. (2012, 2013), this assignment is incorrect and they suggested that the sandy sediments are extrusive sands of possibly Paleocene age. In contrast, Eidvin & Rundberg (2001) and Rundberg & Eidvin (2005, 2015) considered these as Pleistocene turbiditic sands. Two samples (1180 and 1150 m) were studied below the sandy sediments (1034–1115 m), where three samples were investigated. Also, one sample (980 m) of the overlying Nordland Group was investigated.

The assemblages are dominated by *Filisphaera filifera, Operculodinium centrocarpum* sensu Wall & Dale (1966) and *Spiniferites/Achomosphaera* spp. indet., comparable to the assemblages in the other wells. A major difference with other wells is that all samples are characterised by considerable reworking. Reworking is substantial in sample 1080 m, where several Miocene species are recorded, amongst others *Cleistosphaeridium placacanthum, Cordosphaeridium minimum* and *Hystrichosphaera obscura.*

Biostratigraphy and age assessment

The different lithological units could not be differentiated using dinoflagellate cysts and acritarchs. The assemblages are characterised by few stratigraphic markers, substantial reworking and potentially also caving which makes an age assessment difficult and open to alternative interpretations. Firstly, considering the dominant species *Operculodinium centrocarpum* sensu Wall & Dale (1966) and *Filisphaera filifera*, a Pliocene to Pleistocene age can be proposed. Both taxa are an important component of the assemblages recorded in the Pliocene and Pleistocene of the other wells in this study. It follows that the deposits are not younger than 1.4 Ma, given the presence of *Amiculosphaera umbraculum* and the well-established LA of *Filisphaera filifera*. Secondly, the studied interval could be Late Miocene based on the occurrence of *Cleistosphaeridium placacanthum* in nearly all samples and an abundance peak in sample 1080 m. However, this species is most likely reworked since the overall assemblage is not characteristic for the Miocene. Thirdly, the studied interval could be older than 4.6 Ma based on the presence of *Reticulatosphaera actinocoronata in* almost all samples. However, *Reticulatosphaera actinocoronata, Batiacasphaera minuta, Operculodinium*? *eirikianum* and *Operculodinium tegillatum* have a near-contemporaneous LA in the Early Pliocene Nordic Seas, whereas in this well they have a HO at different depths in the studied interval. Furthermore, *Operculodinium*? *eirikianum* disappears first (sample 1180 m) in the studied interval, while it is known to range into the Upper Pliocene (Table 3). Finally, considering the occurrences of *Operculodinium*? *eirikianum* and *Lavradosphaera crista* in 1180 m as their HO, the samples between 1150 and 980 m could be younger than 3.0–2.6 Ma. This interpretation implies reworking of most of the Lower Pliocene and Miocene markers. Reworking does occur in the studied interval, and especially in sample 1080 m where several Miocene taxa (*Cleistosphaeridium placacantha, Cordosphaeridium minimum, Distatodinium, Palaeocystodinium*) were recorded. The Nordland Group sample is dominated by cool-water taxa (e.g., F. filifera) suggesting an age <2.6 Ma. At best, a Pliocene–Pleistocene age can be concluded based on the marine palynology, but a more precise dating remains speculative.

It is not possible to judge whether this sand is, in fact, extrusive sand (Løseth et al., 2012, 2013) or the result of turbiditic sedimentation (Eidvin & Rundberg, 2001; Rundberg & Eidvin, 2015) based on the palynological record. This is mainly due to the occurrence of both unspecified reworked and in situ palynomorphs, and also importantly, the potential of contamination via caving (cutting samples). Extrusion of sand may have occurred in pulses, with intermittent more quiet periods (Løseth et al., 2012). In such a scenario, both reworked (extruded) and in situ (Pleistocene) palynomorphs would be mixed and incorporated in the sediment. However, the palynomorph assemblage may equally reflect a Pleistocene palynological signature, where onshore or subsea erosion and/or remobilisation of sediments containing pre-Pleistocene palynomorphs contributed to the assemblage.

