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# Expressions of shallow gas in the Netherlands North Sea

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## Abstract

Surface and sub-surface expressions of shallow gas in the Netherlands part of the southern North Sea are described, using standard E&P 2D and 3D seismic surveys, as well as higher frequency acoustic surveys. Surface expressions observed are pockmarks, which are geomorphologic features at the seabed indicative for venting of gas, and cemented sandstones. The sub-surface expressions found comprise both phenomena indicating efficient trapping of gas in reservoir sands, such as shallow bright spots and flat spots, and phenomena, which are indications of migration or leakage to the seabed. We refer to the latter as 'seismic anomalies indicating leakage'. These anomalies include gas chimneys or seismic chimneys. All chimneys found in the area have in common, that they belong to a seepage style, which is called 'small and localised'. Much of this seepage is situated over salt domes, with the accompanying normal fault above the domes acting as pathways for the gas or fluids. Although there is admixture of biogenic gas, it is believed that many of the features observed relate to thermo-genic gas.

*Keywords:* North Sea, chimneys, pockmarks, seepage, shallow gas.

## Introduction

Shallow gas has been of interest for different reasons for quite some time. For the hydrocarbon exploration and production (E&P) industry shallow gas has always been important. First of all, the gas can be a hazard and a risk when drilling a borehole, or when positioning an offshore platform at the seabed. Secondly, the presence of shallow gas can be an indication for deeper hydrocarbon reserves, and thus an exploration tool. Finally, some of the shallow gas accumulations are even large enough to be considered as commercial gas-fields. Recently, North Sea shallow gas also became a subject of studies within the scope of a three-year European Commission sponsored project on 'Natural Analogues to the Storage of $CO_2$ in the geological Environment' (NASCENT). In this respect, studying shallow gas will provide information on either the conditions under which gas can efficiently be kept underground, or alternatively, on conditions under which the earth is apparently not capable of containing gas at the same place for a longer period of time. In particular, a closer look at the expressions of seepage and leakage of gas in the near-surface environment is thought to provide more information about gas migration mechanisms. The knowledge obtained will be of help when the geological boundary conditions for safe and efficient storage of $CO_2$ will have to be formulated in the near future.

### Shallow gas, occurrence and origin

In the context of our study we refer to 'shallow gas' if the gas occurs between the seabed and a depth of 1000 m below MSL. In the Netherlands North Sea sector this means that the geological formations containing the gas are mostly unconsolidated clastic sediments of Miocene – Holocene age. Shallow gas in marine sediments is mostly composed of methane, but the gas composition may also include carbon dioxide, hydrogen sulphide and ethane. The origin of these gases is attributed to either biogenic or thermogenic processes. In both cases the gas is derived from organic material, with the biogenic process relying on bacterial activity and the thermogenic process being essentially temperature and pressure dependent (Davis, 1992). Biogenic methane was originally believed to be produced only within the top few metres of seabed sediment, but now there is evidence for bacterial activity even at a few hundred metres below seabed. Firm evidence for a maximum depth of bacterial activity is not available at present. With rapid sedimentation, bacterial gas accumulations may be buried to depths far below those at which the gas was biogenically produced. For example, Rice & Claypool (1981) reported biogenic gas at a depth of 3350 m. Thermogenic methane is produced from organic precursors at high temperatures and high pressures, and consequently is generated at depths greater than 1000 m. Such gas may, however, migrate towards the surface and accumulate in shallow sediment layers. It is not easy to determine whether methane was biogenically or thermogenically formed (Floodgate & Judd, 1992). Evidence for the source of the gas requires geochemical analysis of concentrations of the various hydrocarbons present or measurements of stable carbon and hydrogen isotope ratios. However, the evidence may not always be conclusive, e.g. bacterial oxidation close to the seabed may be responsible for disguising its true origin (Davis, 1992).

Laier et al. (1990) found that off northern Denmark there are two types of biogenic gas. There is gas associated with post-glacial fills of glacial valleys and readily observable by sub-bottom profilers and there is another type observed as discrete seeps in coarser grained sediments with associated carbonate-cemented structures originating in late Pleistocene marine deposits. This last type was found to consist largely of methane that has been formed by $CO_2$ reduction (Laier et al., 1992) by methanogenic Archaebacteria. These bacteria live under anaerobic conditions in e.g. marine muds. They can only form hydrocarbons from a very limited number of substrates. Many bacteria species can reduce carbon dioxide to methane using hydrogen (Floodgate & Judd, 1992). Other methane-related cements were reported by Hovland et al. (1987) in North Sea pockmarks. They found extremely light carbon isotopic compositions, showing that the cements contain carbonate produced by oxidation of biogenic methane. Traces of higher hydrocarbon gases suggested an admixture of thermogenic methane.

