

A biostratigraphic, strontium isotopic and lithostratigraphic study of the upper part of Hordaland Group and lower part of Nordland Group in well 34/7-2, 34/7-12 and 34/7-R-1 H from the Tordis Field in the Tampen area (northern North Sea).

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Abstract

A major incident happened at the Tordis Field in the Tampen area (northern North Sea) at the 14th of Mai 2008 when oily water, which was injected into the upper part of the Hordaland Group, migrated to the sea bottom. Surveillance of the seabed detected a sink hole (30-40 m length and 7 m depth) about 60 m from the nearest template where oil-contaminated water poured out. StatoilHydro assumed that the fluids which were injected close to the top of the Hordaland Group were going to be stored in an aquifer in the lowermost part of the Nordland Group (Utsira Formation).

Our biostratigraphic, strontium isotopic and lithostratigraphic study of the upper part of Hordaland Group and lower part of Nordland Group in well 34/7-12 and 34/7-R-1 H from the Tordis Field and 34/7-2 (about 3.6 km to the north) showed that the Utsira Formation is not present in the area where the oily water was injected. In this area, glacial Upper Pliocene deposits lie unconformably on Oligocene sediments of the Hordaland Group. In well 34/7-2, to the north, the Utsira Formation consists of a thin glauconitic unit, about 10 m thick.

Introduction

According to StatoilHydro's Corporate Audit (2008) and Annual and Sustainability Report (2008) a major incident happened at the Tordis Field at the 14th of Mai 2008 in which oily water, which was injected into the upper part of the Hordaland Group, migrated to the sea bottom. After surveillance of the seabed, a sink hole with a length of 30-40 m and a depth of 7 m was discovered approximately 60 m from nearest template at the Tordis Field. Oil-contaminated water was pouring from the hole. The injection was closed down the 31st of Mai, and the discharge was estimated to be close to 175 cubic meters of oil to the sea.

According to StatoilHydro's Corporate Audit (2008), it was assumed the fluids that were injected close to the top of the Hordaland Group were going to be stored in an aquifer in the lowermost part of the Nordland Group (Utsira Formation). However, this aquifer does not exist at the Tordis Field, and the injected fluids thus fractured the Nordland Group up to the sea floor. According to StatoilHydro's Corporate Audit (2008) one reason for the incident was that the Tordis Increased Oil Recovery Group (TIOR) was unaware of the reservoir properties in the lowermost part of the Nordland Group. It was assumed that the Utsira Formation was present and that it consists of a large sandy aquifer.

The poor development of the Utsira Formation in wells from the Snorre Field and Visund Field in the Tampen area, not far to the north and north-east of the Tordis Field (Fig. 1), was first described in an oral presentation at Norsk Geologisk Vintermøte (Stavanger; Eidvin and Rundberg, 1999). It was further documented in the paper of Eidvin and Rundberg (2001). The Utsira Formation in the Tampen area was later placed into a regional model which showed the

development of the entire Utsira Formation. This was first presented in a poster presentation at the Norwegian Geological Society (NGF) conference (Trondheim; Eidvin et al., 2002), and further elaborated in the paper of Rundberg and Eidvin (2005). In these presentations the Utsira Formation was described as thin beds (20-60 m) consisting mainly of glauconitic sand. It was also emphasized that in well reports and composite logs, the top of the Utsira Formation was placed about 100 m to high, in the glacial Upper Pliocene (see the discussion chapter below).

In this study, we have investigated the upper part of the Hordaland Group and lower part of the Nordland Group in the Tordis Field injection well 34/7-R-1 H, well 34/7-12 (about 0.5 km to south-west) and 34/7-2 (about 3.6 km to north-east, Fig. 1). The investigation is based on analyses of biostratigraphy, lithostratigraphy and strontium isotopes.

All absolute ages referred to are based on Berggren et al. (1995), and all depths are expressed as meters below the rig floor (mRKB).

Material and methods. We have analysed 40 ditch cutting samples and 20 sidewall cores. Between 50 to 100 g of material were used to analyse the ditch cutting samples. Sidewall cores contain less sample material (6-32 g), and thus sometimes produce less complete faunal assemblages. Sidewall core analyses do, however, provide very useful *in situ* assemblages, because the material is generally not contaminated by caved material.

The fossil identification was performed in the 106-500 μm sediment fraction. In some cases the fraction larger than 500 μm and the fraction less than 106 μm were also studied. From the ditch cutting samples approximately 300 foraminiferal tests were picked out from the 106-500 μm fraction. In order to optimise the identification of the foraminiferal assemblages of the 106-500 μm fraction was gravity-separated in heavy liquid. We analysed all the microfossils in the sidewall cores.

The lithologic analyses are based on visual examination of the samples prior to treatment, and also of the dissolved and fractionated material after preparation. All the sidewall cores were photographed before treatment. Owing to problems caused by caved material, only a general description was deemed appropriate for some parts of sections. However, the sidewall cores gave accurate lithological information for most parts.

Strontium Isotope Stratigraphy (SIS) is used for high resolution chronostratigraphic control of sedimentary sequences, and is here used to support the biostratigraphical correlation of the Utsira Formation. The analytical work was conducted by the Mass Spectrometry Laboratory at the University of Bergen, Norway. All the Sr isotopic ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and to NIST 987 = 0.710248. Measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were converted to age estimates using the SIS Look-up table of Howard and McArthur (1997; see McArthur et al. (2001) and Eidvin and Rundberg (2001, 2007) for more details about the use and precision of the method).

Biostratigraphic correlation. The fossil assemblages are correlated primarily with the biozonation of King (1983, 1989), which outlines a micropalaeontological zonation for Cenozoic sediments in the North Sea. In addition, a number of articles describing benthic foraminifera from onshore basins in the area surrounding the central and southern North Sea are utilized. The planktonic foraminifera were, in addition, correlated with the zonations of

planktonic foraminifera on the Vøring Plateau (Norwegian Sea, ODP Leg 104) of Spiegler & Jansen (1989).

Well 34/7-2

Based on analyses of benthic and planktonic foraminifera, pyritized diatoms, sponge spicules and Sr isotopes in well 34/7-2 (61°17'57.16"N, 02°09'40.90"E; Fig. 1) we recorded approximately 35 m with unspecified Oligocene sediments, approximately 10 m with Upper Miocene-Lower Pliocene sediments and approximately 105 m Upper Pliocene deposits. The base of the Oligocene and the top of the Upper Pliocene are not investigated. The units were investigated with 16 ditch cutting samples at ten meters interval and ten sidewall cores (Figs. 2 and 3).

Biostratigraphy

Oligocene (1070 m (lowermost investigated sample) to approximately 1035 m (log), Hordaland Group)

The greater proportion of the fossils recorded in this unit are sponge spicules (both rod-shaped and *Geodia* sp.). Pyritized diatoms are also recorded throughout and in the lower part also radiolaria. In the diatom flora the index fossil Diatom sp. 3 is recorded in the ditch cutting samples at 1070 and 1060 m. King (1989) describe a Diatom sp. 3 Subzone (NSP 9c) from the uppermost Lower Oligocene to the lowermost Lower Miocene of the North Sea area.

Upper Miocene-Lower Pliocene (approximately 1035 m (log) to approximately 1025 m (log), Utsira Formation)

Benthic foraminifera of the *E. variabilis* assemblage and planktonic foraminifera of the *Neogloboquadrina atlantica* (sinistral) assemblage (lower part) recorded in the ditch cutting sample and the sidewall core at 1030 m give a Late Miocene-Early Pliocene age for this unit. In addition to the nominate species, the benthic foraminiferal fauna also includes *G. subglobosa*, *Cibicides telegdi* and *Hoeglundina elegans* (Figs. 2 and 3).

E. variabilis is recorded from the Upper Oligocene to Lower Miocene of Germany (Grossheide and Trunco, 1965; Spiegler, 1994) and from the Upper Oligocene to Lower Pliocene on the Norwegian continental shelf (Skarbø and Verdenius, 1986). *G. subglobosa* is known from the Upper Oligocene to Upper Miocene of Germany (Spiegler, 1974) and from the Middle to Upper Miocene of the Netherlands (Doppert, 1980). *C. telegdi* is recorded from the Oligocene of Denmark and Germany (Grossheide and Trunco, 1965; Hausmann, 1964; Kummerle, 1963 and Ulleberg, 1974). However, on the Norwegian continental shelf *C. telegdi* is known from the Upper Miocene-Lower Pliocene according to Stratlab (1986) and Eidvin and Rundberg (2001, 2007). *H. elegans* is recorded from the uppermost Middle to Upper Miocene of the Netherlands (Doppert, 1980). *N. atlantica* (sinistral) is known from Late Miocene to Late Pliocene deposits on the Vøring Plateau (Norwegian Sea; Spiegler and Jansen, 1989).