Palaeoenvironment

Abundant freshwater algae and terrestrial palynomorphs in all samples suggest a shallow depositional environment close to the coast during cool temperate conditions (*Filisphaera filifera, Habibacysta tectata).*

Correlating the wells based on dinoflagellate cysts and dating the Utsira Formation

The Utsira Formation is thickest in the Viking Graben (Fig. 1) and becomes much thinner towards the north in the Tampen area. Our palynological study indicates an Early Pliocene to Early Pleistocene age for the Southern, Northern and Glauconitic Utsira Members, with the different members showing a large spread in their age estimates. Three palynological events can be used to correlate the different wells and lithological units: the LA of a group of Early Pliocene taxa (*Reticulatosphaera actinocoronata, Operculodinium tegillatum*, Cyst type I of de Vernal & Mudie, 1989) at around 4.6 Ma, the LA of *Lavradosphaera crista* around 3.0 Ma and the LA of *Filisphaera filifera* at around 1.4 Ma (Fig. 6A, B).

The type section for the Southern Utsira Member was proposed in well 24/12–1 by Eidvin et al. (2013) (Fig. 3). Our palynological analysis demonstrated that this section contains the most complete record of the Utsira Formation of all investigated wells (Fig. 5). It must be noted, however, that we have likely investigated only see the upper part of the Utsira Formation in well 24/12 (Rundberg & Eidvin, 2005; Eidvin et al., 2014a). This implies that the Southern Utsira Member (e.g., in wells 16/1–1, 16/2–1) may include deposits older than the Early Pliocene (age of the cored interval in well 15/9–A–23). In this well, we also find clear evidence for two distinct depositional phases possibly separated by a hiatus within the Southern Utsira Member. The oldest sediments were deposited in the Late Miocene (≥5.3 Ma) to Early Pliocene (>4.6 Ma), whereas younger sediments were deposited in the Late Pliocene to Early Pleistocene between 3.0 and 1.95 Ma. Three samples from a 1-m interval investigated from well 15/9–A–23 corroborate the Early Pliocene age for the oldest phase of deposition of the Utsira Sands (see also Piasecki et al., 2002). The Southern Utsira Member in well 25/2–10S, which lies at the transition between the southern and northern depocentre (Fig. 1), consists of sediments dated between 3.0 and 4.6 Ma. This implies that deposition took place in between the oldest (> 4.6 Ma) and youngest (<3.0 Ma) depositional phase of the Southern Utsira Member in well 24/12–1. In summary, the Southern Utsira Member contains sediments deposited in the Early Pliocene as well as in the Pleistocene in its type well (24/12–1), and even during the Late Pliocene (25/2–10S; Figs. 5 & 6B).

The Northern Utsira Member could be Early Pleistocene in age although dating is speculative and can be questioned (Figs. 5 & 6B). The palynology of well 30/6–3, which contains the reference section of the Northern Utsira Member between 750 and 680 m, was not conclusive for an Early Pliocene, Late Pliocene and/or Early Pleistocene age. Similarly, the investigated sediments in well 34/7–2 were deposited in the Pliocene and/or Pleistocene, but a more precise age could not be given.

The Glauconitic Utsira Member was deposited in the Pliocene (34/4–6) to Early Pleistocene (34/4–7; Figs. 5 & 6B). According to the palynology, the sediment intervals assigned to the Glauconitic Utsira Member (wells 34/4–6 and 34/4–7) were deposited at different times. In well 34/4–6, the interval between 1250 and 1210 m contains the reference section for the Glauconitic Utsira Member. Our palynological analyses revealed that this unit contains Miocene and Early Pliocene palynomorphs, which could indicate an age of deposition before 4.6 Ma. However, the Miocene and Early Pliocene palynomorphs could also be interpreted as reworked and as a consequence, the Glauconitic Utsira Member would then most likely have been deposited between 3.0 and 1.4 Ma. In well 34/4–7, this member appears to have been deposited between 4.6 Ma and 3.0 Ma. It follows that the Northern Utsira Member is older than the Glauconitic Utsira Member, in locations where the latter member stratigraphically overlies the Northern Utsira Member.

The discrepancy between the ages reported in the literature for the Utsira Formation and our palynological investigation (Figs. 2 & 5) shows the incompatibility of Sr-ages and foraminifer stratigraphy vs. dinoflagellate cyst stratigraphy. Sr-ages show a wide spread within the same sample and/or the same lithological unit, which suggests that these data should be treated with care (for discussion on Sr-ages in the North Sea, see Eidvin et al., 2014b). The foraminifer stratigraphy is based mainly on benthic assemblages, since planktonic foraminifers are scarce in the record. The disadvantage of benthic assemblages is that these may be diachronous over large distances. In contrast, dinoflagellate cysts are a diverse group of planktonic organisms that have a wide distribution. Several late Neogene biostratigraphic events have been calibrated to magnetostratigraphy and/or marine isotope stratigraphy in both nearby (Norwegian Sea) and farther afield regions (Iceland Sea, North Atlantic), with see clear indications of asynchrony between the Norwegian/Iceland seas and the North Atlantic (De Schepper et al., 2015, 2017). Notwithstanding this issue, it can be concluded from the palynostratigraphy that the Utsira Formation was deposited during the latest Miocene to Pleistocene, which is generally younger than previous age estimates (Figs. 4 & 5).