In 1995 about 30 vibrocores of 4m length were taken in a 10 by 12 km area in the K18/L16 blocks in the Netherlands North Sea sector (Baum et al., 1996). Geochemical and stable isotope analysis and UV fluorescence and microbacterial investigations of the cores pointed to the presence of gases of thermogenic origin of two different provenances: methane-poor gases from a Mesozoic oil-source rock, and methane-rich gases derived from gas-producing Paleozoic (Carboniferous) source rocks. While normal background values for gas concentration in near-surface sediments in the southern North Sea are in the order of 30-50 ppb, Baum et al. (1996) found values to range between 250-1400 ppb in the K18/L16 area.

In blocks F2 and F3 samples taken from 2-4 m cores yielded 50-3500 ppb (mean 360) thermogenic methane (after removal of bacterial gas), rather high values from an area close to hydrocarbon reservoirs (Baum, pers. comm. 1996). Faber (1996) found values of 2 to 402 ppb $CH_4$ (with one exceptional value of 3852 ppb from a sample at -56 m in a borehole in the Danish sector) in 20 southern North Sea samples from 7-218 m below seabed. Isotope analysis confirmed that most of these samples contained thermogenic gas, with the exception of the 3852 ppb peak value. This last one was of mainly bacterial origin with a certain admixture of thermogenic gas given the $C_1/(C_2+C_3)$ ratio of 133.

Methane concentrations near the sediment surface and through the sulphate-containing zone are very low (see above) in the Netherlands North Sea. There is a rapid increase in methane concentration near the sulphate-methane transition zone. The depth of this zone varies from very close to the surface to several meters down. The typical methane profile in marine sediments can only exist if there is a net oxidation of the upward methane flux at the sulphate-methane transition zone. In places where the sulphate-methane transition zone is located close to the sediment surface, the rates of methane oxidation are not sufficient to give a net oxidation of methane and frequent bubble ebullitions may occur. In sediments with methane seepage, the methane concentration profile does not resemble the typical geochemical methane profiles. There seems to be lateral diffusion of methane in those sediments. The result is that methane oxidation activity is located at around the methane seeps (Iversen, 1990).

## *Geological setting*

The structural and depositional development of the southern North Sea basin has been well documented. At the large scale the Southern North Sea sedimentary basin can be seen as a basin dominated by rifting during most of the Mesozoic with a Cenozoic post-rift sag phase. Rifting already started in the Triassic, and culminated in the Jurassic and Early Cretaceous with the various Kimmerian extensional tectonic phases related to the opening of the Atlantic Ocean. Active rifting was followed by a post-rift sag phase from Late Cretaceous to Present, which was mostly characterised by tectonic quiescence and subsidence of the basin, with the exception of a few compressional tectonic pulses during the Late Cretaceous and Tertiary. During most of the post-rift phase the basin accumulated thick sedimentary mega-sequences. Within this sedimentary basin the most prominent hydrocarbon source rocks are the Westphalian coalbeds for gas, and the Lower Jurassic Posidonia shales for oil. The last significant regional tectonic pulse was during the Mid-Miocene, resulting in the Mid-Miocene unconformity. This surface is now buried at depths ranging from about 1000 – 1500 m. The sediments relevant to the shallow gas discussed in this paper all belong to the clastic sedimentary sequences deposited after the Mid-Miocene.

From the end of the Miocene onwards a large number of seismo-stratigraphic units representing a complex fan delta system, with associated pro-delta deposits, gradually evolved into a fluvial delta and an alluvial plain, which prograded from the east over the Mid-Miocene unconformity (Sha, 1991). These wedge-shaped units represent material from the Baltic River System mainly consisting of mature quartz sands, coarse and gravelly in the east, and fining towards the west. near the Central Graben with thinning or pinching out to west and east. An overall gradual shallowing of the area took place with time. Fluctuations in eustatic sea-level together with tectonic movements and shifting depocenters resulted in regressive and transgressive deposits, combined in sedimentary cycles. Within such cycles the marine facies is situated to the west of terrestrial facies (later on, from the end of the early Pleistocene, this changed to northwest versus southeast). Only in the very south the Pliocene-Pleistocene is overlying much older Tertiary deposits. In the same area crag-like deposits were very locally deposited in Pliocene-Pleistocene times, similar to those presently outcropping in East Anglia (Cameron et al, 1989a). Coastlines shifted back and forth over the Netherlands North Sea and surrounding areas from the end of the Pliocene onwards (Sha, 1991) leading to a variety of sedimentary environments and grain sizes.