The planktonic foraminiferal fauna in this unit is correlated with the lower part of the *Neogloboquadrina atlantica* (sinistral) Zone of Spiegler and Jansen (1989, Norwegian Sea). The benthic foraminiferal fauna is correlated with *G. subglobosa*-*E. variabilis* zone of Stratlab (1986) from the Norwegian Sea continental shelf and *Ehrenbergina variabilis*

assemblage of Eidvin and Rundberg (2001) from the Tampen area in the northern North Sea. Calcareous benthic index foraminifera from the latter assemblage have been analysed for Sr isotopes in several wells which gave $^{87}\text{Sr}/^{86}\text{Sr}$ -ratios corresponding to ages about 5 Ma (close to the Late Miocene/Early Pliocene boundary; Eidvin and Rundberg, 2001 and Eidvin et al., in prep.).

Upper Pliocene (approximately 1025 m (log) to 920 m (uppermost investigated sample, Nordland Group)

Benthic foraminifera of the *Cibicides grossus* assemblage and planktonic foraminifera of the *Neogloboquadrina atlantica* (sinistral) assemblage (upper part) and *Globigerina bulloides* assemblage give a Late Pliocene age for this Unit. In addition to the nominate species, the benthic foraminiferal fauna also includes *Elphidiella hannai* throughout most of the section (Figs. 2 and 3).

With the exception of *C. grossus* and *E. hannai* all the *in situ* benthic foraminifera are extant species. According to King (1989) *C. grossus* and *E. hannai* are found in the northern North Sea in the Upper Pliocene to lowermost Pleistocene deposits. In the North Sea, first appearance datums (FADs) of these species are considerably later than the Early/Late Pliocene boundary (3.56 Ma). However, *N. atlantica* (sinistral) is described from the Vøring Plateau in deposits no younger than 2.4 Ma. In the Norwegian Sea there is a marked dominance of this species together with *G. bulloides* in Pliocene deposits older than this (Spiegler and Jansen, 1989). *G. bulloides* is also known from the North Atlantic and Norwegian Sea in deposits from the warmest interglacials during the Pleistocene (Kellogg, 1977).

The planktonic foraminiferal fauna in this unit is correlated with the upper part of the *Neogloboquadrina atlantica* (sinistral) Zone of Spiegler and Jansen (1989, Norwegian Sea). The benthic foraminiferal fauna is correlated with Subzone NSB 15a of King (1989, North Sea), and both the benthic and planktonic assemblages are correlated with the *Cibicides grossus-Elphidiella hannai-Globigerina bulloides-Neogloboquadrina atlantica* (sinistral) assemblage of Eidvin and Rundberg (2001, Tampen area, northern North Sea).

Sr isotope stratigraphy

Two samples from the sidewall core at 1030 m were analysed for $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. The samples are based on 27-25 tests of the benthic calcareous foraminifera *Ehrenbergina variabilis* (in one sample a few tests of *Globocassidulina subglobosa* are also used). The obtained $^{87}\text{Sr}/^{86}\text{Sr}$ -ratios gave ages of 5.0 and 4.74 Ma (Early Pliocene, Table 1).

Well 34/7-2

Litho. Unit	Sample (SWC)	Corrected $^{87/86}\text{Sr}$	2S error	Age (Ma)	Analysed fossils
Utsira Fm	1130 m	0.709044	0.000008	4.74	25 tests of <i>E. variabilis</i> , <i>G. subglobosa</i>
Utsira Fm	1130 m	0.709051	0.000008	4.21	27 tests of <i>E. variabilis</i>

Table 1: Strontium isotope data from well 34/7-2. SWC = Sidewall core.

Lithology

Oligocene (1070 to approximately 1035 m (Log), Hordaland Group)

This unit contains mainly silty mudstone with some sand rich in sponge spicules (Figs. 2 and 3).

Upper Miocene to Lower Pliocene (approximately 1035 m (log) to approximately 1025 m (log), Utsira Formation)

Both the ditch cuttings and the sidewall core from 1030 m in this unit are dominated by glauconitic sand. Some quartzose sand, silt and clay are also recorded (Figs. 2-4).

Upper Pliocene (approximately 1025 m (log) to 920 m, Nordland Group)

Most of this unit consists of poorly sorted clastics (diamicton) with clay (dominant), silt, sand and a few ice rafted pebbles in some samples. Quartzose sand is dominant from approximately 1020 m to 1000 m, but the sample at 1021.5 m (SWC, Fig. 5) and 1020 m (DC) contain also some glauconitic sand (Figs. 2 and 3).

Well 34/7-12

Based on analyses of benthic and planktonic foraminifera and sponge spicules in well 34/7-12 (61°16'17.86"N, 02°06'47.26"E, Tordis Field, Fig. 1) we recorded approximately 40 m with unspecified Oligocene sediments and approximately 103 m Upper Pliocene deposits. The base of the Oligocene and the top of the Upper Pliocene is not investigated. The units were investigated with ten ditch cutting samples and ten sidewall cores. The ditch cuttings were sampled for most parts at ten meters interval, but unfortunately in the intervals between 1040-1010 m and 1010-980 m no ditch cuttings were sampled.

Biostratigraphy

Oligocene (1061 m (lowermost investigated sample) to approximately 1021 m (log), Hordaland Group)

Nearly all the micro fossils recorded in this unit are sponge spicules (both rod-shaped and *Geodia* sp.). A few pyritized diatoms and radiolaria are recorded in some samples, but the diatom flora does not include the index Diatom sp. 3 as in the Oligocene section in well 34/7-2 (Figs. 6 and 7). However, otherwise the fossil assemblage is very similar to that of 34/7-2, and is probably of the same age.

Upper Pliocene (approximately 1021 m (Log) to 918 m (uppermost investigated sample), Nordland Group)

Benthic foraminifera of *Cibicides grossus* assemblage and planktonic foraminifera of the *Neogloboquadrina atlantica* (sinistral) assemblage give a Late Pliocene age no younger than 2.4 Ma for this unit. In addition to nominate species the benthic foraminiferal fauna also includes a few specimens of *E. hannai* in parts of section. The planktonic foraminiferal fauna also include *G. bulloides* throughout (Figs. 6 and 7).

The planktonic foraminiferal fauna is correlated with the upper part of *Neogloboquadrina atlantica* (sinistral) Zone of Spiegler and Jansen (1989; Norwegian Sea). The benthic foraminiferal fauna is correlated with Subzone NSB 15a of King (1989; North Sea), and both the benthic and planktonic assemblages are correlated the *Cibicides grossus-Elphidiella hannai-Globigerina bulloides-Neogloboquadrina atlantica* (sinistral) assemblage of Eidvin and Rundberg (2001; Tampen area, northern North Sea).

Lithology

Oligocene (1061 m to approximately 1021 m (log), Hordaland Group)

The Oligocene section contains mainly silty mudstone with some sand rich on sponge spicules (Figs. 6 and 7).

Upper Pliocene (approximately 1021 m (Log) to 918 m, Nordland Group)

Most of the Upper Pliocene unit contains poorly sorted clastics (diamicton) with clay (dominant), silt and sand. A few ice rafted pebbles are recorded in some of the samples. The largest pebble (1.8 x 1.0 cm) is found in the side wall core at the base of the unit (1021 m, Fig. 8). It is angular and consists of quartzite (Figs. 9 and 10). This sample also contains some glauconite. Sand beds from 10 to 5 m thick are recorded at about 1010, 980 and 930 m. Quartzose sand is dominant in the samples recovered from these beds (Figs. 6 and 7).

Well 34/7-R-1 H

Based on analyses of benthic and planktonic foraminifera and sponge spicules in well 34/7-R-1 H (61°16'32.22"N, 02°06'54.69"E, Tordis Field, Fig. 1) we recorded approximately 29 m with unspecified Oligocene sediments and approximately 45 m Upper Pliocene deposits. The base of the Oligocene and the top of the Upper Pliocene is not investigated. The units were investigated with 14 ditch cutting samples at 3-11 meters interval.

