Biostratigraphy and Strontium Isotope Stratigraphy (SIS) of the Utsira Formation and overlying Upper Pliocene sandy unit in well 15/9-13 (close to the CO_2 injection site on the Sleipner Field)

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For this study, new micropalaeontological and Sr-isotope analyses for the interval 1110 to 820 m in well 15/9-13 are obtained. 30 ditch cutting samples were analysed (Table 1, Figs. 1 and 2).

Micropalaeontological analyses
Micropalaeontological investigations were based on analyses of planktonic and benthic foraminifera and *Bolboforma*. The fossil assemblages are correlated with the micropalaeontological zonation for Cenozoic sediments of King (1989). Gradstein and Bäckström's (1996) faunal zonation from the North Sea and Haltenbanken is also used. The zonations of planktonic foraminifera (Spiegler and Jansen, 1989) 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).

24 samples were investigated for their Sr isotopic compositions with a total of 53 analyses (Table 1). The majority (48 analyses) was conducted on mollusc fragments and the remainder on of calcareous index foraminifera (5 analyses). 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 micropalaeontological zonation of Gradstein and Bäckström (1996) is based on the time scale of Cande and Kent (1992) in which the absolute ages are identical to those 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 15/9-13 (58º22'25.96"N, 01º56'02.86"E, Fig. 2) is based on correlations of benthic and planktonic foraminifera, *Bolboforma* and Sr isotopes. We have recorded approximately 60 m with Middle Miocene deposits, 110 m with Upper Miocene sediments, 50 m with Lower Pliocene sediments and 40 m with Upper Pliocene deposits (the uppermost part may be of earliest Pleistocene age *sensu* ICS, 2013). Between sandy sections in the Lower and Upper Pliocene there is significant positive peak on the gamma log indicating fine-grained sediment. This bed is not sampled in well 15/9-13, but data from a similar unit in a nearby well indicate an Early Pliocene age (see Eidvin et al., 2013). The base of the Middle Miocene is not shown in the present paper, and the top of the Upper Pliocene were not investigated. The units are investigated with ditch-cutting samples at ten metre intervals (Fig. 2). The interval 1550 to 1110 m (Upper Oligocene to Middle Miocene) is presented in Eidvin et al. (2013).

Biostratigrapy

Middle Miocene (1110-1030 m, Nordland Group and lowermost part of the Utsira Formation)

Benthic foraminifera of the *Florilus bouanus* assemblage (lower main part) and *Bolboforma* of the *Bolboforma badenensis - Bolboforma reticulata* assemblage, together with a Sr isotope age, give a Middle Miocene age to this unit (Fig. 2). The *Florilus bouanus* assemblage is correlated with Zone NSB 12 of King (1989, North Sea). Spiegler and Müller (1992) described a *B. badenensis* Zone and a *B. reticulata* Zone from the North Atlantic in deposits with an age of slightly older than 14 to 11.7 Ma.

Upper Miocene (1030-920 m, Utsira Formation (middle main part))

Benthic foraminifera of the *Florilus bouanus* assemblage (uppermost part), *Uvigerina venusta saxonica - Florilus bouanus* assemblage (lower main part), *Bolboforma* of

the *Bolboforma fragori* assemblage and *Bolboforma metzmacheri* assemblage give a Late Miocene age to this unit (Fig. 2). In addition to the nominate species, the benthic foraminiferal assemblages also include *Globulina subglobosa* (lower part) and *Astigerina guerici staeschei* (throughout). The latter is probably reworked from Lower and Middle Miocene deposits. The *Bolboforma fragori* assemblage also includes *Bolboforma pseudohystrix* (a few specimens) and *Bolboforma clodiusi* (throughout). The benthic foraminiferal assemblages are correlated with Zone NSB 13 of King (1989, North Sea). 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).