In the southern part of the Netherlands sector the main provenance of the Pleistocene clastic material is from the southeast or south, rarely from the west (British sources). During the latest parts of the Early Pleistocene and the earlier parts of the Middle Pleistocene coastlines were situated to the north of the Netherlands sector most of the time. However, occasional transgressions, interrupting the prevailing alluvial plain conditions, reached as far south as the present Dutch north coast. Sediments are predominately sandy with minor clays and peat. Channelling is common and continuous reflectors are scarce. Sands of Rhine provenance reached the northern half of the Netherlands sector.

The first glacial event directly affecting the depositional conditions in the present Netherlands North Sea is the Elsterian glaciation (Laban, 1995). Scandinavian and British ice masses coalesced and spread over most of the Netherlands sector, only the area S of 52° 30' remained ice-free. Sedimentary conditions changed completely: glacial channels up to 400 m deep were being excavated, mainly in an E-W belt crossing the Netherlands sector between 53° and 54° 20'N (Laban, 1995). Sediments generally consist of planar deposits of glacial clays and sandy outwash, while within the channels a chaotic, coarse basal fill is overlain by laminated, clayey, lacustrine deposits with clayey and sandy deposits related to the transgression of the next interglacial on top. Ice-loading affected pre-existing faulting and salt tectonics, while the glacial channels disrupted sediment continuity and created pathways for fluids and gases. The blockage by ice of the North Sea area caused a diversion of previously north-flowing rivers to the west through Dover Straits to the Gulf of Biscay.

The following Holsteinian and subsequent transgressions resulted over much of the Netherlands sector in sheets of marine transgression sands with some clays near the transgression limits. The land bridge around the former Elsterian ice limit was only gradually removed. The subsequent Saalian glaciation brought Scandinavian ice to the eastern part of the Netherlands sector where tills, glacial clays and sandy and gravelly outwash were laid down. Glacial channels were fewer and much shallower, but ice-pushing and tongue basins more common. The next Eemian transgression again resulted in transgression sands. Falling sea-level at the end of the Eemian interglacial in combination with remnants of a glacial-conditioned seabed morphology resulted in sheet-like clays deposited in depressions, the largest of which centres around Brown Ridge (Cameron et al., 1989b). These plastic clay sheets are able to retain near-seabed gas. British ice of the youngest glacial, the Weichselian, covered the NW of the Netherlands North Sea sector resulting in mainly clayey, sandy and gravelly glacial deposits and some glacial channels. Dogger Bank consists of an appreciable thickness of glacial sands remodelled by the next transgression. Elsewhere, outside the ice limit, discontinuous wind-blown sands and fluvial channel-fills may be found. The fill of these glacial and fluvial channels, large and small, may contain dispersed gas.

The present interglacial, the Holocene, has so far seen a drowning of the Netherlands sector resulting in scattered, thin, muddy, lagoonal and tidal flat deposits overlain in most places by transgressive sand sheets at the seabed. In the south sand was and still is transported by tidal currents towards the north, elsewhere seabed sands consist of reworked glacial sand. The large saucer-shaped depression between Dogger Bank and the Frisian Islands has muddy sand and mud at the seabed. Sands immediately below these muddy seabed sediments in places show evidence of dispersed gas.

## Database used

We have conducted a 'quick-scan' of some released in-house seismic data and other acoustic data mainly from the northern part of the Netherlands North Sea sector, in search of different expressions of shallow gas. Fig. 1 shows the position of standard E&P seismic lines used for the inventory, as well as the location of a number of known potentially commercial shallow gas fields in the northernmost part of the Netherlands North Sea sector. 2D seismic lines from a 1989 regional survey covering the northern part of the Netherlands offshore were studied, as well as a 1987 3D-survey covering most of block F3. In addition to the digital seismic data shown in Fig. 1, available digital sleeve gun and sparker data and analogue records of sub-bottom profilers and sonar data have been studied in order to describe the shallower phenomena. The objective of the inventory was first of all to find features that are indicative for the occurrence of shallow gas or for seepage and migration to the seabed.