Biostratigraphy

Oligocene (1065 m (lowermost investigated sample) to approximately 1036 m), Hordaland Group)

Just like nearby well 34/7-12, nearly all the micro fossils recorded in this unit are sponge spicules (both rod-shaped and *Geodia* sp.). A few pyritized diatoms and radiolaria are recorded in some samples, but the diatom flora does not include the index Diatom sp. 3 as in the Oligocene section in well 34/7-2 (Fig. 11). However, otherwise the fossil assemblage is very similar to that of 34/7-2, and is probably of the same age.

Upper Pliocene (approximately 1036 to 991 m (uppermost investigated sample), Nordland Group)

Benthic foraminifera of *Cibicides grossus* assemblage and planktonic foraminifera of the *Neogloboquadrina atlantica* (sinistral) assemblage give a Late Pliocene age no younger than 2.4 Ma for this unit. In addition to nominate species the benthic foraminiferal fauna also includes a few specimens of *E. hannai* in parts of section. The planktonic foraminiferal fauna also include common *G. bulloides* throughout (Fig. 11).

As in well 34/7-12, the planktonic foraminiferal fauna is correlated with the upper part of *Neogloboquadrina atlantica* (sinistral) Zone of Spiegler and Jansen (1989; Norwegian Sea). The benthic foraminiferal fauna is correlated with Subzone NSB 15a of King (1989; North Sea), and both the benthic and planktonic assemblages are correlated the *Cibicides grossus-Elphidiella hannai-Globigerina bulloides-Neogloboquadrina atlantica* (sinistral) assemblage of Eidvin and Rundberg (2001; Tampen area, northern North Sea).

Lithology

Oligocene (1065 to approximately 1036 m, Hordaland Group)

The Oligocene contains mainly silty mudstones with some sand rich on sponge spicules (Fig. 11).

Upper Pliocene (approximately 1036 to 991 m, Nordland Group)

The Upper Pliocene contains poorly sorted clastics (diamicton) with clay (dominant), silt, sand and some ice rafted pebbles. Thin sand beds are present at several levels (Fig. 11).

Palaeoenvironments

The definition of bathymetric zones used in this study is according to van Hinte (1978); inner neritic: 0-30 m, middle neritic: 30-100 m, outer neritic: 100-200 m and upper bathyal: 200-600 m.

Oligocene

Most of the micro-fossils recorded in the Oligocene sections are sponge spicules (dominant), radiolarians and pyritized diatoms (common in lower parts). The occurrence of radiolarians and diatoms indicates relatively deep, open marine environments. The scarcity of planktonic and benthic calcareous foraminifera indicates hypoxic bottom conditions and dissolution of most calcareous tests. The bathymetric environment was probably upper bathyal during the deposition of the Oligocene succession.

Upper Miocene to Lower Pliocene

This glauconitic sandy unit contains only a fair number of *in situ* micro-fossils. The benthic assemblage includes calcareous foraminifera and a few sponge spicules. Planktonic foraminifera are very scarce, but a few radiolarian are also recorded. Of the *in situ* benthic foraminifera, which we recorded in the sidewall core at 1030 m, three forms are extinct and four are extant. The extinct *E. variabilis* and *Cibicides dutemplei* and the extant *Cibicidoides pachyderma* and *Cibicides scaldisiensis* are deep to shallow water indicators according to Skarbø and Verdenius (1986). *Cibicides lobatulus* and *Bulimina marginata* inhabit the inner part of the continental shelf in recent deposits, but are also found on the middle and outer shelf according to Sejrup et al. (1981). No fossils typical of shallow marine conditions are recorded in this unit. However, planktonic foraminifera are few in numbers and these are common in deep shelf deposits of Late Miocene to Early Pliocene sediments in other areas of the Norwegian continental shelf (Eidvin et al., 1998, 1999 and 2007). According to Odin and Matter (1981) and Van Houten and Purucker (1984), glauconitic facies are most common on outer present-day shelves (200-300 m). We propose that the sedimentary environment during the Late Miocene to Early Pliocene, in the 34/7-2 area, probably was outer neritic.

Upper Pliocene

The fossil assemblages in the Upper Pliocene deposits are dominated by calcareous benthic foraminifera. Planktonic foraminifera are also common throughout most parts. With the exception of *C. grossus* and *E. hannai*, all the *in situ* benthic foraminifera are extant. According to Skarbø and Verdenius (1986) and King (1989), *E. hannai* (rare) inhabited shallow-water areas whereas *C. grossus* (common) was a deep to shallow-water form. The

extant *Nonion affine* and *Cassidulina teretis*, which are common in most parts of sections, dwell mostly in deeper shelfal areas (Sejrup et al., 1981; Mackensen et al., 1985). *C. scaldisiensis* (common), *C. pachyderma*, *Elphidium excavatum*, *Haynesina orbiculare* and *Islandiella islandica* are deep to shallow water indicators according to Skarbø and Verdenius (1986). *C. lobatulus* and *B. marginata* inhabit the inner part of the continental shelf in recent deposits, but is also found on the middle and outer shelf according to Sejrup et al. (1981). Several shallow-water forms of the genus *Elphidium* including *Elphidium groenlandicum* and *Elphidium albiumbilicatum* occur in varying abundances in most intervals (Skarbø and Verdenius, 1986).

On the Visund Field not far to the north-east of the Tordis Field, the basal Upper Pliocene was sampled in detail in cored sections in well 34/8-A-1 H and 34/8-9 S (Fig. 1; Eidvin and Rundberg, 2001). Analyses revealed that shallow marine foraminifera were concentrated in clasts interpreted as being included within debris flow deposits and therefore transported into position.

A north-western to south-eastern seismic line NVGTI-92-105 across the Norwegian northern North Sea through wells 34/8-3 A (Visund Field) and 34/7-1 (Snorre Field), just to the north, shows well-resolved clinoformal pattern of the Upper Pliocene deposits (see Figs. 12 and 13 and Fig. 2 in Eidvin and Rundberg, 2001). According to Eidvin and Rundberg (2001) this gives a direct estimate of the palaeo-water depths of this time, and they suggested that water depth, in the Snorre and Visund Field areas, was in the order of 150-200 m at the onset of progradation, and that it gradually increased to a maximum of about 400 m as the system evolved during the Late Pliocene. We suggest that the sedimentary environment during deposition of the Upper Pliocene section, also in the Tordis Field area, probably was outer neritic to upper bathyal.

Discussion

In the Snorre and Visund Field areas Eidvin and Rundberg (2001) demonstrated a situation where an about 100 m thick autochthon basal Upper Pliocene unit lies unconformable on a 20-60 m thick glauconitic sand unit from close to the Late Miocene/Early Pliocene boundary. In well reports, composite logs and even in published literature, the basal upper Pliocene unit and usually an overlying thin sandy unit were included in the Utsira Formation. One reason for this may be the fact that contracted biostratigraphical consultants have erroneously dated the units to Late Miocene-Early Pliocene in most wells. Eidvin and Rundberg (2001) interpreted the basal Upper Pliocene unit to consist mainly of debris-flow deposits. Inclusion of angular crystalline stones and pebbles in sidewall cores and conventional cores show that glacial or glacio-marine sediments constitute parts of the transported deposits. The thin sandy sections were interpreted as turbidites. The inclusion of a considerable amount of glacial detritus reflects that the sediments were deposited after the first expansion of the northern glaciers down to sea level. Studies of ice rafted detritus (IRD) in ODP-cores from the Norwegian Sea show that this expansion started about 2.75 Ma (Jansen and Sjøholm, 1991; Fronval and Jansen, 1996; Fig. 14). The biostratigraphical investigation of sidewall cores and conventional cores from the Snorre and Visund fields gave a Late Pliocene age older than about 2.4 Ma. This limits the time for the sedimentation of the autochthon deposits to less than 0.3-0.4 My.

The investigation of well 34/7-2 shows a situation very similar to that described above. The deposits in well 34/7-2 are especially similar to those in well 34/7-1, 34/4-7 and 34/4-6 from the Snorre Field and well 34/8-1 from the Visund Field (Eidvin and Rundberg, 2001). In all these wells there is recorded a thin glauconitic unit (about 10 m thick in well 34/7-2, about 20 m in the Snorre Field wells and about 50 m in well 34/8-1 from Visund; Fig. 15). Likewise the well reports and composite logs, from these areas, show that the top of the Utsira Formation is placed too high and within the Upper Pliocene (about 80 to 100 m). The lithology and the fossil contents, in the glauconitic unit and in the basal Upper Pliocene, are also near identical in all wells (Eidvin and Rundberg, 2001). Well 34/7-2 is situated about 20 km to the south of well 34/7-1 on Snorre Field, about 16 km to the south-west of well 34/8-1 on the Visund Field and about 3.6 km to the north-east of the injection well 34/7-R-1 H on the Tordis Field (Fig. 1).