Lower Pliocene (920-870 m, Utsira Formation (upper part))

Bentic foraminifera of the *Uvigerina venusta saxonica - Florilus bouanus* assemblage (uppermost part) and *Monspeliensina pseudotepida* assemblage and planktonic foramiminifera of *Neogloboquadrina atlantica* (sinistral) assemblage (lower part) give an Early Pliocene age for this unit (Fig. 2). In addition to the nominate species, the *Uvigerina venusta saxonica - Florilus bouanus* assemblage also includes *A. guerici staeschei* (probably reworked from Lower and Middle Miocene deposits). The upper part of the *Uvigerina venusta saxonica - Florilus bouanus* assemblage is correlated with the upper part of Subzone NSB 13a and the *Monspeliensina pseudotepida* assemblage is correlated with lower part of Zone NSB 14 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.

Undefined interval (870-860 m, Nordland Group)

The un-sampled positive gamma log peak between the samples at 870 and 860 m obviously consists of fine-grained sediments (Fig. 2). A sample from a similar fine-grained unit, just above the Utsira Formation, in the nearby well 15/12-3 contains Early Pliocene foraminifera (Eidvin and Rundberg, 2007; Eidvin et al., 2013).

Upper Pliocene (860-820 m, Nordland Group)

Benthic foraminifera of the *Cibicides grossus- Elphidiella hannai* assemblage and planktonic foramiminifera of the *Neogloboquadrina atlantica* (sinistral) assemblage (upper part) give a Late Pliocene age (on the time scale of Berggren et al., 1995) for this unit (Fig. 2). A few specimens of *M. pseudotepida* and *F. bouanus* indicate some reworking from the Utsira Formation. The benthic foraminiferal fauna is correlated with Subzone NSB 15a of King (1989, North Sea) and Zone NSR 12 of Gradstein and Bäckström (1996, North Sea and Haltenbanken area). The LAD of *N. atlantica*

on the Vøring Plateau is approximately 2.4 Ma according to Spiegler and Jansen (1989).

Sr isotope stratigraphy

Most of the analysed samples in well 15/9-13 were taken from the sandy Utsira Formation, which was given a late Middle Miocene to Early Pliocene age by the biostratigraphical correlation (Fig. 2). A large number of the mollusc samples gave late Early Miocene ages indicating reworking from the Skade Formation, and a significant number of the mollusc samples gave Early and Late Pliocene ages indicating caving within the Utsira Formation and from the sandy unit just above. Some of the analysed foraminiferal tests also gave ages indicating both reworking and caving. We have listed the results off all of the analyses in Table 1. However, in Fig. 2 we have only included Sr data from tests interpreted to be *in situ* or close to *in situ*. We have also recorded common reworked and caved fossil tests from the Utsira Formation in most of the other wells we analysed, but rarely or never to the same extent (Eidvin et al., 2013).

Utsira Formation samples, which we interpret to be *in situ* or close to *in situ*, include a mollusc sample from 1040 m (upper part of the unit) corresponding to the *Bolboforma badenensis - Bolboforma reticulata* assemblage (Fig. 2). This sample gave an age of 12.2 Ma. The biostratigraphic correlation indicates an age of slightly more than 14 to 11.7 Ma. Two samples from 950-930 m, within the unit corresponding to the *Bolboforma metzmacheri* assemblage, gave 11.5 and 10.2 Ma. The biostratigraphic correlation indicates an age of 10.0-8.7 Ma. Five samples, based on mollusc fragments, from the upper part of the Utsira Formation gave ages from 5.7 to 4.4 Ma confirming an Early Pliocene age indicated by the biostratigraphic correlations (Fig. 2).