## Surface expressions

### *Pockmarks*

Morphological surface expressions include pockmarks. These are rimmed circular depressions, which in the North Sea are normally 10-300 m in diameter and up to 15 m deep (McQuillin and Fannin, 1979). Pockmarks may contain coarser sediments or carbonate crusts and/or bacterial mats inside. They are thought to be created by either sudden and enigmatic or periodical or semi-continuous escape of gas. They can be detected on (side-scan) sonar or on very high frequency (VHF) acoustic data. Within a pockmark there may be lots of small pockmarks (coined unit pockmarks by Hovland & Judd, 1988) of a few metres across. The presence of carbonate crusts in pockmarks may be inferred from very high seismic reflectivity values (Judd, 1990). Pockmarks were first found in the central and northern North Sea in the seventies (Hovland & Judd, 1988), but first noticed in the Netherlands sector in the early nineties (Laban, 1999) during a re-examination of SONIA 3.5 kHz profiler records from the seventies in blocks A5 and F10. A 1998 side-scan sonar record from block A11 presented us for the first time with an image of a larger pockmark. Actual gas venting has not yet been observed with certainty. Fig. 1 shows the locations of these pockmarks observed to date.

The diameter of the pockmark seen in block A5 on 3.5 kHz data (Fig. 2) is about 40 m, and the depth is about 2 m. This record also indicates the presence of shallow gas underneath the pockmark by acoustic blanking. Fig. 3 shows the larger (about 140 m in diameter) pockmark found in block A11. There is reason to assume that this particular pockmark has a partly cemented pockmark floor. Hovland et al., (1985, 1987) described slabs and crusts of carbonate-cemented sands found within a pockmark in 1981 and 1983. Cements consisted of Mg calcite microspar and fibrous aragonite. Oxygen isotopic composition was normal for temperate marine carbonates, while carbon isotopic composition was extremely depleted in $^{13}C$, indicating that most of the cement derived from the oxidation of biogenic or a mixed biogenic/thermogenic methane source. Mg calcite cements precipitated in the sulphidic diagenetic environment while aragonite seems to be the mineral associated with oxic methane oxidation. According to Hovland et al. (1987) the position of the boundary between the two diagenetic environments depends on gas migration, on pore water flow rates and on sediment accumulation or removal.

### *Gas-induced carbonate-cemented sediments*

Recent carbonate-cemented sediments have been reported from Jutland coastal sites already for quite some time (Juel, 1839). Van Straaten (1957) summarised cemented sandstone findings along the Dutch coast from the late 19th century (Lorié, 1897) onwards, unfortunately none in-situ. They were collected on the Frisian islands Terschelling, Ameland (between KP 17 and 21 only, 2 surveys, some 60