In the injection well 34/7-R-1 H and the nearby well 34/7-12 (about 0.5 km to south-west) we have not recorded any glauconite unit or any other deposits with a Late Miocene-Early Pliocene fossil assemblage typical for the Utsira Formation. The well report and composite log for well 34/7-12 (and our interpretation) place the top of the Hordaland Group at about 1021 m. The lowermost part of the Nordland Group and the uppermost part of the Hordaland Group are sampled with few ditch cutting samples (Fig. 6), but a sidewall core contains the sediment just above the Nordland Group/Hordaland Group boundary. This sample (1021 m, Figs. 7 and 8) is barren of foraminifera, but contains a large, angular pebble of quartzite (about 1.8 x 1.0 cm, Figs. 9 and 10). This pebble has most likely been ice rafted and/or transported with debris-flows from the fennoscandian continent to its current position in well 34/7-12. Consequently, this shows that the sediments immediately above the Hordaland Group were deposited after the first expansion of the northern glaciers at about 2.75 Ma. However, in the well report and composite log there are erroneously traced a section from 1021-930 m which is defined as the Utsira Formation and given a Late Miocene-Early Pliocene age. We recorded some glauconite in the sidewall core at 1021 m (Fig. 8). We suggest that these are reworked from the glauconite unit (Utsira Formation) probably not far away, but the glauconite may also originate from the Hordaland Group. The lithology in the sidewall core at 1021 m is very similar to the lithology in the sidewall core at 1021.5 m in well 34/7-2 (Fig. 5), which is situated just above the glauconitic unit. This sample is also barren of foraminifera. The investigation of the injection well 34/7-R-1 H, which does not contain any side-wall cores but is closely sampled with ditch cuttings, also shows that glacial Upper Pliocene deposits lie unconformably on Oligocene sediments of the Hordaland Group (Fig. 11).

Our interpretation of the palaeoenvironment during deposition of the basal Upper Pliocene parts (Nordland Group) in well 34/7-2, 34/7-12 and 34/7-R-1 H indicates quite deep water, probably outer shelf environment (see above). The sand beds recorded in these units are consequently most likely turbidites. There is neither recorded shallow water foraminifera in the glauconite unit (Utsira Formation) in well 34/7-2, and this unit was probably deposited in a middle shelf environment. We believe that the unconformities between the basal Upper Pliocene and the glauconitic unit and between the glauconitic unit and the Hordaland Group were formed sub marine. The base Upper Pliocene hiatus can be explained by that at this time the expanding glaciers started loading large volumes of material off the coast areas which probably started extensive submarine mass flowing and erosion. We believe that contour currents or tidal currents have been an important factor in making the unconformity at the base of the glauconitic unit (Eidvin et al., in prep.).

Conclusion

We have investigated the upper part of Hordaland Group and lower part of Nordland Group in well 34/7-12 and 34/7-R-1 H on the Tordis Field and well 34/7-2 (about 3.6 km to the north). The study is based on biostratigraphic, strontium isotopic and lithostratigraphic analyses. At the base of the Nordland Group in well 34/7-2 we recorded a unit of approximately 10 m with glauconitic sand belonging to the Utsira Formation. This unit was dated to Late Miocene-Early Pliocene (4.7-4.2 Ma based on Sr-analyses, Table 1). Unconformably above this unit lie glacial marine deposits of Late Pliocene age and unconformably below there are Oligocene mudstones of the Hordaland Group. The glauconitic sand of the Utsira Formation is not present in the Tordis Field wells 34/7-12 and 34/7-R-1 H. In those wells Upper Pliocene glacial marine deposits of the Nordland Group lie unconformably on the Hordaland Group.

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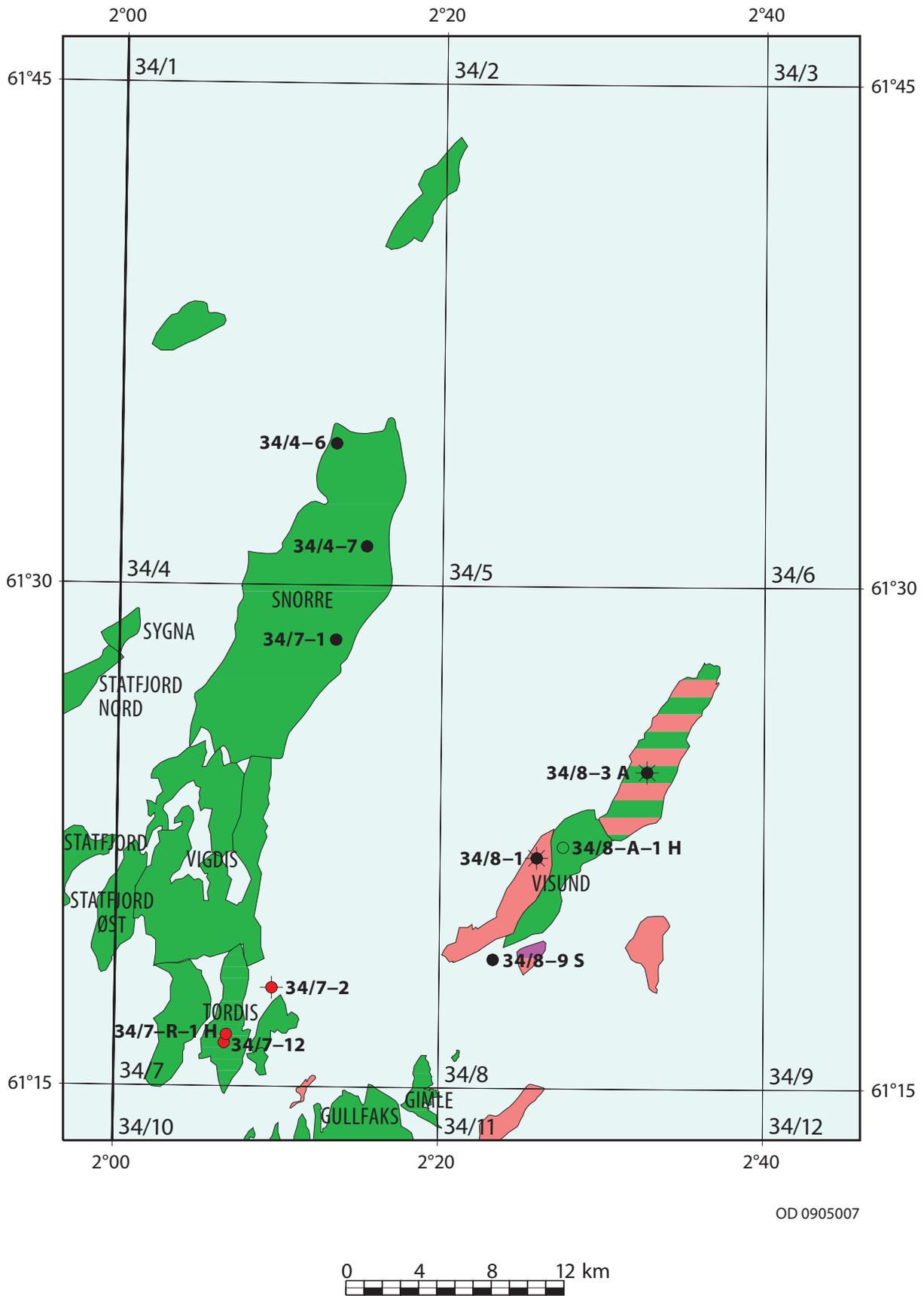
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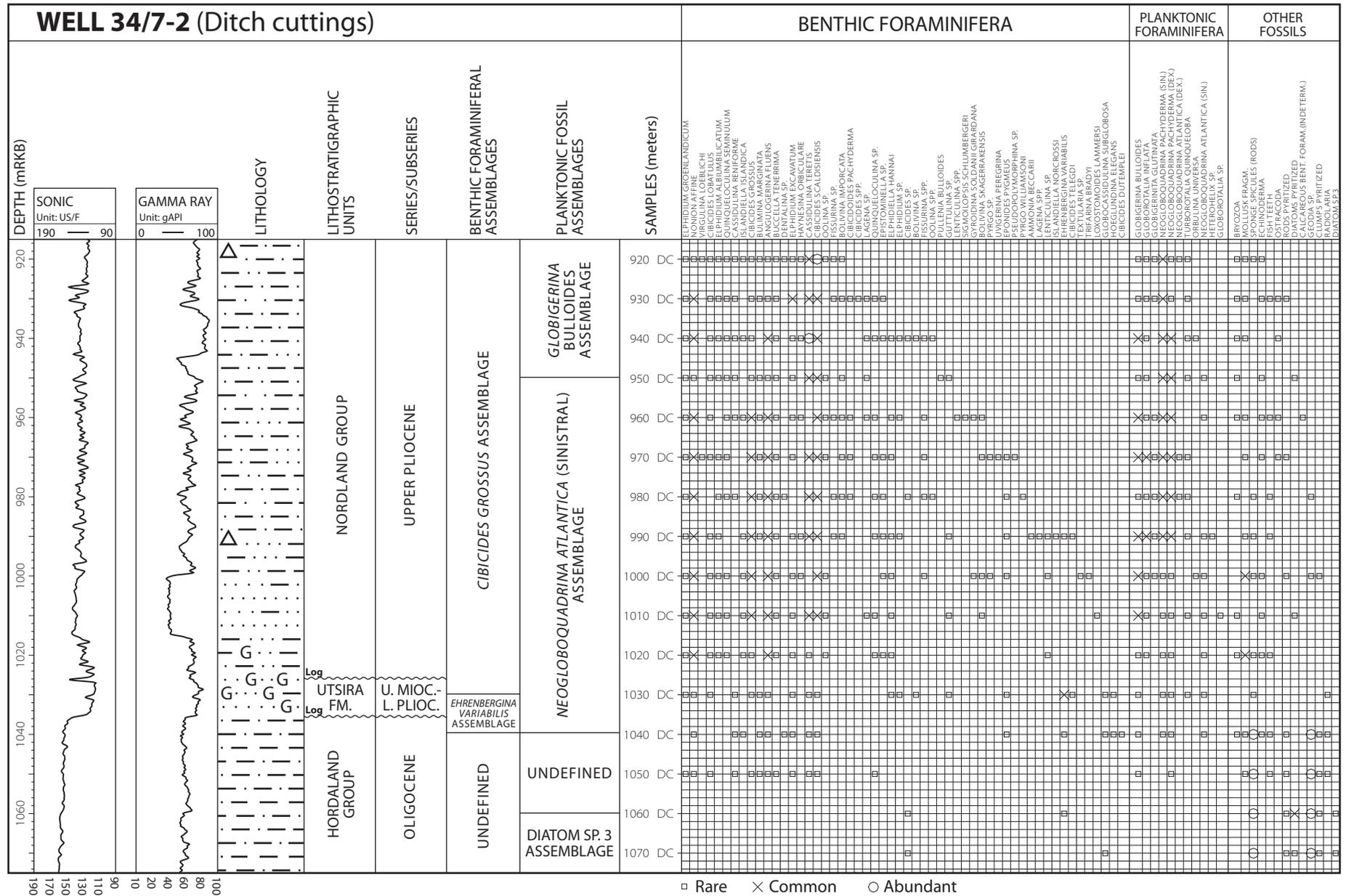
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OD 0905007

