Biostratigraphy and Strontium Isotope Stratigraphy (SIS) of well 26/10-1 (Zulu gas discovery) including the Skade, Eir (informal) and Utsira formations

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For this investigation, micropalaeontological and Sr-isotope analyses for the interval 1025 to 750 m in well 26/10-1 are obtained. 42 ditch cutting samples were analysed (Table 1, Figs. 1 and 2).

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 also very important for the dating of the sediments since these 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 (SIS) 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).

23 intervals were investigated for their Sr isotopic compositions with a total of 55 analysed samples (Table 1). The majority (48 samples) was conducted on mollusc fragments and the remainder on of calcareous index foraminifera and *Bolboforma* (seven samples). However, the Utsira and Skade formations, which usually are quite rich on mollusc fragments, are quite poor on such in well 26/10-1. 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 new time scale of Cohen *et al.* (2016). The most important difference is that the base Pleistocene has been moved from 1.85 Ma to 2.588 Ma. There exist no strontium isotope stratigraphy look-up table based on the time scale of Cohen et al. (2016). Please also note that the micropalaeontological zonation of King (1989) and the the planktonic 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).

Stratigraphy of well 26/10-1 (59° 0' 1.86'' N, 3° 4' 14.69'' E, Fig. 1)
There are recorded 119 m of Lower Miocene sediments, 81 m of Middle Miocene deposits, 6 m of Upper Miocene sediments, 18 m of Upper Miocene-Lower Pliocene sediments and 51 m of Upper Pliocene (mainly Pleistocene *sensu* Cohen *et al.* (2016)) deposits. The base of the Lower Miocene and the top of the Upper Pliocene/Pleistocene were not sampled. The ditch-cutting samples were investigated at nine to three metres intervals (Fig. 2).

Biostratigraphy

Lower Miocene (1025-906 m, Hordaland Group including the Skade Formation)

Benthic foraminifera of the *Uvigerina tenuipustulata-Astigerina guerichi staeschei* assemblage, pyritized diatoms of the Diatom sp. 4 assemblage and planktonic foraminifera of the *Globorotalia zealandica-Globigerina angustiumbilicata* assemblage, together with five Sr ages give an Early Miocene age to this unit (Fig. 2). In addition to the nominate species the benthic foraminiferal fauna also includes *Bulimina elongata*, *Trifarina gracilis* var. A, *Elphidium inflatum* (few), *Bolivina cf. antiqua* (few) and *Rolfina arnei* (few in the lowermost sample). A few specimens of *Gyroidina soldanii girardana* are also recorded, but these are probably reworked from Oligocene sediments. The *Globorotalia zealandica-Globigerina angustiumbilicata* assemblage also includes *Globigerina praebulloides* and *Globigerina woodi* (few). The *Uvigerina tenuipustulata-Astigerina guerichi staeschei* assemblage is correlated with Zone NSB 9 and Zone NSB 10, the Diatom sp. 4 assemblage is correlated with Zone NSP 10 and the *Globorotalia zealandica-Globigerina angustiumbilicata* assemblage is correlated with Zone NSP 11 of King (1989) from the North Sea.

Middle Miocene (906-825 m, Nordland Group including the Eir formation (informal)

Bolboforma of the *Bolboforma badenensis* assemblage benthic foraminifera of the *Trifarina gracilis-Trifarina gracilis* var. A assemblage and *Bulimina elongata* assemblage give a Middle Miocene age to this unit (Fig. 2). In addition to the

nominate species the *Bolboforma badenensis* assemblage also includes *Bolboforma clodiusi, Bolboforma reticulata* (few) and *Bolboforma pseudohystrix*. The benthic foraminiferal assemblages also include *Florilus boueanus*, *Cibicides dutemplei*, *Sphaeroidina bulloides* and *B. elongata*. 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. reticulata* 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 (825-819 m, Nordland Group including the lower part of Utsira Formation)

Bolboforma of the *Bolboforma subfragori* assemblage date this unit to the Late Miocene (Fig. 2). In addition to the nominate species, *Bolboforma subfragori* assemblage also includes *B. clodiusi, B. badenensis* (few) and *B. reticulata* (few). The two latter are probably reworked from Middle Miocene deposits.

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 (Spiegler and Müller, 1992; Müller and Spiegler, 1993).