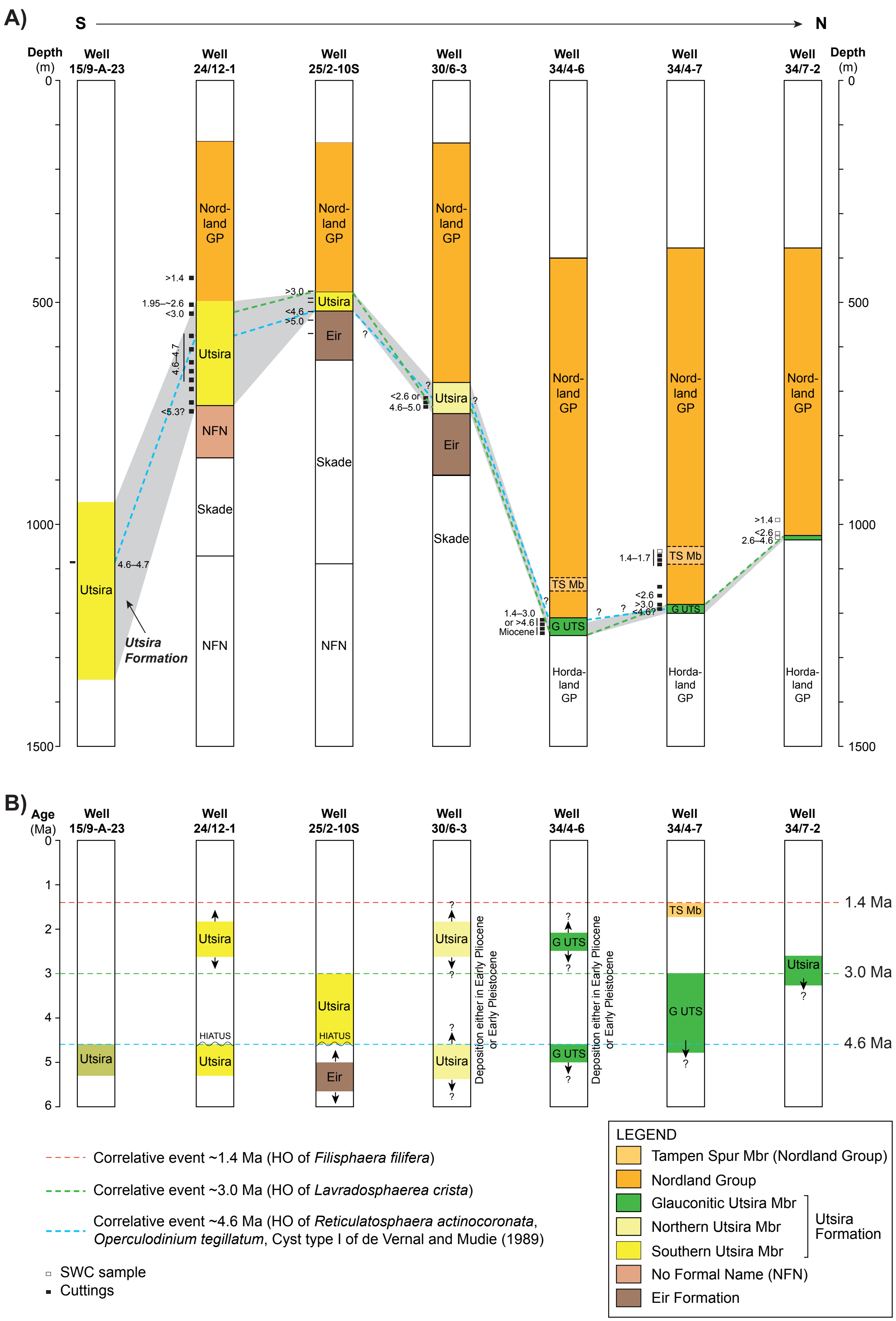

Figure 6. Depths in each well (A) and ages of deposition (B) for the different lithological units based on dinoflagellate cyst and acritarch stratigraphy, with indication of three bioevents useful for correlation in the Pliocene of the northern North Sea. The well stratigraphy is based on Eidvin & Rundberg (2007), Eidvin et al. (2013, 2014a).

