Biostratigraphy and Strontium Isotope Stratigraphy (SIS) of the Skade and Utsira formations in well 16/2-14 (Johan Sverdrup Field)

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For this investigation, micropalaeontological and Sr-isotope analyses for the interval 1210 to 620 m in well 16/2-14 are obtained. 57 ditch cutting samples and nine conventional core samples were analysed (Table 1, Figs. 1-3).

Micropalaeontological analyses
Micropalaeontological investigations were based on analyses of planktonic and benthic foraminifera, *Bolboforma* and pyritized diatoms. The fossil assemblages are correlated with the micropalaeontological zonation for Cenozoic sediments of King (1989). The zonations of planktonic foraminifera (Spiegler and Jansen, 1989; Weaver and Clement 1986) and *Bolboforma* (Spiegler and Müller, 1992; Müller and Spiegler, 1993) from ODP and DSDP drillings in the Norwegian Sea and the North Atlantic are very important for the dating of the sediments. Correlation with these zones yields the most accurate age determinations, because the zones are calibrated with both nannoplankton and palaeomagnetic data.

Lithological analyses
The lithological analyses are based on visual examination of the samples prior to treatment, and the dissolved and fractionated material after preparation.

Sr isotope analyses
Strontium isotope stratigraphy is used as an additional control for the biostratigraphic correlations. The method has best resolution in sediments older than 15 Ma (Howard and McArthur, 1997). For samples with ages younger than eight Ma, the Sr isotope ages have to be treated with more caution. This is due to less variation in the Sr isotopic composition and a relatively flat curve between 2.5 and 4.5 Ma and also to some extent between 5.5 and 8 Ma (Hodell et al., 1991; Farrell et al., 1995; Howard and McArthur, 1997).

26 intervals were investigated for their Sr isotopic compositions with a total of 34 analysed samples (Table 1). The majority (29 samples) was conducted on mollusc fragments and the remainder on of calcareous index foraminifera (5 samples). The analytical work was carried out by the Mass Spectrometry Laboratory at the University of Bergen, Norway. Sr values were converted to age estimates using the strontium isotope stratigraphy look-up table of Howard and McArthur (1997). This table is based on the time scale compiled by Berggren *et al*., (1995), which does not deviate significantly from the time scale of the International Commission on Stratigraphy (ICS, 2013). The most important difference is that the base Pleistocene

has been moved from 1.85 Ma to 2.588 Ma. Please also note that the micropalaeontological zonation of King (1989) and the the plantonic foraminiferal zonation of Spiegler and Jansen (1989) are based on the time scale of Berggren *et al*. (1985), but we have converted the ages to the time scale of Berggren *et al*. (1995). The *Bolboforma* zonation of Spiegler and Müller (1992) and Müller and Spiegler (1993) is based on the time scale of Berggren *et al*. (1995).

The stratigraphy of well 16/2-14 (59° 50' 25.99'' N, 02° 31' 02.20'' E, Fig. 3), is based on analyses of benthic and planktonic foraminifera, *Bolboforma*, pyritised diatoms and Sr isotopes. We recorded 70 m with Upper Oligocene sediments, a 150 m-thick column with Lower Miocene deposits, 60 m with Middle Miocene deposits, 50 m with Upper Miocene sediments, 70 m with Lower Pliocene sediments and a 180 m-thick column with Upper Pliocene (Gelasian; mainly early Pleistocene *sensu* ICS, 2013) deposits. The base of the Lower Oligocene and the top of the Upper Pliocene were not investigated. The ditch-cutting samples were investigated at mainly 10 metres intervals. The core samples were investigated at much smaller intervals (Fig. 3).

The sediments of the sandy Skade and Utsira formations differ from the same units in other wells, we have investigated from the southern Viking Graben, in that these units contain fewer mollusc tests (Eidvin et al. 2013). This may be due to the deeper water depositional environments of the units in well 16/2-14. The scarcity of mollusc tests prevented us from analyzing as many samples for Sr isotopes as desired.