Upper Miocene-Lower Pliocene (819-801 m, Nordland Group including the upper, main part of Utsira Formation)

Benthic foraminifera of the *Florilus boueanus* assemblage and planktonic foraminifera of the *Globigerina bulloides* assemblage (lower main part) give a general Late Miocene to Early Pliocene age to this unit (Fig. 2). In addition to the nominate species, the benthic foraminiferal assemblage also includes *Uvigerina venusta saxonica*, *S. bulloides* (few) and *C. dutemplei* (few). The *Globigerina bulloides* assemblage also includes *Neogloboquadrina atlantica* (sinistral; few) and *Neogloboquadrina atlantica* (dextral; few). The benthic foraminiferal fauna is correlated with Subzone NSB 13b and Subzone NSB 12a of King (1989; North Sea).

Spiegler and Jansen (1989) described a lower *N. atlantica* (dextral) Zone from Upper Miocene sediments on the Vøring Plateau (Norwegian Sea). However, Spiegler and Jansen (1989) also described an upper *N. atlantica* (dextral) Zone from the Upper Pliocene. Consequently, caved specimens of *N. atlantica* (dextral) can be recorded in the Lower Pliocene and Upper Miocene. *G. bulloides* occurs through the Upper Miocene and Lower Pliocene and into the Upper Pliocene (Weaver, 1987; Weaver and Clement, 1987; Spiegler and Jansen, 1989; Norwegian Sea and North Atlantic).

Upper Pliocene (mainly Gelasian, 801-750 m, Nordland Group (Naust Formation equivalent))

Benthic foraminifera of the *Cibicides grossus* assemblage and planktonic foraminifera of the *Globigerina bulloides* assemblage (uppermost part) and *Globigerina bulloides-Neogloboquadrina pachyderma* (dextral) assemblage give a Late Pliocene (mainly Gelasian age (*sensu* Berggren *et al*., 1995; mainly early Pleistocene *sensu* Cohen *et al*. (2016)) for this unit (Fig. 2). In addition to the nominate species, the benthic foraminiferal assemblage also includes *Elphidiella hannai* (few). The benthic foraminiferal fauna is correlated with Subzone NSB 15a of King (1989, North Sea).

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/Pleistocene deposits older than 2.4 Ma (Spiegler and Jansen, 1989; ODP Leg 104). A *N. pachyderma* (dextral) Zone is described by King (1989) for the North Sea, by Weaver (1987) and Weaver and Clement (1986) from the North Atlantic and by Spiegler and Jansen (1989) from the Vøring Plateau. On the Vøring Plateau the zone is dated to 1.9-1.8 Ma.

Sr isoptope stratigraphy

Most of the analysed samples in well 26/10-1 were taken from the sandy Skade and Utsira formations and sandy to clayey lower part of the Nordland Group (including the sandy Eir formation (informal, see Eidvin *et al*., 2013)). The obtained ages show that an unusual large proportion of the material is caved. The biostratigraphical correlations gave an Early Miocene age to the Skade Formation, a Middle Miocene age to the lower part of the Nordland Group and Late Miocene-Early Pliocene age to the Utsira Formation. Most of the analyses of the mollusc fragments, from all parts, gave Late Miocene or younger ages. We have listed the results of all of the analyses in Table 1. However, in Fig. 2 and in the discussion below, we have only included Sr data from tests interpreted to be *in situ* or close to *in situ*.

Most of the nine samples taken from the Utsira Formation are probably originate from the Naust Formation equivalent. One analysis of a mollusc fragment from 819 m (lower part of the Utsira Formation) gave ca. 9.5 Ma and three fragment from 825 m, immediately bellow the Utsira Formation, gave ca. 7.5 Ma (Table 1, Fig. 2).

Samples from 843 m and 852 m, both which are based on foraminiferal test, gave 10.8 and 10.4 Ma respectively (Table 1, Fig. 2). These samples are from the upper part of the lower Nordland Group unit which was given a Middle Miocene age by the biostratigraphical correlations. The Middle/Late Miocene boundary is at 11.2 Ma according to Berggren *et al.* (1995). The obtained Sr ages are within the precision of the method.