Fig. 1: Map of location of the studied wells 34/7-2, 34/7-R-1 H (Tordis Field), 34/7-12 (Tordis Fields; red well symbols) and previously investigated wells 34/4-6, 34/4-7, 34/7-1 on the Snorre Field and 34/8-3 A, 34/8-1, 34/8-A-1 H, 34/8-9 S on the Visund Field (black and open well symbols). The wells from the Snorre and Visund fields are published in Eidvin and Rundberg (2001) and Rundberg and Eidvin (2005).

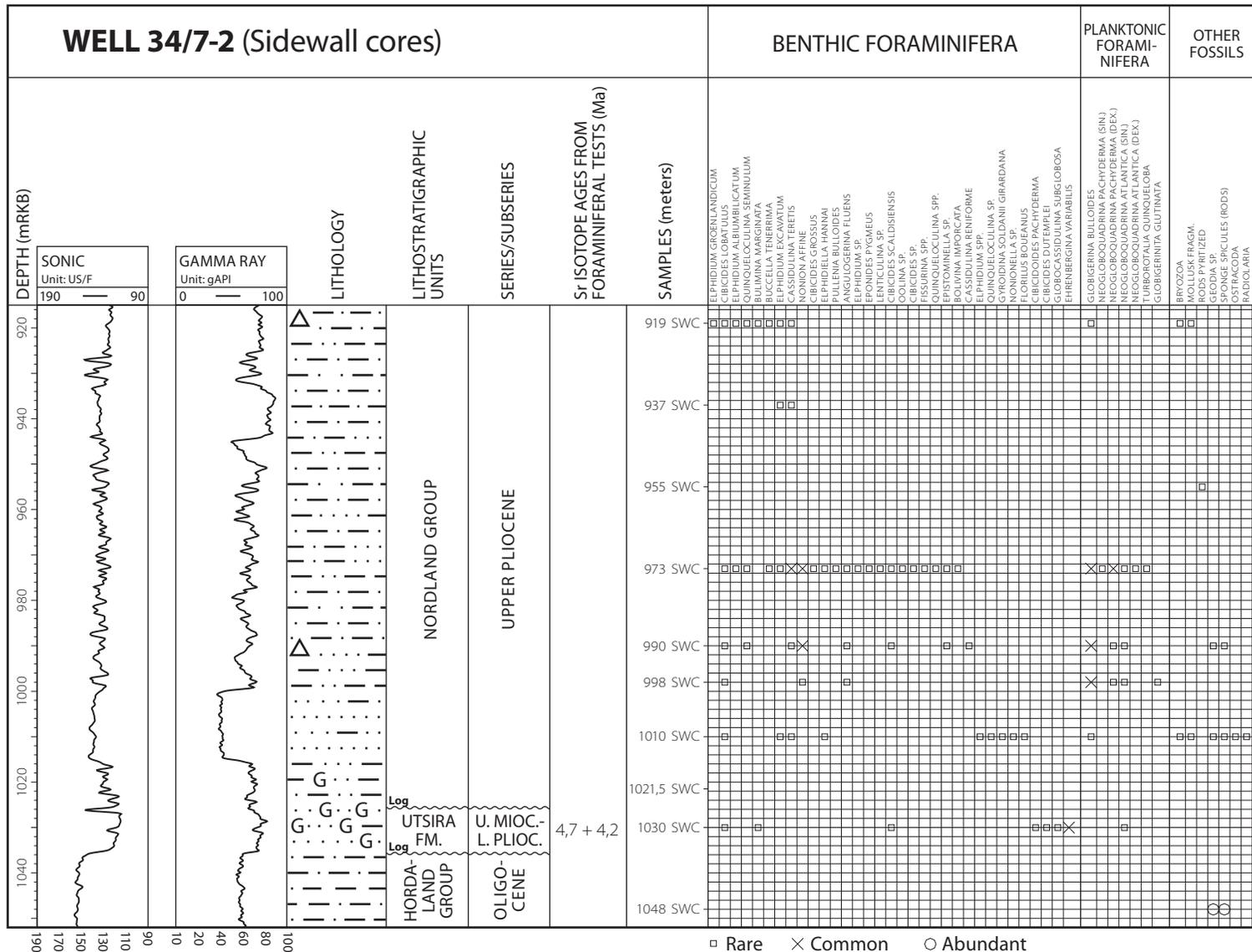


Sea floor = 271 meters below rig floor
 DC = Ditch cuttings
 gAPI = American Petroleum Institute gamma ray units

US/F = Microseconds per foot
 A = Ice rafted pebbles
 G = Abundant glauconite

OD 0903013

Fig. 2: Range chart for micro fossils in ditch cutting samples in the investigated interval of well 34/7-2. Legends for columns: rare = 0-5%, common = 5-20% and abundant = 20% or more.