Eight samples based on mollusc fragments were taken from three levels in the sandy unit close to the base of the section given a Late Pliocene age by the biostratigraphic correlations. The obtained 87Sr/86Sr ratios displayed some scatter yielding ages from 4.6 to 4.2 Ma in the lowermost sampled level and from 4.0 to 1.7 Ma in the uppermost level (Fig. 2, Table 1). The variation could be explained from the fact that most of the values fall within the flat part of the $^{87}Sr/^{86}Sr$ curve where the corresponding ages are less precise (Hodell et al., 1991; Farrell et al., 1995; Howard and McArthur 1997). It is not likely that the mollusc fragments showing the youngest ages indicate caving since the clay-rich diamicton immediately above is sparse on molluscs. One can't exclude that the mollusc fragments showing the oldest ages indicate reworking from the Utsira Formation since it is likely that a few of the foraminifera originate from that formation (see above). Mean age of all eight samples is approximately 3.3 Ma (Late Pliocene), and mean age of the six uppermost samples is approximately 2.9 Ma (Late Pliocene).

Well 15/9-13

Litho. Unit	Sample (DC)	Corrected $^{87/86}Sr$	2S error	Age (Ma)	Comments	Analysed fossils
Nordlland Gr	840 m	0.709056	0.000008	3.98		One mollusc fragment
Nordlland Gr	840 m	0.709062	0.000008	3.45		One mollusc fragment
Nordland Gr	840 m	0.709096	0.000008	1.66		One mollusc fragment
Nordland Gr	850 m	0.709073	0.000008	2.41		One mollusc fragment
Nordland Gr	850 m	0.709077	0.000008	2.27		One mollusc fragment
Nordland Gr	850 m	0.709062	0.000007	3.45		One mollusc fragment
Nordland Gr	860 m	0.709052	0.000009	4.21		One mollusc fragment
Nordland Gr	860 m	0.709046	0.000009	4.64		One mollusc fragment
Utsira Fm	870 m	0.709050	0.000009	4.38		One mollusc fragment
Utsira Fm	870 m	0.708666	0.000008	17.22	Reworked	One mollusc fragment
Utsira Fm	880 m	0.709042	0.000008	4.82		One mollusc fragment
Utsira Fm	890 m	0.708673	0.000009	17.14	Reworked	One mollusc fragment
Utsira Fm	890 m	0.709046	0.000007	4.64		One mollusc fragment
Utsira Fm	890-900 m	0.708924	0.000008	8.48	Reworked	Approximately 40 testes of *F. boueanus*
Utsira Fm	900 m	0.709056	0.000009	3.98	Caved	One mollusc fragment
Utsira Fm	900 m	0,708711	0.000008	16.62	Reworked	One mollusc fragment
Utsira Fm	910 m	0.709036	0.000008	5.03		One mollusc fragment
Utsira Fm	910 m	0.709010	0.000009	5.69		One mollusc fragment