Two samples from 915 m and one sample from 924 m, all based on foraminiferal tests, gave 15.9, 16.4 and 16.3 Ma respectively (Table 1, Fig. 2). These samples are from the upper part of the Skade Formation which was given an Early Miocene age by the biostratigraphical correlations. The Early/Middle Miocene boundary is at 16.4 Ma according to Berggren et al. (1995), consequently the Sr ages are very close to the ages obtained by the biostratigraphical correlations.

One sample from 942 m, based on a mollusc fragment, gave 17.8 Ma (Table 1, Fig. 2). This sample is from the upper half of the Skade Formation, given an Early Miocene age by the biostratigraphical correlations. Consequently, the Sr age support the biostratigraphical correlations.

One sample from 1025 m, based on foraminiferal tests, gave 18.3 Ma (Table 1, Fig. 2). The sample is from the Hordaland Group below the Skade Formation, given an Early Miocene age by the biostratigraphical correlations (the base of the Lower Miocene was not sampled). The Sr age support the biostratigraphical correlations.

Well 26/10-1

Litho. Unit	Sample (DC)	Corrected $^{87/86}$Sr	2S error	Age (Ma)	Comments	Analysed fossils
Utsira Fm	804 m	0.709200	0.000009	0	Caved	One mollusc fragment
Utsira Fm	804 m	0.709188	0.000008	0	Caved	Two mollusc fragment
Utsira Fm	807 m	0.709207	0.000008	0	Caved	One mollusc fragment
Utsira Fm	810 m	0.709069	0.000009	2.57	Caved	Two mollusc fragment
Utsira Fm	816 m	0.709106	0.000008	1.436	Caved	Two mollusc fragment
Utsira Fm	819 m	0.708901	0.000009	9.51		One mollusc fragment
Utsira Fm	819 m	0.709075	0.000008	2.34	Caved	One mollusc fragment
Utsira Fm	822 m	0.709185	0.000009	0	Caved	One mollusc fragment
Utsira Fm	822 m	0.709055	0.000009	4.09	Caved	One mollusc fragment
Nordland Gr	825 m	0.708928	0.000009	7.52		Three mollusc fragment
Nordland Gr	825 m	0.709153	0.000009	0.645	Caved	One mollusc fragment
Nordland Gr	825 m	0.709039	0.000008	4.94	Caved	One mollusc fragment
Nordland Gr	825 m	0.709000	0.000009	5.83	Caved	Three mollusc fragment
Nordland Gr	843 m	0.708897	0.000013	9.67	Caved	Ca. 30 tests of *T. gracilis* var. A
Nordland Gr	843 m	0.708867	0.000013	10.80		Ca. 45 tests of *B. badenensis, B. clodiusi*
Nordland Gr	852 m	0.708877	0.000010	10.44		Ca. 30 tests of *T. gracilis* var. A, 50 tests of *B. badenensis* and *B. clodiusi*
Eir fm	867 m	0.708928	0.000008	8.27	Caved	One mollusc fragment
Eir fm	867 m	0.708916	0.000008	8.87	Caved	One mollusc fragment
Eir fm	870 m	0.708922	0.000008	8.58	Caved	One mollusc fragment
Eir fm	870 m	0.708918	0.000009	8.79	Caved	One mollusc fragment
Eir fm	873 m	0.708902	0.000008	9.47	Caved	One mollusc fragment
Eir fm	873 m	0.708908	0.000009	9.21	Caved	One mollusc fragment
Nordland Gr	876 m	0.708899	0.000009	9.59	Caved	One mollusc fragment
Nordland Gr	876 m	0.708913	0.000008	9.00	Caved	One mollusc fragment
Nordland Gr	876 m	0.708917	0.000009	8.83	Caved	One mollusc fragment
Nordland Gr	879 m	0.708913	0.000007	9.00	Caved	One mollusc fragment
Nordland Gr	879 m	0.708902	0.000008	9.47	Caved	One mollusc fragment
Skade Fm	915 m	0.708920	0.000008	8.69	Caved	One mollusc fragment
Skade Fm	915 m	0.708911	0.000008	9.09	Caved	One mollusc fragment