OD 0905010

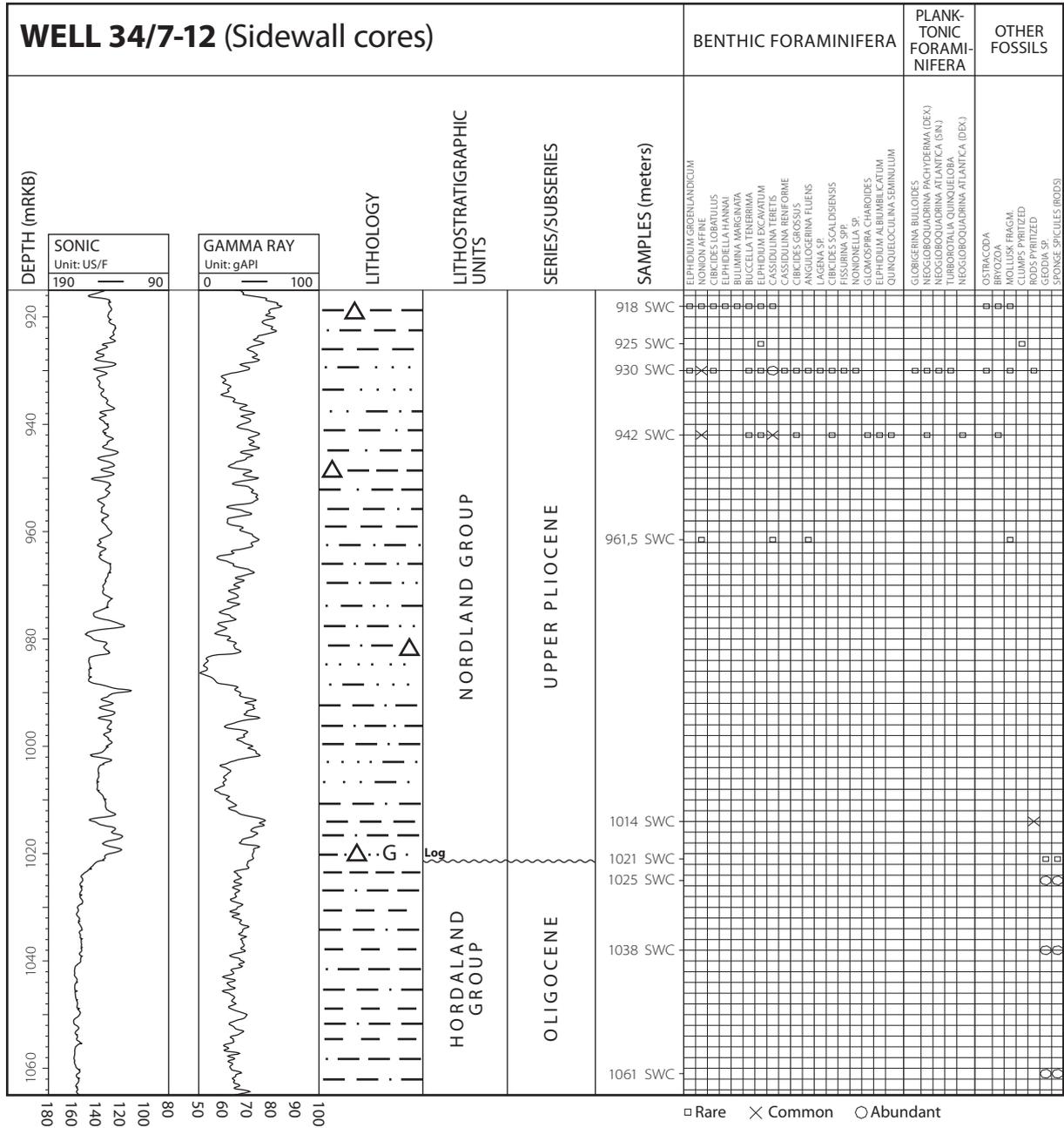
Fig. 4: Photography of sidewall core at 1030 m in well 34/7-2.

Well 34/7-2
1021,5 m SWC



OD 0905011

Fig. 5: Photography of sidewall core at 1021.5 m in well 34/7-2.



Sea floor = 216 meters below rig floor
 SWC = Sidewall cores
 gAPI = American Petroleum Institute gamma ray units
 US/F = Microseconds per foot
 △ = Ice rafted pebbles
 G = Abundant glauconite

OD 0903018

Fig. 7: Range chart for micro fossils in sidewall core samples in the investigated interval of well 34/7-12. Legends for columns: rare = 0-5%, common = 5-20% and abundant = 20% or more.

Well 34/7-12
1021 m SWC



OD 0905012

Fig. 8: Photography of sidewall core at 1021 m in well 34/7-12.

Well 34/7-12, 1021 m SWC, Quartzite



OD 0905013

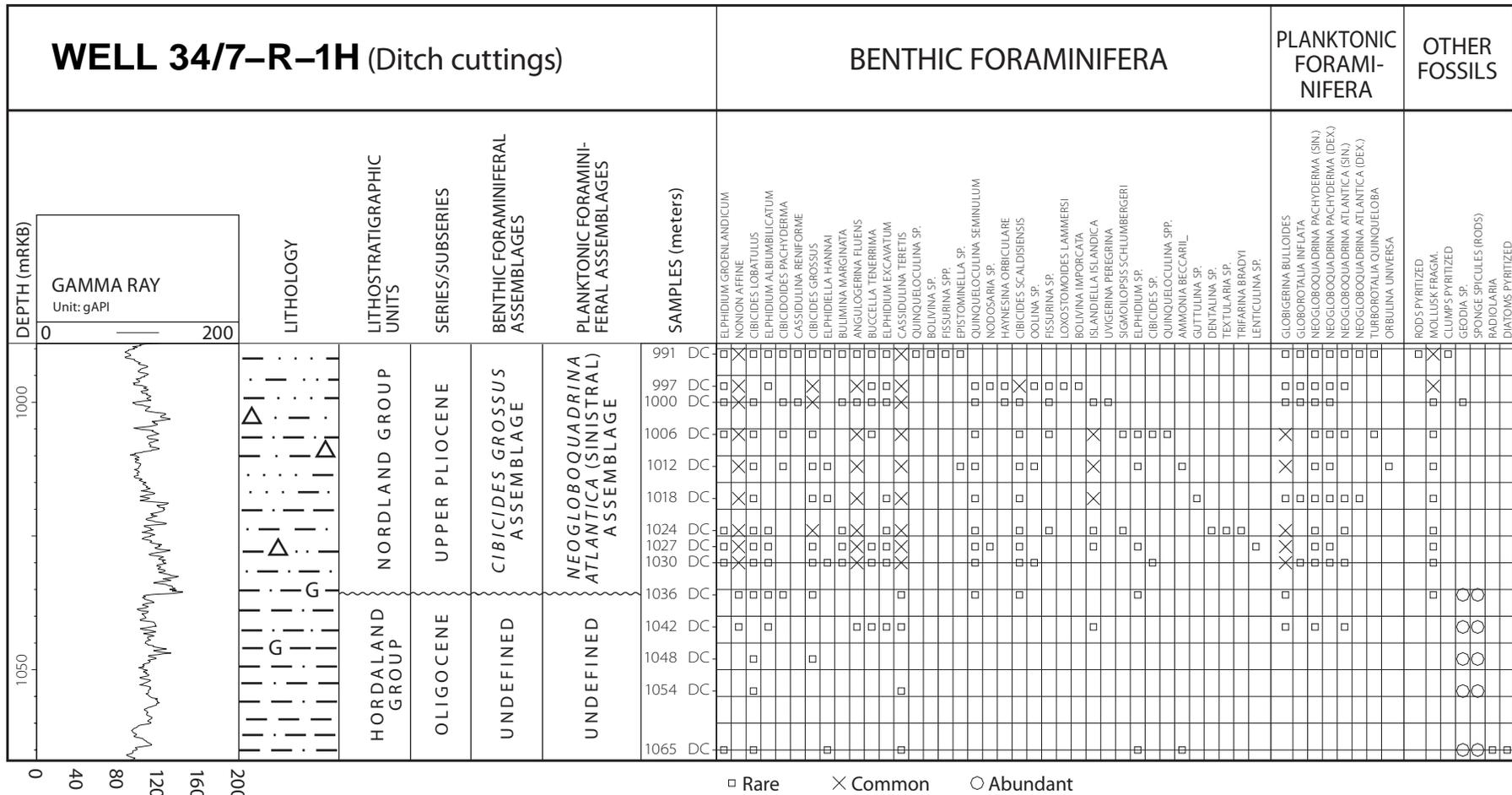
Fig. 9: Photography of ice rafted quartzite pebble (height and length) recorded from a sidewall core at 1021 m in well 34/7-12.

Well 34/7-12, 1021 m SWC, Quartzite



OD 0905014

Fig. 10: Photography of ice rafted quartzite pebble (width and length) recorded from a sidewall core at 1021 m in well 34/7-12.



Sea floor = 229 meters below rig floor
 DC = Ditch cuttings
 gAPI = American Petroleum Institute gamma ray units
 △ = Ice rafted pebbles
 G = Abundant glauconite

OD 0905006

Fig. 11: Range chart for micro fossils in ditch cutting samples in the investigated interval of well 34/7-R-1H. Legends for columns: rare = 0-5%, common = 5-20% and abundant = 20% or more.