Utsira Fm	910-920 m	0.708877	0.000008	10.44	Reworked	34 testes of *F. boueanus*
Utsira Fm	920 m	0.708807	0.000009	13.45	Reworked	One mollusc fragment
Utsira Fm	920 m	0.709041	0.000009	4.86	Caved	One mollusc fragment
Utsira Fm	930 m	0.708542	0.000009	18.68	Reworked	One mollusc fragment
Utsira Fm	930 m	0.709057	0.000009	3.89	Caved	One mollusc fragment
Utsira Fm	930-940 m	0.708884	0.000008	10.19		Approximately 50 testes of *F. boueanus*
Utsira Fm	940 m	0.709034	0.000009	5.08	Caved	One mollusc fragment
Utsira Fm	940 m	0.708730	0.000009	16.30	Reworked	One mollusc fragment
Utsira Fm	950 m	0.708792	0.000009	14.56	Reworked	One mollusc fragment
Utsira Fm	950 m	0.709036	0.00000008	5.03	Caved	One mollusc fragment
Utsira Fm	950 m	0.708845	0.000009	11.52		36 testes of *F. boueanus*
Utsira Fm	960 m	0.709070	0.000009	2.52	Caved	One mollusc fragment
Utsira Fm	960 m	0.708752	0.000008	15.83	Reworked	One mollusc fragment
Utsira Fm	960-970 m	0.708771	0.000007	15.34	Reworked	20 testes of *F. boueanus*
Utsira Fm	970 m	0.708604	0.000009	17.91	Reworked	One mollusc fragment
Utsira Fm	970 m	0.708680	0.000010	17.06	Reworked	One mollusc fragment
Utsira Fm	980 m	0.708918	0.000009	8.79	Caved	One mollusc fragment
Utsira Fm	980 m	0.709035	0.000008	5.06	Caved	One mollusc fragment
Utsira Fm	990 m	0.708660	0.000009	17.29	Reworked	One mollusc fragment
Utsira Fm	990 m	0.708686	0.000008	16.98	Reworked	One mollusc fragment
Utsira Fm	1000 m	0.708674	0.000008	17.13	Reworked	One mollusc fragment
Utsira Fm	1000 m	0.708677	0.000008	17.09	Reworked	One mollusc fragment
Utsira Fm	1010 m	0.708761	0.000008	15.34	Reworked	One mollusc fragment
Utsira Fm	1010 m	0.709031	0.000008	5.16	Caved	One mollusc fragment
Utsira Fm	1020 m	0.708490	0.000008	19.47	Reworked	One mollusc fragment
Utsira Fm	1020 m	0.708677	0.000009	17.09	Reworked	One mollusc fragment
Utsira Fm	1030 m	0.708751	0.000008	15.85	Reworked	One mollusc fragment
Utsira Fm	1030 m	0.708784	0.000008	14.91	Reworked	One mollusc fragment
Utsira Fm	1040 m	0.708832	0.000008	12.16		One mollusc fragment
Utsira Fm	1040 m	0.708663	0.000008	17.25	Reworked	One mollusc fragment
Utsira Fm	1050 m	0.708933	0.000008	7.69	Caved	One mollusc fragment
Utsira Fm	1050 m	0.709055	0.000009	4.09	Caved	One mollusc fragment
Nordland Gr	1060 m	0,709059	0.000009	3.68	Caved	One mollusc fragment
Nordl. Gr	1060 m	0.709051	0.000009	4.30	Caved	One mollusc fragment
Nordland Gr	1110 m	0.708871	0.000008	10.66	Caved	Approximately 50 tests of *B. badenensis* and *B. clodiusi*