Biostratigraphy

Upper Oligocene (1200-1130 m, Hordaland Group)

Pyritised diatoms of the Diatom sp. 3 assemblage and benthic foraminifera of the *Turrilina alsatica* assemblage, together with one Sr isotope age, date this unit to Late Oligocene (Fig. 3). The planktonic fossil assemblage also contains a few specimens of *G. praebulloides*. In addition to the nominate species, the benthic foraminiferal assemblage also includes *G. soldanii girardana* and *G. subglobosa.* The diatom assemblage is correlated with the upper, main part of Subzone NSP 9c, and the benthic foraminiferal fauna is correlated with Zone NSB 8 of King (1989) from the North Sea.

Lower Miocene (1130-980 m, Hordaland Group including the Skade Formation)

Benthic foraminifera of the *Uvigerina tenuipustulata* assemblage, pyritised diatoms of the Diatom sp. 4 assemblage and planktonic foraminifera of the *Globigerina praebulloides* assemblage and *Globorotalia zealandica – Globigerina angustiumbilicata* assemblage, together with a number of Sr ages, give an Early

Miocene age to this unit (Fig. 3). In addition to the nominate species the benthic foraminiferal fauna includes *A. guerichi staeschei*, *G. subglobosa*, *T. gracilis*, *T. gracilis* var. A and *C. dutemplei.* The *Globigerina praebulloides* assemblage also includes *G. angustiumbilicata* and the *Globorotalia zealandica – Globigerina angustiumbilicata* assemblage also includes *G. praebulloides* and *G. woodi.* The *U. tenuipustulata* assemblage is correlated with Zone NSB 9 and Zone NSB 10, the *Globigerina praebulloides* assemblage and Diatom sp. 4 assemblage are correlated with Zone NSP 10 and the *Globorotalia zealandica – Globigerina angustiumbilicata* assemblage is correlated with Zone NSP 11 of King (1989, North Sea).

Middle Miocene (980-920 m, Nordland Group)

Bolboforma of the *Bolboforma reticulata* assemblage and *Bolboforma badenensis* assemblage and benthic foraminifera of the *Uvigerina tenuipustulata* assemblage (uppermost part) and *Bulimina elongata* assemblage give a Middle Miocene age to this unit (Fig. 3). In addition to the nominate species the *Bolboforma* assemblages also include *B. clodiusi*. The benthic foraminiferal assemblages also include *T. gracilis* and *T. gracilis* var. A. Spiegler and Müller (1982) described a *B. badenensis* Zone and a *B. reticulata* Zone from the North Atlantic and Müller and Spiegler (1993) described a *B. badenensis/B. reticulate* Zone from the Vøring Plateau (Norwegian Sea) in deposits with an age slightly older than 14 to 11.7 Ma. The benthic foraminiferal fauna is probably correlated with the uppermost part of Zone NSB 10, Zone NSN 11 and Zone NSB 12 of King (1989, North Sea).

Upper Miocene (920-870 m, Nordland Group including the lower part of Utsira Formation)

Bolboforma of the *Bolboforma subfragori* assemblage and *Bolboforma metzmacheri* assemblage, planktonic foraminifera of the *Neogloboquadrina atlantica* (dextral) assemblage and benthic foraminifera of the *Uvigerina venusta saxonica* assemblage (lower main part) date this unit to the Late Miocene (Fig. 3). In addition to the nominate species, the benthic foraminiferal assemblage also includes *G. subglobosa* and *M. pseudotepida*. A *B. fragori/B. subfragori* Zone is described from deposits with an age of 11.7-10.3 Ma from the North Atlantic and the Vøring Plateau, and a *B. metzmacheri* Zone is recorded from sediments with an age of 10.0-8.7 Ma from the same areas (Spiegler and Müller, 1992; Müller and Spiegler, 1993). In the upper part of the unit, the late Tortonian (7.5 Ma) transition from dextral to sinistral *N. atlantica* is recorded (Spiegler and Jansen, 1989; King, 1989). The benthic foraminiferal fauna is correlated with Zone NSB 13 of King (1989, North Sea).