Northern Viking Graben - 61°N

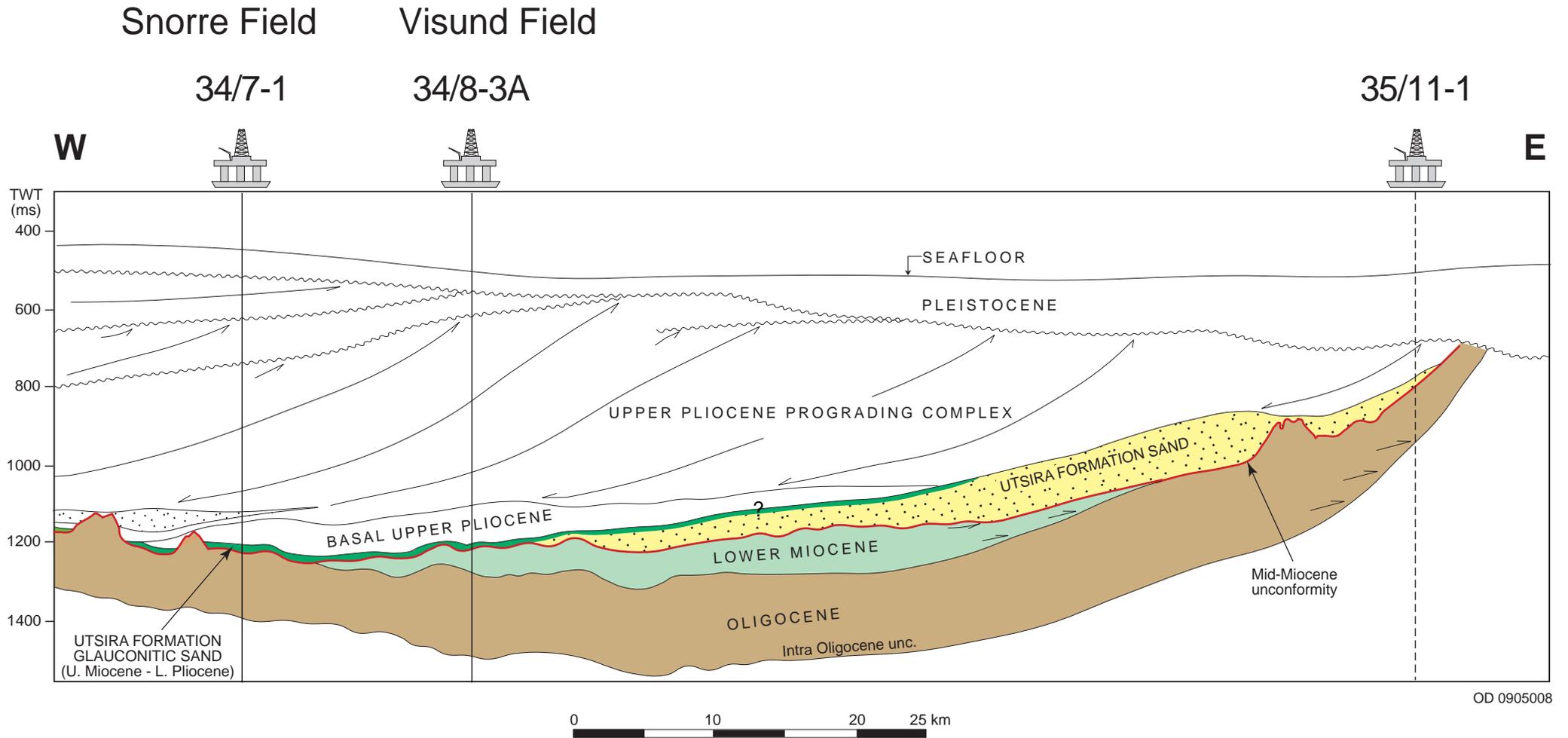


Fig. 12: East-West transect of post Eocene strata in the Tampen area in the northern North Sea at about 61°N. Note the thin beds with glauconitic sand of the Utsira Formation (dark green) in the Snorre and Visund areas which is considered to overlie or partly interdigitate with the main Utsira Formation sand (yellow with dots) to the east. Note also the mid-Miocene unconformity (red line). See Fig. 13 for location (modified after Eidvin & Rundberg, 2001 and Rundberg & Eidvin, 2005).

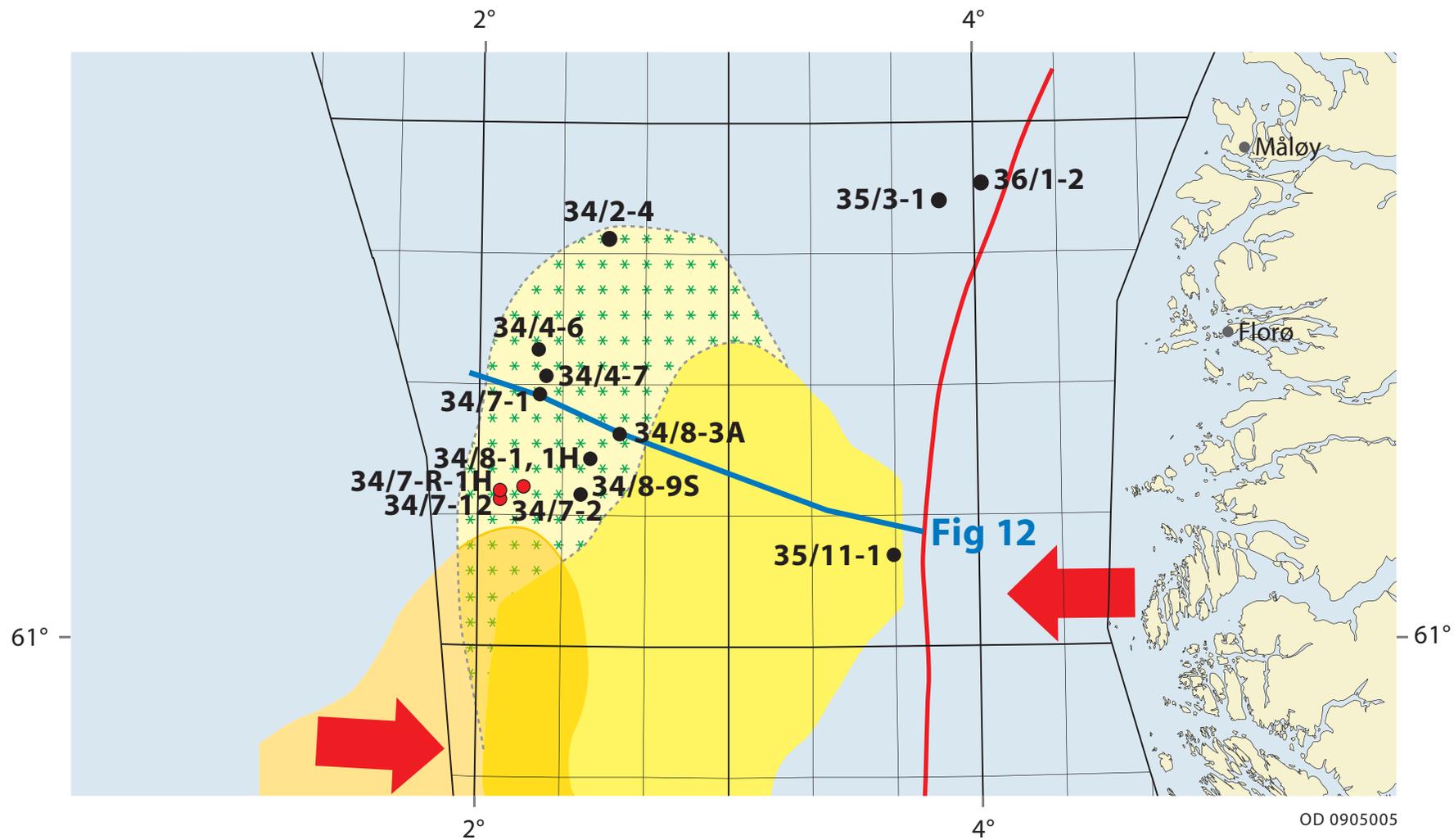
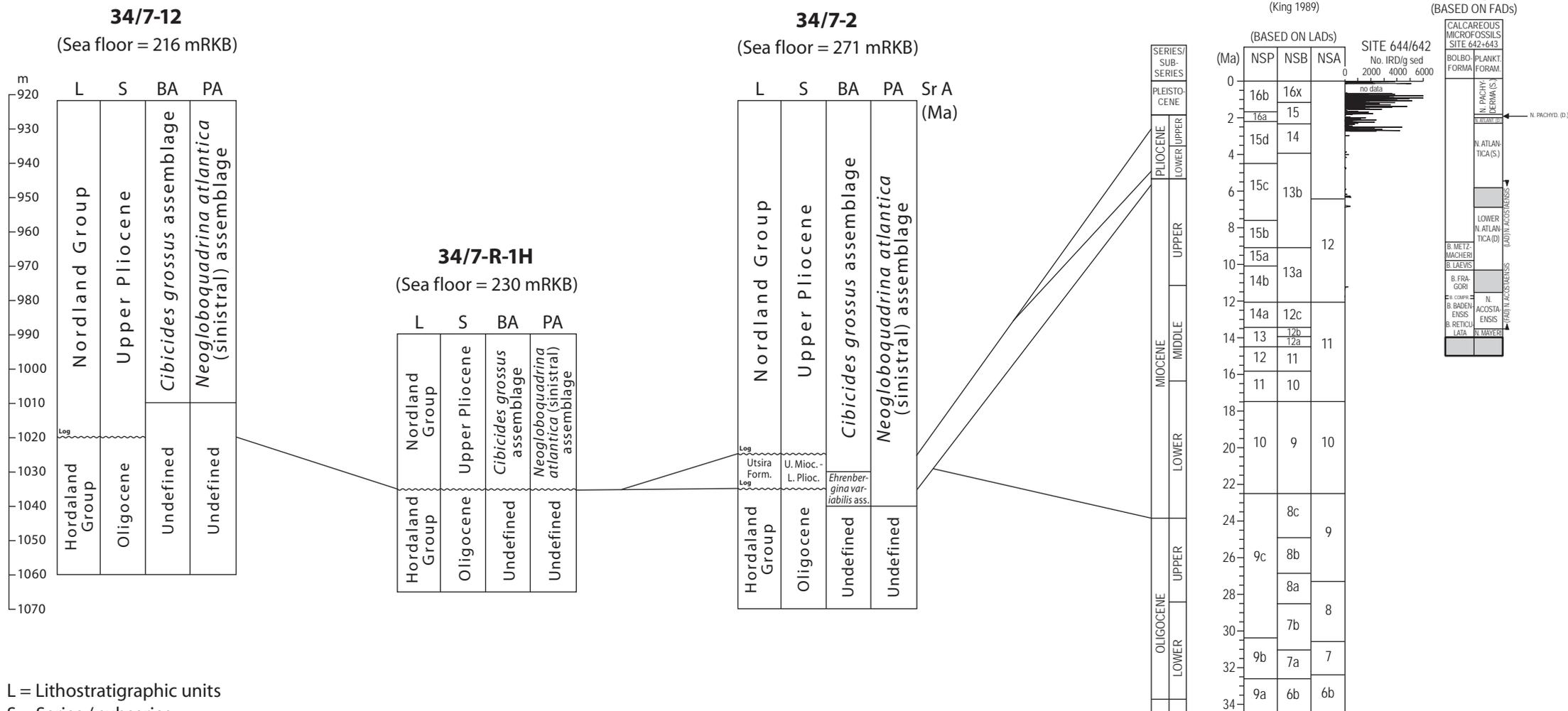