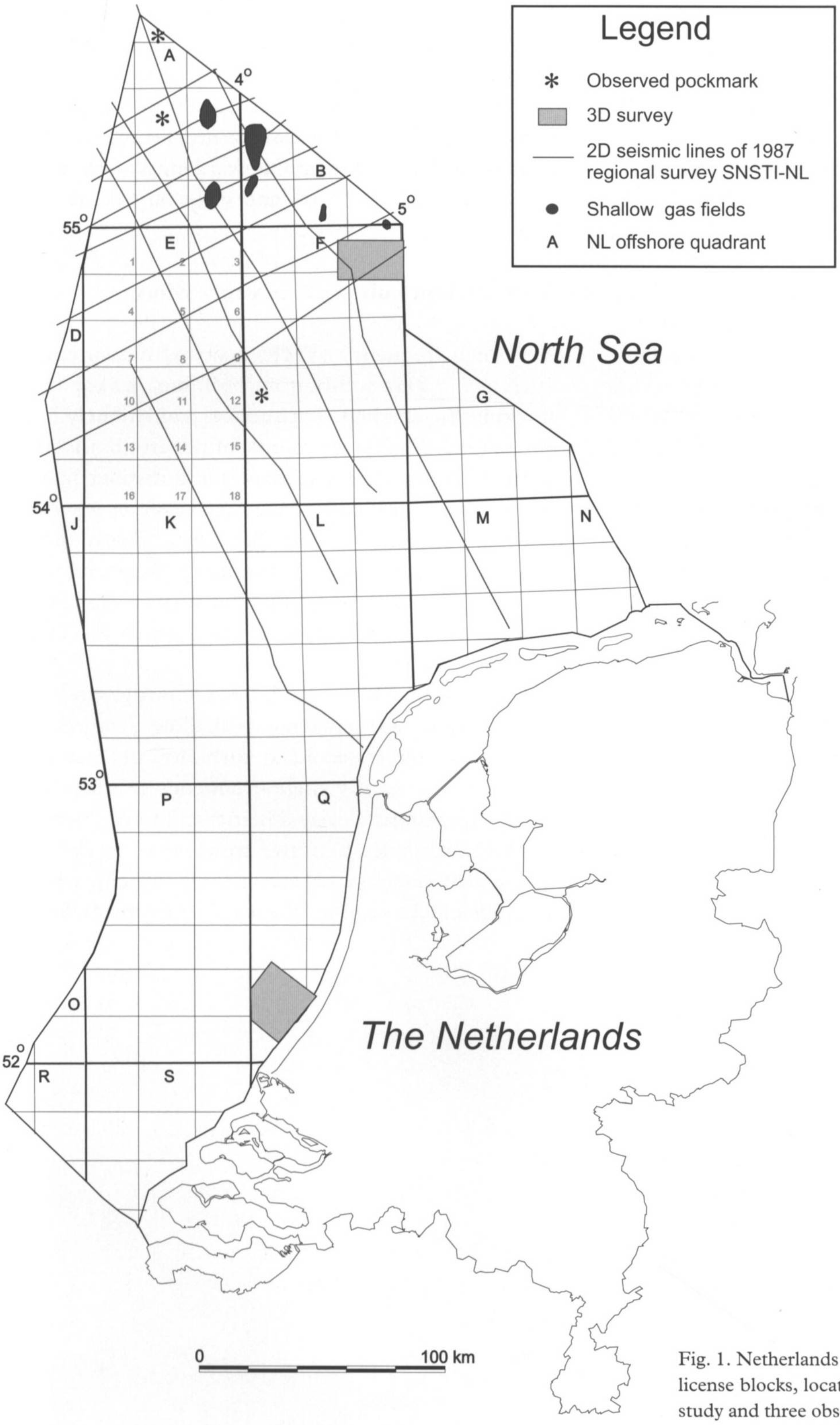

Fig. 1. Netherlands offshore sector, showing quadrants and license blocks, location of 2D and 3D surveys used for the study and three observed pockmarks.

years apart, i.e. over the present Ameland-East gas field), Borkum and Langeoog and along the continuous Holland coast with concentrations between IJmuiden and Bergen NH. The sandstone collected between IJmuiden and Bergen, NH contains a Recent nearshore marine mollusc fauna and was generally formed on the shoreface, not the beach. Some shell material taken from the stones gave a $^{14}C$ age of 2400 ±70 BP. Sandstone from Ameland, Zandvoort and off Callantsoog contains a Wadden Sea cq. a tidal flat fauna indicating a derivation from older back-barrier sediments. Searches for cemented sandstone chunks along the Katwijk – Noordwijk beach and near Callantsoog proved fruitless. Van Straaten (1957), at a

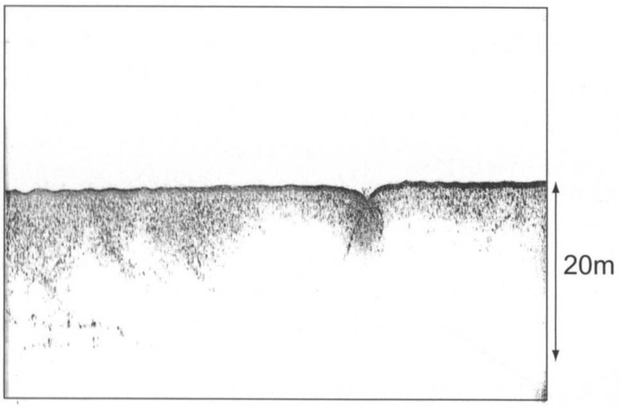

Fig. 2. A seabed pockmark observed in license block A5 on a SONIA 3.5 kHz record from the seventies. Diameter 40 m and depth 2 m.

loss with regard to the cause of the carbonate cementation, noted that cemented sandstone was found both in the lime-rich beach sands south of Bergen, and in the lime-poor beach sands of the Frisian Islands. This implied that the carbonate content of local sands was not a factor for their occurrence.