Lower Pliocene (870-800 m, Nordland Group including the upper part of Utsira Formation)

Benthic foraminifera of the *Uvigerina venusta saxonica* assemblage (uppermost part) and *Globocassidulina subglobosa* assemblage and planktonic foraminifera of the *Neogloboquadrina atlantica* (sinistral) assemblage together with some Sr isotope ages give an Early Pliocene age to this unit (Fig. 3). In addition to the nominate species the foraminiferal assemblages also include *S. bulloides* and *M. pseudotepida.* The *Uvigerina venusta saxonica* assemblage is correlated with the upper part of Subzone NSB 13b and the *Globocassidulina subglobosa* assemblage is correlated with lower part of Subzone NSB 14a of King (1989, North Sea). Spiegler and Jansen (1989) described a *Neogloboquadrina atlantica* (sinistral) Zone from the Vøring Plateau (Norwegian Sea) from Upper Miocene to Upper Pliocene deposits.

Upper Pliocene (Gelasian, 800-620 m, Nordland Group)

Benthic foraminifera of the *Cibicides grossus* assemblage and *Elphidium excavatum* assemblage and planktonic foraminifera of the *Neogloboquadrina atlantica* (sinistral) assemblage (upper part) and *Globigerina bulloides* assemblage give a Late Pliocene (Gelasian) age (*sensu* Berggren et al., 1995; mainly early Pleistocene *sensu* ICS, 2013) for this unit (Fig. 3). The benthic foraminiferal fauna is correlated with Subzone NSB 15a of King (1989, North Sea). Spiegler and Jansen (1989) described a *N. atlantica* (sinistral) Zone from the Vøring Plateau (Norwegian Sea) from Upper Miocene to Upper Pliocene deposits. The LAD of *N. atlantica* (sinistral) in that area is approximately 2.4 Ma. A *G. bulloides* Zone is described from the North Atlantic (DSDP Leg 94) in Pliocene sediments as young as 2.2 Ma (Weaver and Clement 1986). On the Vøring Plateau, *G. bulloides* is common in Pliocene deposits older than 2.4 Ma (Spiegler and Jansen, 1989). *G. bulloides* is also common in the warmest interglacials of the last 0.5 Ma in the North Atlantic (Kellogg, 1977).

Sr isotope stratigraphy

The obtained $^{87}Sr/^{86}Sr$ ratio from the sample at 1167 m (Table 1, Fig. 3) gave 25.6 Ma (Late Oligocene) and supports the biostratigraphical correlations. Twenty-two samples from the unit which were given an Early Miocene age by the biostratigraphical correlations, corresponding mainly to the Skade Formation (based on both foraminiferal and mollusc tests), gave ages from 24.4 to 15.5 Ma. Most of the ages follow a trend with increasing ages with depth and support the biostratigraphical correlations. However, three ages are obvious based on caved tests (Table 1, Fig. 3).

The part of the well which was given Late Miocene and Early Pliocene ages by the biostratigraphical correlations (Utsira Formation) was investigated with nine samples based on mollusc tests and two samples based on foraminiferal tests. In the upper part of the Utsira Formation, four samples from the uppermost cored section (819.57-817.85 m) gave 4.5, 3.7, 2.7 and 2.3 Ma. These ages show a surprisingly scatter, and since the samples are from a cored section, the two youngest ages (2.7 and 2.3 Ma) can not be explained as caved sample material. Most likely the scatter are due to the fact that the values fall within the flat part of the $^{87}Sr/^{86}Sr$ curve where the corresponding ages are less precise or some analytical error. Similar scattered ages were obtained from a cored section in the uppermost part of the Utsira Formation in well 15/9-A-23 (Eidvin et al., 2013). The oldest ages (4.5 and 3.7 Ma) fits well with the biostratigraphical correlations (Table 1, Fig. 3). In the middle part of the Utsira Formation (860-840 m, ditch cuttings), four samples based on mollusc fragments gave ages from 10.8 to 6.6 Ma. These ages are somewhat older that the ages obtained from the biostratigraphical correlations, but the discrepancy is not so large that is obvious that the sample materials are reworked. In the lower part of the Ursira Formation (890-870 m, ditch cuttings), three samples based on mollusc fragments gave 4.9, 4.0 and 2.2 Ma (Table 1, Fig. 3). All of these samples represent caved material.