Fig. 13: Distribution of Utsira Formation sands in the Snorre, Visund and Tordis Field areas at Tampen in the northern North Sea. Light and dark yellow areas shows outline of main Utsira quartzose sands. Hatched area (with green stars) shows assumed outline of thin glauconitic member extending beyond the main Utsira sand. Red dots show wells we have investigated in this study. Black dots show wells which are published in Eidvin and Rundberg (2001) and Rundberg and Eidvin (2005). Red line shows top Oligocene truncation, red arrows show sediment transport directions and blue line is location of the seismic profile shown in Fig. 12 (modified after Eidvin and Rundberg, 2001; Rundberg and Eidvin, 2005).

TORDIS FIELD

VØRING PLATEAU



L = Lithostratigraphic units
 S = Series / subseries
 BA = Benthic foraminiferal assemblages
 PA = Planktonic foraminiferal assemblages
 SrA = Strontium isotope ages from foraminiferal tests

This vertical scale (in Ma) differs from that of the three wells which have meters.

Fig. 14: Correlation of fossil assemblages between well 34/7-12, 34/7-R-1H, 34/7-2 as well as from these wells to King's (1989) North Sea fossil zonation and to the fossil zonation of the ODP sites 642 and 643 on the Vøring Plateau (Spiegler and Jansen, 1989; Müller and Spiegler, 1993). The ice rafted detritus (IRD) curve is after Jansen and Sjøholm (1991) and Frondval and Jansen (1996).

N

S

SNORRE FIELD

VISUND FIELD

TORDIS FIELD

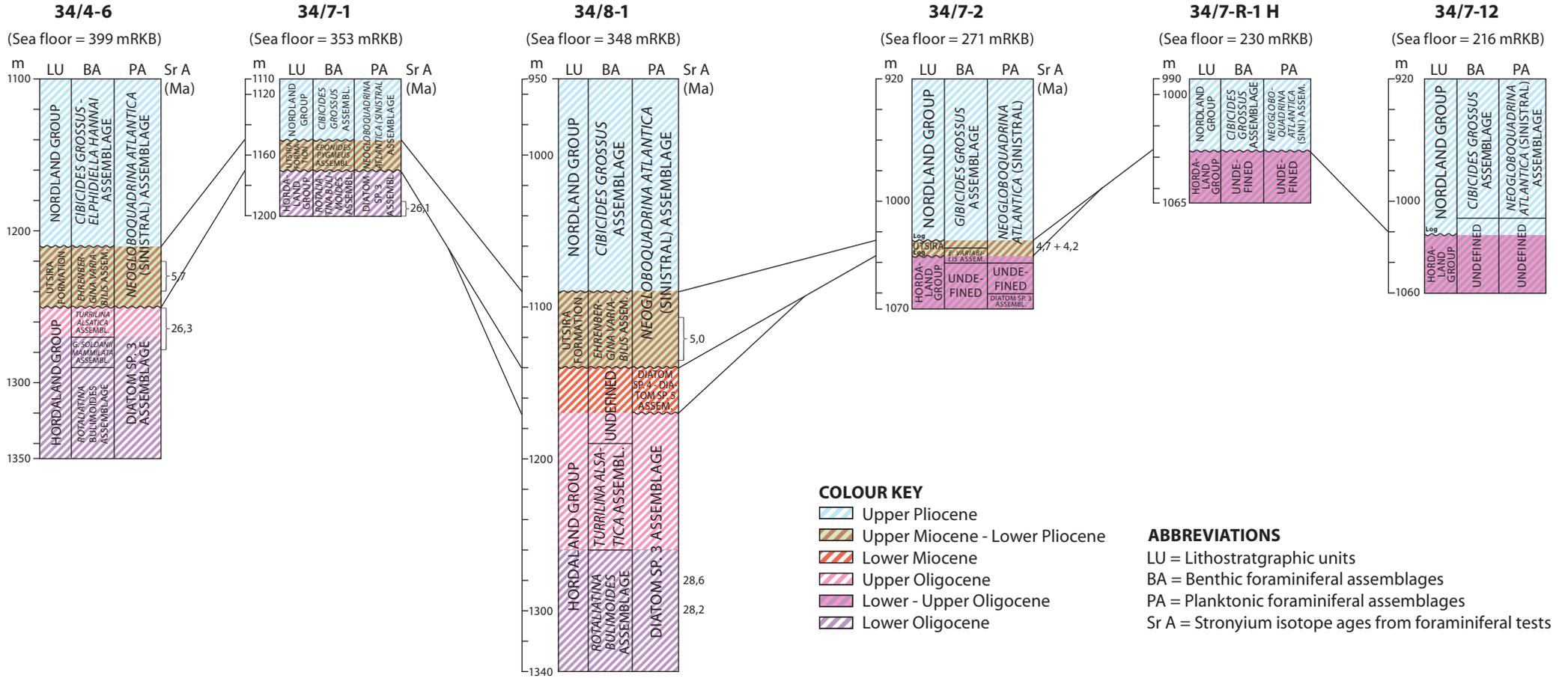


Fig. 15: Correlation of fossil assemblages between the well 34/4-6 (Snorre Field), 34/7-1 (Snorre Field), 34/8-1 (Visund Field), 34/7-2, 34/7-R-1 H (Tordis Field) and 34/7-12 (Tordis Field) in the Tampen area (northern North Sea). The vertical axis is in metres below rig floor.