Skade Fm	915 m	0.708939	0.000009	7.39	Caved	One mollusc fragment
Skade Fm	915 m	0.708747	0.000018	15.94		Ca. 21 tests of *U. tenuipustulata*, *A. guerichi staeschei*
Skade Fm	915 m	0.708725	0.000009	16.39		Ca. 56 tests of *G. angustiumbilicata*, *G. praebulloides*, *G. zealandica*
Skade Fm	924 m	0.709043	0.000009	4.78	Caved	One mollusc fragment
Skade Fm	924 m	0.709040	0.000009	4.90	Caved	Two mollusc fragment
Skade Fm	924 m	0.709030	0.000008	5.18	Caved	Three mollusc fragment
Skade Fm	924 m	0.708729	0.000010	16.32		Ca. 35 tests of *G. angustiumbilicata*
Skade Fm	933 m	0.709016	0.000007	5.56	Caved	One mollusc fragment
Skade Fm	933 m	0.709030	0.000009	5.18	Caved	One mollusc fragment
Skade Fm	933 m	0.708957	0.000009	6.68	Caved	One mollusc fragment
Skade Fm	942 m	0.708617	0.000008	17.76		One mollusc fragment
Skade Fm	942 m	0.708979	0.000009	8.83	Caved	Two mollusc fragment
Skade Fm	942 m	0.709033	0.000009	5.11	Caved	Three mollusc fragment
Skade Fm	951 m	0.708898	0.000009	9.63	Caved	One mollusc fragment
Skade Fm	951 m	0.708902	0.000007	9.47	Caved	One mollusc fragment
Skade Fm	951 m	0.708900	0.000008	9.55	Caved	One mollusc fragment
Skade Fm	960 m	0.708981	0.000008	6.06	Caved	Three mollusc fragment
Skade Fm	960 m	0.708934	0.000009	7.62	Caved	Four mollusc fragment
Skade Fm	960 m	0.708933	0.000008	7.69	Caved	Three mollusc fragment
Skade Fm	969 m	0.709056	0.000008	3.98	Caved	One mollusc fragment
Skade Fm	969 m	0.708941	0.000008	7.32	Caved	Three mollusc fragment
Skade Fm	969 m	0.709024	0.000008	5.35	Caved	One mollusc fragment
Skade Fm	978 m	0.708915	0.000008	8.92	Caved	One mollusc fragment
Skade Fm	978 m	0.708931	0.000007	7.95	Caved	Two mollusc fragment
Skade Fm	978 m	0.708915	0.000009	8.92	Caved	Three mollusc fragment
Hordaland Gr	1025 m	0.708568	0.000021	18.33		Ca. 27 testes of *T. gracilis* var. A

Table 1: Strontium isotope data from well 26/10-1. 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

Lower Miocene (lower part, 1025 m to approximately 987 m (log), Hordaland Group)
Clay dominates the ditch cutting samples in the lower part of the unit, but sand and silt are also quite common. Sand is even more common in the upper part. Glauconite is the dominant mineral in the sand fraction except for the in uppermost part where quartz is dominant (Fig. 2). However, some of the quartz grains are probably caved from the overlying Skade Formation.

Lower Miocene (main part, approximately 987 m (log) to approximately 906 m (log), Skade Formation of the Hordaland Group)
Medium to fine sand dominates the samples from the Skade Formation. Quartz is the dominant mineral with minor glauconite (Fig. 2). Glauconite is somewhat more common in the uppermost part of the unit, but this is probably caved from the overlying Middle Miocene Nordland Group.

Middle Miocene (approximately 906 (log) to approximately 825 m (log), lower part of the Nordland Group including the Eir formation (informal)
The samples in this unit contain sand, silt and clay. Sand is dominant in the Eir formation (informal) in the middle part of the unit (approximately 876 m (log) to approximately 867 m (log)). Sand is also quite common below and above the Eir formation. Quartz is the dominant mineral with minor glauconite in the Eir formation

(Fig. 2). Below and above the Eir formation both glauconite and quartz are common with minor mica.

Upper Miocene to Lower Pliocene (approximately 825 m (log) to approximately 801 m (log), Utsira Formation of the 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. 2).

Upper Pliocene (mainly Gelasian, approximately 801 m to 750 m, Nordland Group (Naust Formation equivalent))
The ditch cutting samples in the Upper Pliocene unit contain a clay-rich diamicton with some sand, silt and minor pebbles (Fig. 2).