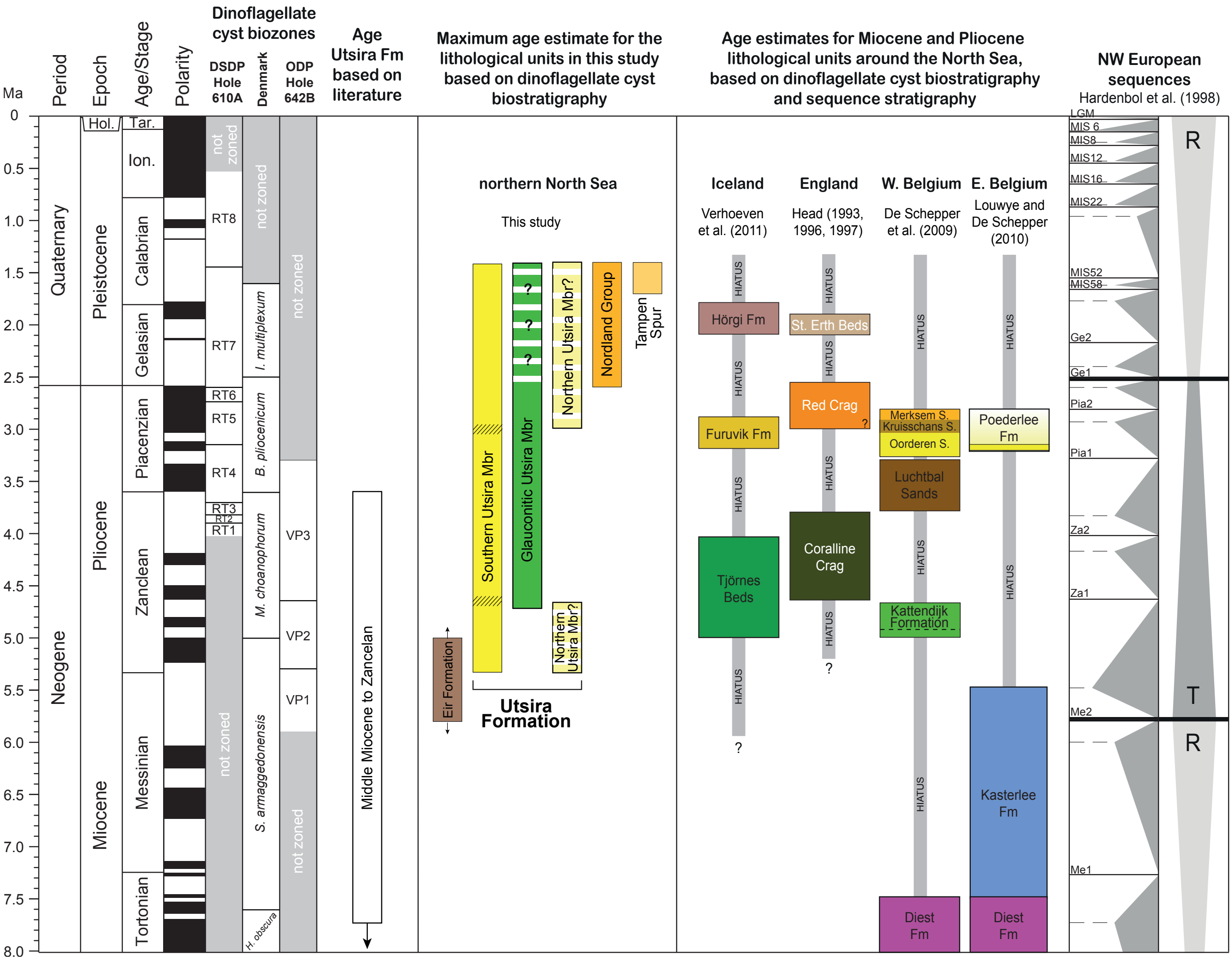

Figure 7. Comparison of the Utsira Formation, and its different members, to the late Neogene shallow-water deposits in the North Sea, North Atlantic and Iceland Sea. The NW European sequence-chronostratigraphic interpretation is after Hardenbol et al. (1998). T and R are transgressive and regressive facies cycles.