Well 16/2-14

Litho. Unit	**Sample**	**Corrected $^{87/86}Sr$**	**2S error**	**Age (Ma)**	**Comments**	**Analysed fossils**
Utsira Fm	817.85 m (core)	0.709054	0.000008	3.68		41 tests of *F. bouanus, C. lobatulus, G. bulloides*, *Elphidium* sp., *C. teretis*, *Fissurina* sp.
Utsira Fm	817.85 m (core)	0.709075	0.000010	2.34	Analytical error	One mollusc fragment
Utsira Fm	819.57 m (core)	0.709067	0.000008	2.73	Analytical error	One mollusc fragment
Utsira Fm	819.57 m (core)	0.709049	0.000009	4.45		53 tests of *F. bouanus, C. lobatulus, G. bulloides*, *Elphidium* sp., *C. teretis*, *Fissurina* sp., *B. tenerrima, T. bradyi*
Utsira Fm	840 m (DC)	0.708875	0.000008	10.52		One mollusc fragment
Utsira Fm	850 m (DC)	0.708882	0.000008	10.26		Two mollusc fragments
Utsira Fm	850 m (DC)	0.708958	0.000008	6.64		Two mollusc fragments
Utsira Fm	860 m (DC)	0.708866	0.000008	10.83		Two mollusc fragments
Utsira Fm	870 m (DC)	0.709080	0.000009	2.18	Caved	Three mollusc fragments
Utsira Fm	880 m (DC)	0.709056	0.000008	3.98	Caved	Two mollusc fragments + one large test of *Nodosaria* sp.
Utsira Fm	890 m (DC)	0.709052	0.000009	4.21	Caved	One mollusc fragment + two large teste of *Q. seminulum*
Nordland Gr	980 m (DC)	0.708765	0.000009	15.51		57 tests of *U. tenuipustulata*
Skade Fm	987.5 m (core)	0.708698	0.000008	16.82		37 tests of *F. bouanus*
Skade Fm	987.5 m (core)	0.708696	0.000009	16.84		One mollusc fragment
Skade Fm	990.6 m (core)	0.708686	0.000008	16.98		35 tests of *F. bouanus, A. guerichi staeschei, B. elongate, E. inflatum, G. angustiumbilicata*
Skade Fm	990.6 m (core)	0.708678	0.000009	17.08		One mollusc fragment