Jørgensen (1976), reporting on cemented submarine and littoral sediments from E. Jutland, suggested the crucial role of biogenic methane in their formation, based on isotope analysis which showed that the cements age was about 18,000 $^{14}$C years, while the associated skeletal fragments were up to 4000 BP. In this area there are two main morphological appearances: as slabs or pavements, less than 0.3 m thick and close to the seabed (Mg calcite with some aragonite), and as pillar-like structures, several metres in length, perpendicular to and well-rooted in the seabed (dolomite), with vertically oriented pipe-like structures. The pillar-like structures were most likely formed due to significant upward migration of considerable amounts of gas and gas-charged formation water (Jørgensen, 1994).

## Very shallow sub-surface expressions

Very high frequency (VHF) acoustic measurements, such as 3.5 kHz sub-bottom profiling, are capable of imaging the shallowest sequences immediately below the seabed. The typical depth of penetration is about 25m. From this kind of data some distinct features are known to be sub-surface expressions associated with the presence of shallow gas. These include acoustic blanking, acoustic turbidity, enhanced reflections, bright spots and columnar disturbances. Quite frequently these features may be seen in association with each other.

In the Netherlands North Sea sector the most commonly observed gas-related shallow features are: acoustic blanking, acoustic turbidity and enhanced reflectors. Especially single-frequency profilers show these expressions clearly. Their distribution, however, is highly variable. In some concession blocks these gas-related phenomena are virtually absent, whereas in other blocks (e.g. in block F3) they may affect up

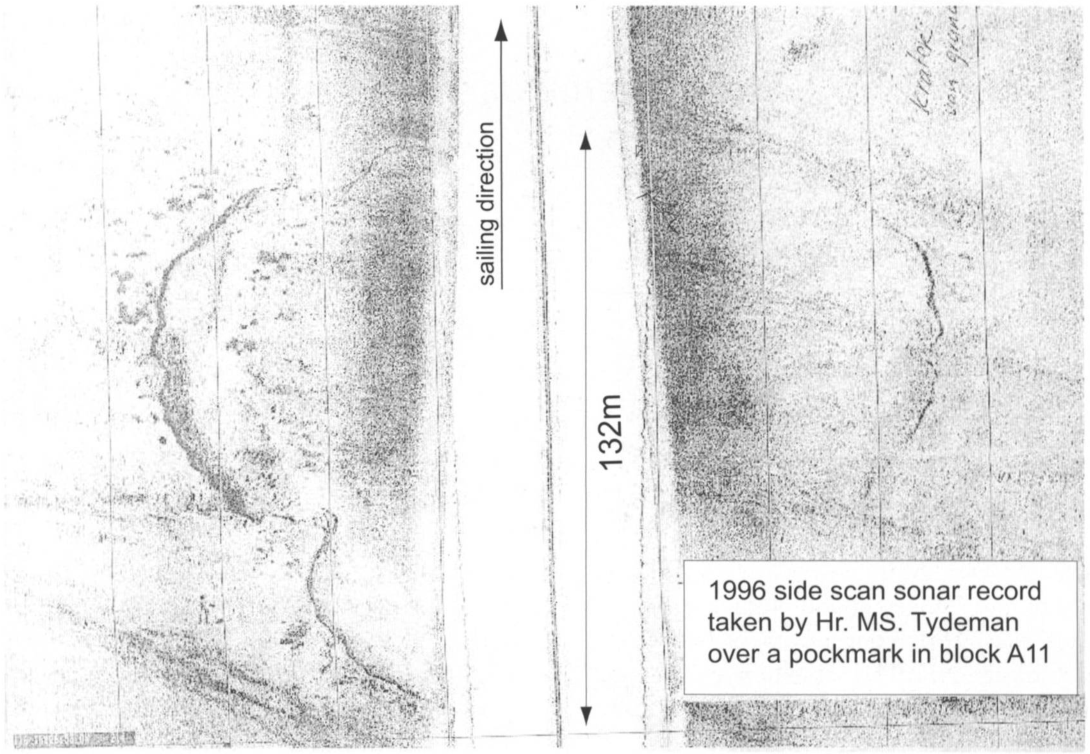

Fig. 3. A seabed pockmark observed in license block A11 on a 1998 sidescan sonar record. Diameter 140 – 150 m.

to 50% of the records. Acoustic blanking, and to a lesser extent acoustic turbidity, are locally very common in channel-fill settings (in the northern part of the Netherlands offshore in particular), but also occur underneath or within clay caps and seabed muds. Figs 4,5 and 6 show a few examples of acoustic blanking that we have found in the Netherlands North Sea sector.