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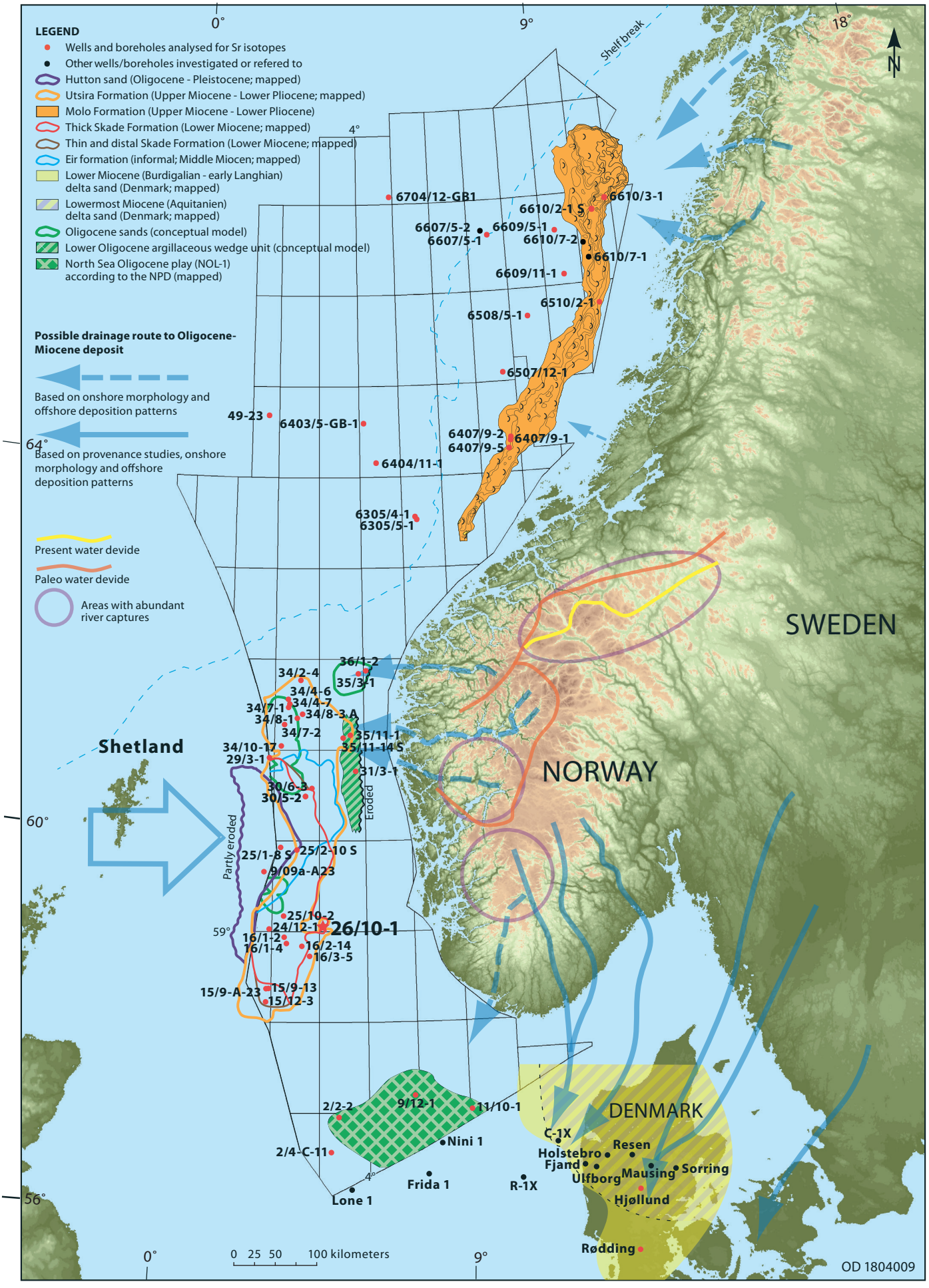

Fig. 1: The location of well 26/10-1 (Zulu gas discovery) shown on a map showing wells and boreholes containing Lower Miocene to Upper Pliocene-Pleistocene deposits (modified after Eidvin et al., 2013, 2014 and Eidvin and Riis, in prep.). The extent of the Utsira, Eir and Skade formations in the North Sea is according to NPD factpages. The extent of the Molo Formation is after Bullimore et al. (2005) and the extent of the Hutton sand (informal) is after Gregersen and Johannessen (2007). The extent of the North Sea Oligocene play (NOL-1) is according to the Norwegian Petroleum Directorate web page (www.npd.no). Provenance study is after Olivarius (2009) and topographic map is after Olesen et al. (2010).