Correlating the Utsira Formation with shallow-water Nordic Seas and North Sea deposits

The time of deposition of the Utsira Formation broadly corresponds to that of other shallow-water sediments in the North Sea and Iceland Sea (Fig. 7). The Early Pliocene deposition phase of the Southern Utsira Member was broadly contemporaneous with deposition of the Tjörnes Beds in Iceland, the Coralline Crag in eastern England and the Kattendijk Formation in Belgium. The second, younger depositional phase of the Southern Utsira Member occurs in the Pleistocene, when deposition had ceased in the Belgian part of the North Sea Basin. The St Erth Beds in western England and the Hörgi Formation in Iceland were deposited at around 2.0 Ma (Early Pleistocene). The dating of the Glauconitic Utsira Member and Northern Utsira Member is more uncertain, making correlations with other units more difficult. The Glauconitic Utsira Member could correspond to the Tjörnes Beds, Coralline Crag and Kattendijk Formation, but it may also correspond to Late Pliocene deposits in Iceland (Furuvik Formation) and Belgium (Oorderen Sands and Poederlee Formation). The Northern Utsira Member could be Early Pliocene or Pleistocene, thus making correlations to other units difficult.

Conclusions

We have demonstrated that palynology is a valuable tool for detailed dating, palaeoenvironmental interpretation and understanding the depositional environment in the late Neogene of the North Sea. Specifically, we have provided a better understanding of the stratigraphy of sediments belonging to the Utsira Formation and their relationship with other late Neogene sedimentological units. The dinoflagellate cysts in the thickest part of the Utsira Formation (i.e., the southern distribution area) are most consistent with a Late Miocene/Early Pliocene and Early Pleistocene age (Fig. 2), considerably younger than earlier age estimates based on foraminifera and Sr-isotope ages (e.g., Eidvin et al., 2014b).

The different ages indicate that the Utsira Formation sediments (or its different members) are not part of one depositional cycle. Likely, several depositional phases were interrupted by sea-level lowering as a result of (global) glaciation events during the Pliocene (Fig. 7).

A more precise dating of the Utsira Formation is hampered by:

1 *The use of cutting samples in this study.* Due to the nature of cutting samples, it has not always been clear for each investigated sample whether specimens were caved, reworked or in situ. This has led to questionable age assignments especially in wells where the thickness of Utsira Formation sediments was limited (e.g., well 34/4–6, 34/4–7). As a result, the palynological assemblage of the Northern Utsira and Glauconitic Utsira members contained a mixture of reworked and in situ palynomorphs and dating of these units thus remains tentative.
2 *The 'loose' definition of the Utsira Formation.* The definition of the Utsira Formation is based on identifying the unit boundaries on gamma-ray profiles, which has led to confusion between the Utsira and Skade formations (Isaksen & Tonstad, 1989; Rundberg & Eidvin, 2005; Eidvin et al., 2013). The Utsira Sands were reported in several industry wells in the Tampen area, but problems with injecting drilling muds resulted in incidents at the sea-floor and revealed a poor geological understanding of this unit (Eidvin & Øverland, 2009). The arising problems can be brought back to the loose sense in which this lithological unit has been identified across the Norwegian Shelf and the different facies included in the unit (e.g., Gregersen et al., 1997; Rundberg & Eidvin, 2005). As a consequence, Miocene, Early Pliocene and Pleistocene sediments have been grouped quite commonly within the Utsira Formation. One solution would be to more accurately define the Utsira Formation, with the introduction of different members (Eidvin & Rundberg, 2007; Eidvin et al., 2013, 2014a) being a good first step towards a better understanding of the Utsira Formation. This is crucial since the unit constitutes an important part of the carbon capture storage capacity on the Norwegian Shelf.
3 *The absence of a calibrated Neogene North Sea Basin biostratigraphy.* A continuously cored reference section in the (northern) North Sea with magneto-stratigraphically calibrated biostratigraphy for both organic-walled palynomorphs and calcareous micro-fossils is essential to avoid the use of potentially diachronous bioevents. For this study, we had to rely on the dinoflagellate cyst biostratigraphy from the Nordic Seas and eastern Atlantic Ocean drill sites. The dinoflagellate cyst and acritarch events from those regions have revealed strong asynchrony in both the Early and Late Pliocene (De Schepper et al., 2015, 2017), hampering an unequivocal application of bioevents for dating sedimentary units in the North Sea. Therefore, a reference section in the (northern) North Sea is likely to be the only solution to ultimately clarify the stratigraphic position of the Utsira Formation and its different members. Such a site would become vitally important for establishing a North Sea, Atlantic–Nordic Seas, and even Arctic Ocean stratigraphy.

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