Skade Fm	1000 m (DC)	0.708741	0.000008	16.08		Three mollusc fragments
Skade Fm	1010 m (DC)	0.708678	0.000009	17.08		One mollusc fragment
Skade Fm	1010 m (DC)	0.708839	0.000009	11.80		Two mollusc fragments
Skade Fm	1020 m (DC)	0.708693	0.000008	16.89		Three mollusc fragments
Skade Fm	1030 m (DC)	0.708539	0.000008	18.72		Two mollusc fragments
Skade Fm	1040 m (DC)	0.708677	0.000009	17.09		One mollusc fragment
Skade Fm	1050 m (DC)	0.708443	0.000008	20.25		Two mollusc fragments
Skade Fm	1067 m (DC)	0.708383	0.000009	21.21		Two mollusc fragments
Skade Fm	1068.8 m (core)	0.708549	0.000009	18.58		One mollusc fragment
Skade Fm	1070.88 m (core)	0.708243	0.000009	24.43		One mollusc fragment
Skade Fm	1073.37 m (core)	0.708391	0.000009	21.06		One mollusc fragment
Skade Fm	1090 m (DC)	0.708576	0.000009	18.23		One mollusc fragment
Skade Fm	1090 m (DC)	0.708716	0.000009	16.54	Caved	One mollusc fragment
Skade Fm	1100 m (DC)	0.708627	0.000009	17.65	Caved	One mollusc fragment
Skade Fm	1110 m (DC)	0.708452	0.000009	20.12		One mollusc fragment
Skade Fm	1110 m (DC)	0.708499	0.000008	19.32		Two mollusc fragments
Skade Fm	1120 m (DC)	0.708517	0.000009	19.04		Three mollusc fragments
Hordaland Gr	1167 m (DC)	0.708158	0.000008	25.63		56 tests of *T. alsatica*

Table 1: Strontium isotope data from well 16/2-14. The samples were analysed at the University of Bergen. Sr ratios were corrected to NIST 987 = 0.710248. The numerical ages were derived from the SIS Look-up Table Version 3:10/99 of Howard and McArthur (1997). NIST = National Institute for Standard and Technology.

Lithology

Upper Oligocene to lowermost Lower Miocene (1210 to approximately 1120 m (log), Hordaland Group)

Clay dominates the ditch cuttings in the lower part of the unit. Minor sand and silt are also present in most samples. Sand is more common in the upper part. Glauconite is the dominant mineral in the sand fraction, but quartz is also quite common in some samples (Fig. 3).

Lower Miocene (main part, approximately 1120 m (log) to approximately 985 m (log), Skade Formation)

Medium to fine sand dominates the samples from the Skade Formation. In some parts clay and silt is also quite common. Quartz dominates the sand fraction, but glauconite is common in parts of section. Minor mica is recorded throughout (Fig. 3).

Middle Miocene to lowermost Upper Miocene (approximately 985 m (log) to approximately 903 m (log), Nordland Group)
Clay dominates the Middle Miocene samples. Minor sand and silt are also recorded (Fig. 3).

Upper Miocene to Lower Pliocene (approximately 903 m (log) to approximately 808 m (log), Utsira Formation and Nordland Group)
Sand dominates this unit, but clay and silt are also common in parts of section. The sand fraction is dominated by quartz, but some glauconite and mica are also recorded (Fig. 3).

Upper Pliocene (Gelasian, approximately 808 m (log) to 620 m, Nordland Group)
The ditch cutting samples in the Upper Pliocene (Gelasian) unit contain a clay-rich diamicton with some sand, silt and minor pebbles (Fig. 3).