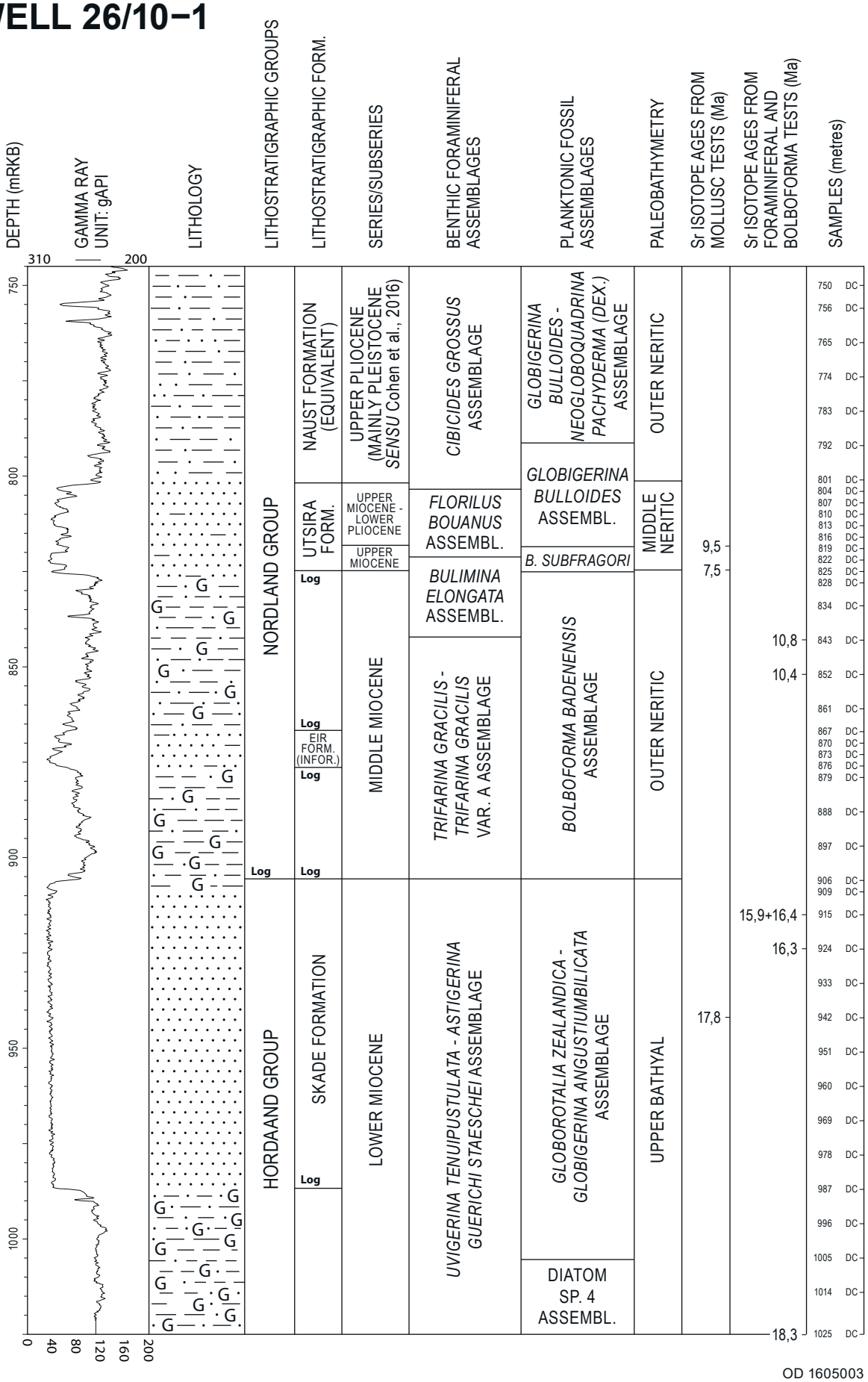

Fig. 2: Well summery figure including gamma ray log, lithology, lithostratigraphic units, series/ subseries, benthic foraminiferal assemblages, planktonic fossil assemblages, paleobathymetry, strontium isotope ages and analysed samples for the investigated sequence in well 26/10-1 (Lower Miocene to Upper Pliocene (Gelasian)).