Table 1: Strontium isotope data from well 15/9-13. 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

Middle Miocene (approximately 1110 to approximately 1055 m, Nordland Group) This unit is dominated by clay with minor sand and silt (Fig. 2).

Uppermost part of the Middle Miocene to Lower Pliocene (approximately 1055 to 870 m, Utsira Formation)
Light grey sand dominates the Utsira Formation. The sand contains mainly quartz grains, but some glauconite and mica grains are also present. Mollusc fragments are common in the middle and upper parts (Fig. 2).

Undefined interval (870-860 m, Nordland Group)
The positive gamma log peak between the samples at 870 and 860 m indicates that there is a bed with fine-grained sediments between the sandy Utsira Formation and a sandy unit in lower part of the Upper Pliocene (Fig. 2).

Upper Pliocene (860-820 m, Nordland Group) The lowermost approximately 10 metres is composed of sand similar to the Utsira Formation below, and as that unit contains common molluscs (Fig. 2). According to Hermanrud et al. (2008) a large proportion of the injected CO_2 is concentrated in this interval. This sandy unit is not recorded in the nearby well 15/12-3. The upper part of Upper Pliocene section contains a clay-rich diamicton with some sand and silt and minor pebbles.

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Utsira Formation, northern North Sea

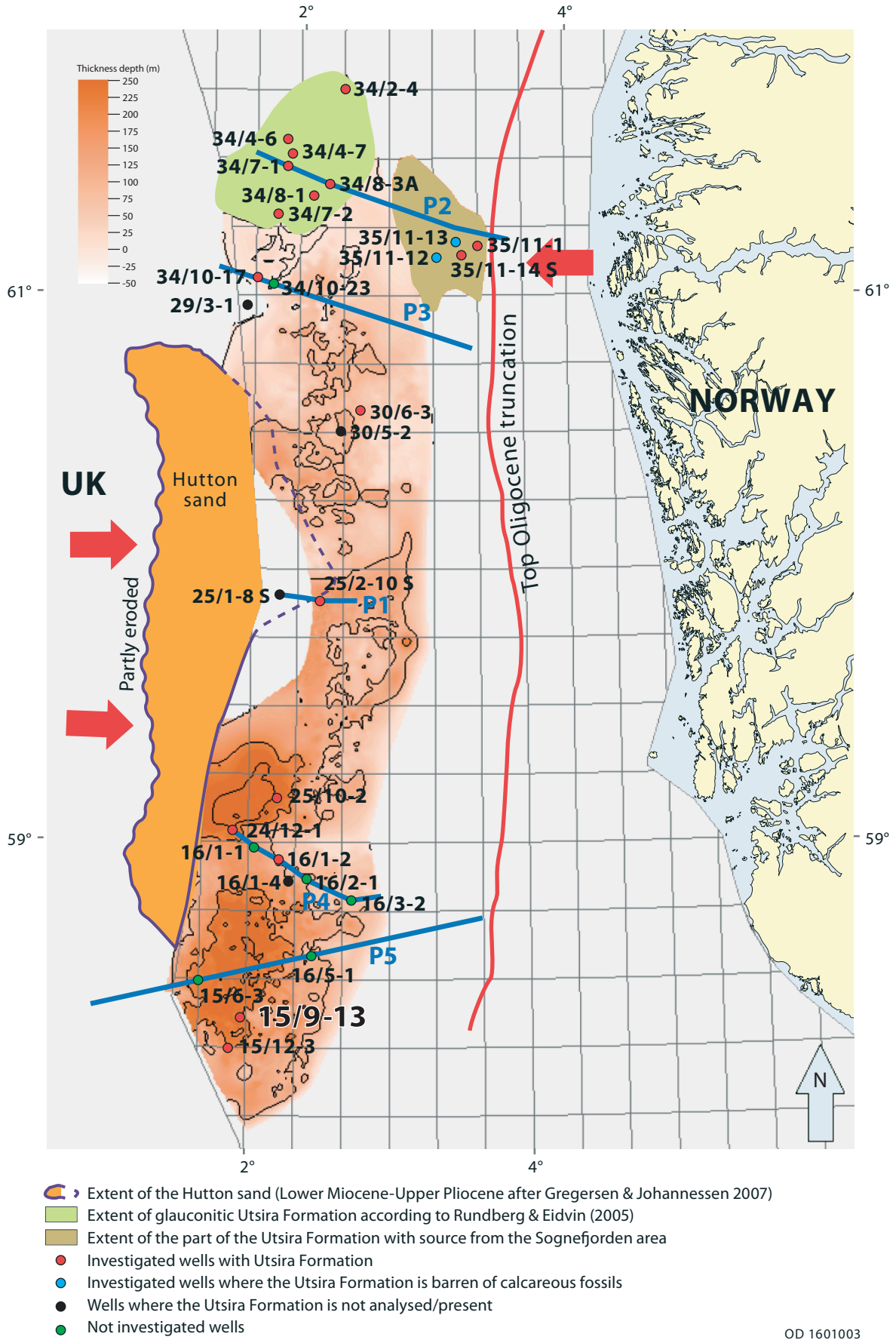
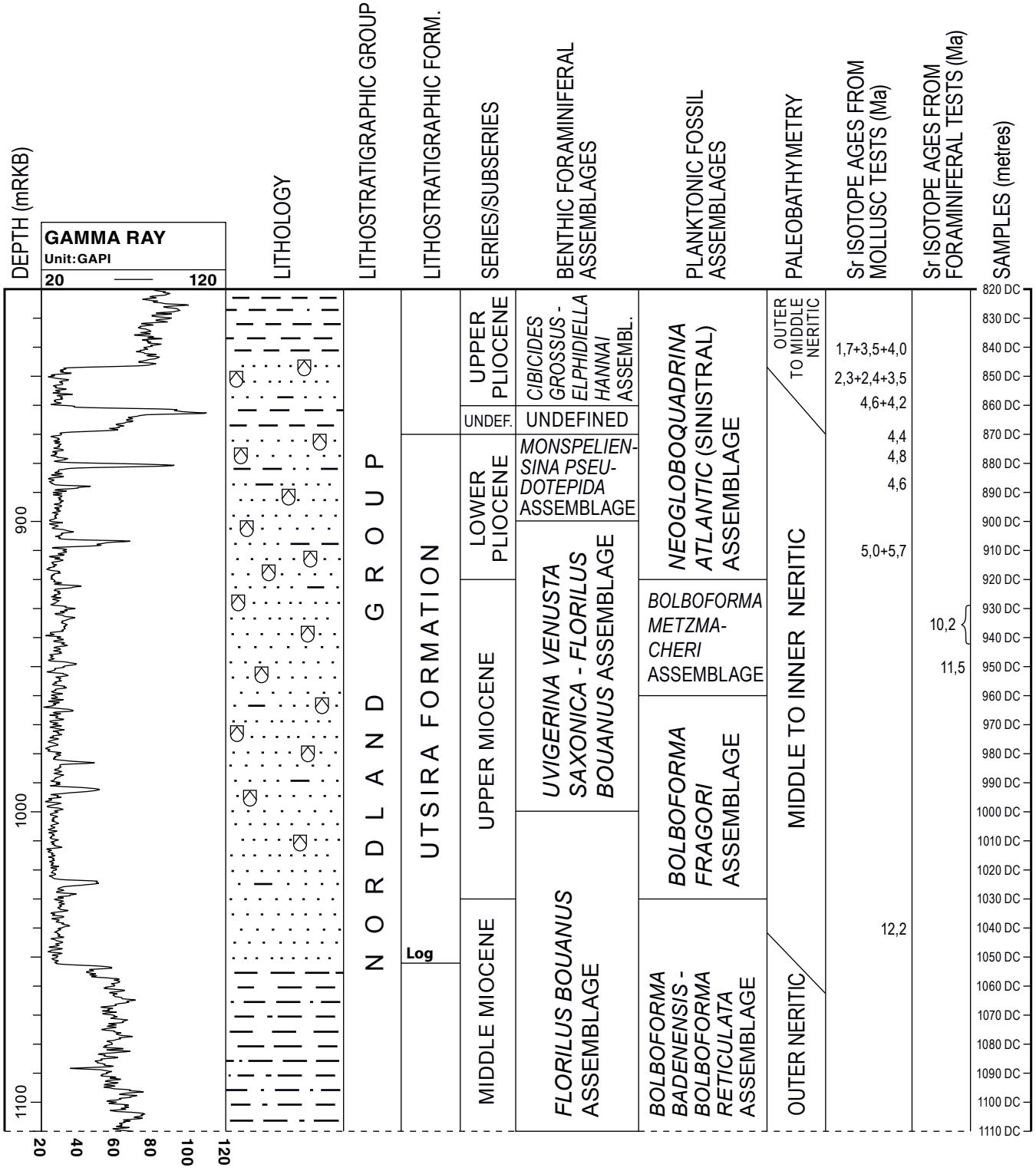


Fig. 1: The Location of well 15/9-13 shown on a map showing the thickness of the Upper Miocene-Lower Pliocene Utsira Formation in the Northern North Sea (modified after NPD, 2011; Eidvin et al., 2013).

WELL 15/9-13



OD 1409004

Sea floor = 107 metres below rig floor (mRKB)
DC = Ditch cuttings
gAPI = American Petroleum Institute gamma ray units
⦰ = Abundant molluscs or mollusc fragments

Fig. 2: Well summery figure including gamma ray log, lithology, lithostratigraphic units, series/subseries, benthic foraminiferal assemblages, planktonic fossil assemblages, paleobathymetry, strontium isotope ages and analysed samples for the investigated sequence in well 15/9-13 (Middle Miocene to Upper Pliocene). See Fig. 1 for location.