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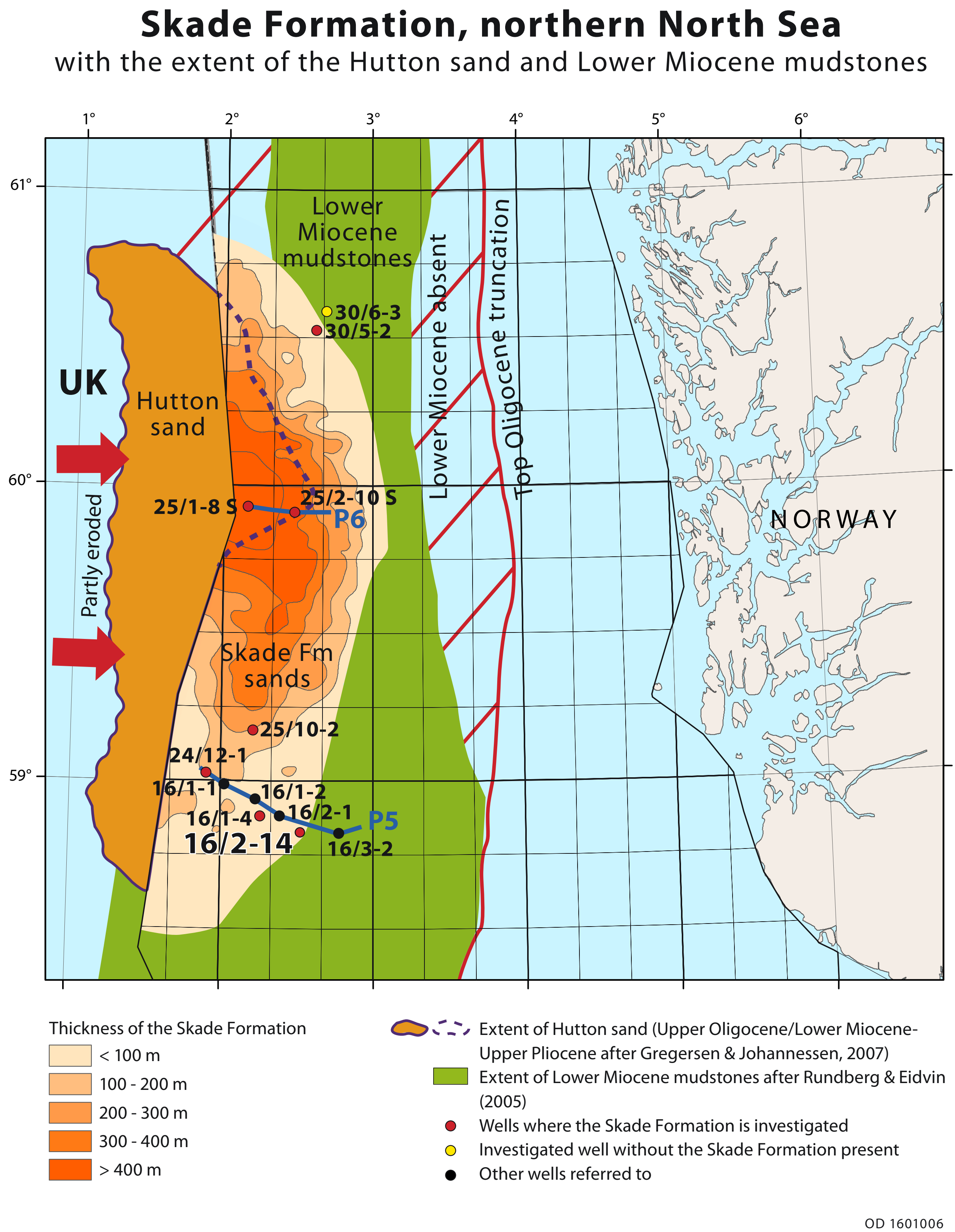


Fig. 1: The location of well 16/2-14 shown on a map showing the thickness of the Lower Miocene Skade Formation in the northern North Sea (modified after NPD, 2011; Eidvin et al., 2013).

Utsira Formation, northern North Sea

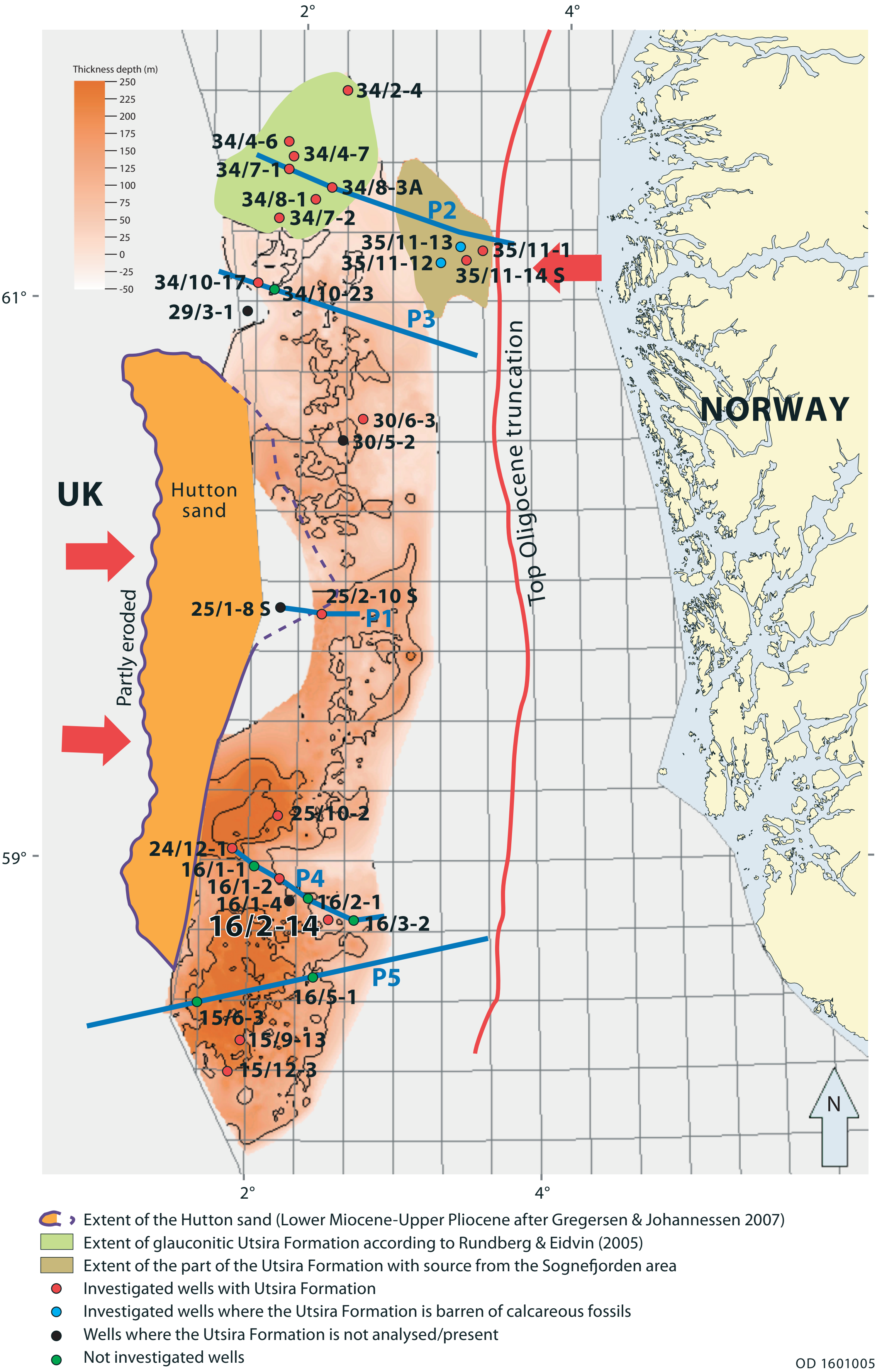
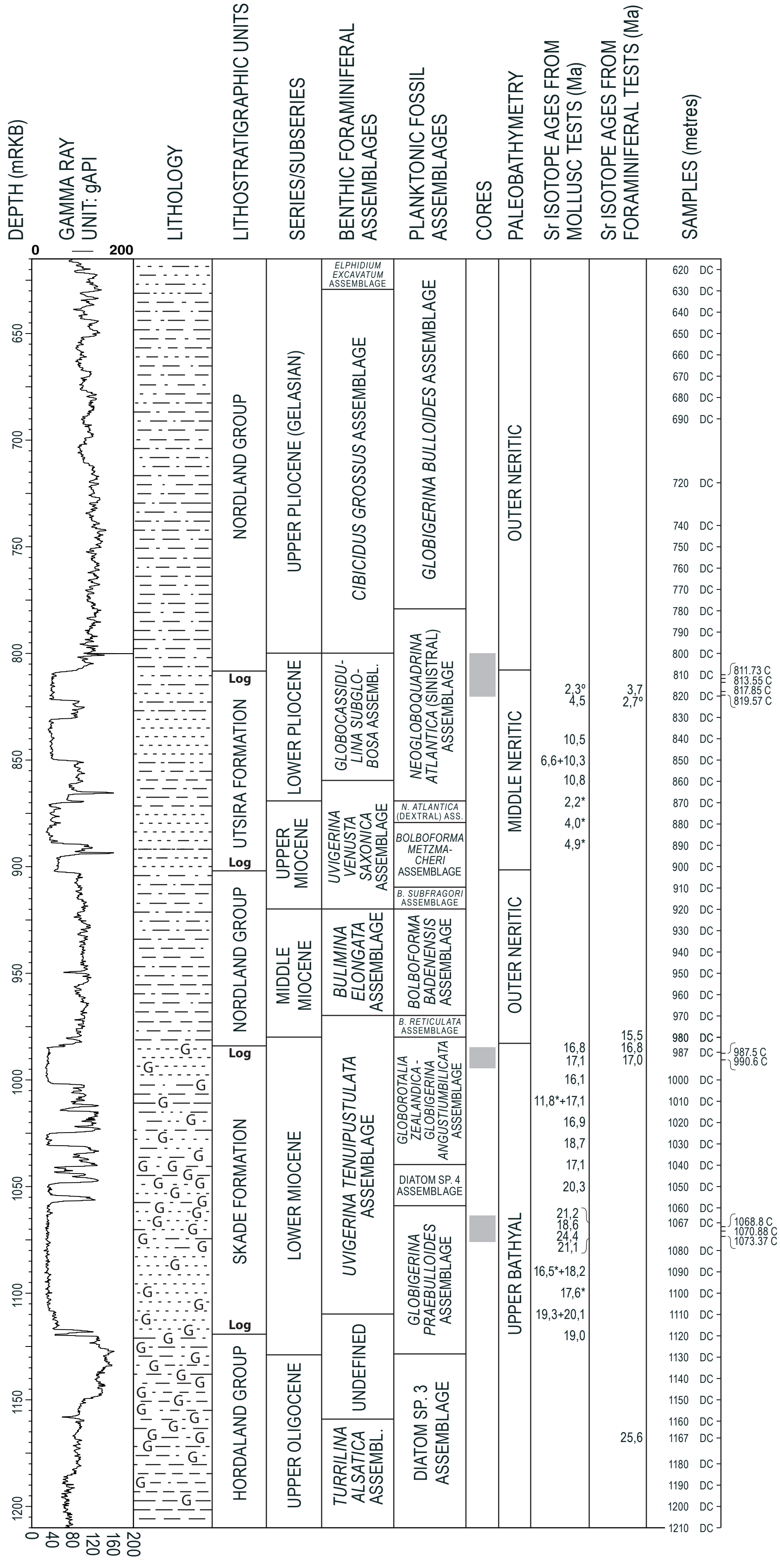


Fig. 2: The location of well 16/2-14 shown on a map showing the thickness of the Upper Miocene-Lower Pliocene Utsira Formation in the northern North Sea (modified after NPD, 2011; Eidvin et al., 2013).

WELL 16/2−14



Sea floor = 113 metres below rig floor (mRKB)
DC = Ditch cuttings
gAPI = American Petroleum Institute gamma ray units
* = Caved
° = Analytical error
C = Core sample
G = Abundant glauconite

Fig. 3: Well summery figure including gamma ray log, lithology, lithostratigraphic units, series/subseries, benthic foraminiferal assemblages, planktonic fossil assemblages, cored sections, paleobathymetry, strontium isotope ages and analysed samples for the investigated sequence in well 16/2-14 (Upper Oligocene to Upper Pliocene (Gelasian)).