*Acoustic blanking and acoustic turbidity*

Acoustic blanking appears as patches where reflections are faint or absent. These may result from the disruption of sediment layering by the migration of pore fluids or gas, or alternatively may be caused by the absorption of acoustic energy in overlying gas-charged sediments. It may also be caused by the reflection of a high portion of the acoustic energy by a highly reflective sedimentary layer; the reduction in the amount of energy penetrating such a layer being represented by a relatively low amplitude return signal (Judd & Hovland, 1992). Acoustic blanking may already occur at gas concentrations of 0.5% and more (pers. comm. F. Abegg, 1997). Shallow acoustic blanking in the Late Pleistocene and Early Holocene strata is locally common outside of major channel-fills as in block F3.

Acoustic turbidity is a term used for shallow chaotic reflections, caused by the scattering of acoustic energy, with the appearance of a dark smear on the VHF record, obliterating all other reflections. It may occur when there is as little as 1% of gas present (Fannin, 1980). Hovland & Judd (1988) and Laban (1995) showed acoustically turbid sediments and acoustic blanking in the Late Weichselian Botney Cut Formation in the Botney Cut glacial valley in Netherlands offshore blocks J3 and K1. On nearby shallow seismic profiles across Markham's Hole and Botney Cut there are also zones of acoustic blanking, suggesting that the sediments are locally gas-charged (Cameron et al., 1986, 1989). Acoustic blanking is largely within the upper, laminated, lacustro-glacial clayey fill. Also in a similar setting in the nearby Outer Silver Pit area acoustic blanking was reported (Jeffery et al., 1989).

In the southern part of the Netherlands sector, in the area of the Flemish Bight (52°-53°N, 2°-4°E , the Netherlands O and P blocks) the Late Eemian-Early Weichselian clayey Brown Bank Formation's internal structure is completely masked by discrete zones of acoustic blanking (Cameron et al., 1984). This is accompanied by a reduction in the amplitude of deeper reflectors beneath these zones on some of the sparker records. Similar acoustic blanking is common within soft, clayey sediments in the central and northern North Sea and was attributed by Fannin (1980) to scattering of the acoustic energy from the seismic source by interstitial gas (Cameron et al., 1989). It seems likely that the sediments of the Brown Bank Formation are similarly gas-charged within these zones, which have a total areal extent of approximately 500 km$^2$ on the Flemish Bight sheet. Similar sediments on the adjoining Indefatigable Sheet 1:250,000

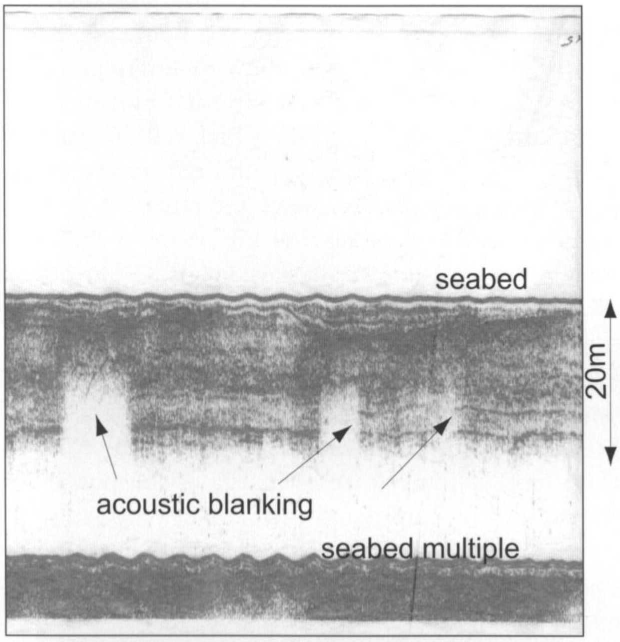

Fig. 4. Acoustic blanking below channel fills on a 1969 SONIA 3.5 kHz record from license block F3.

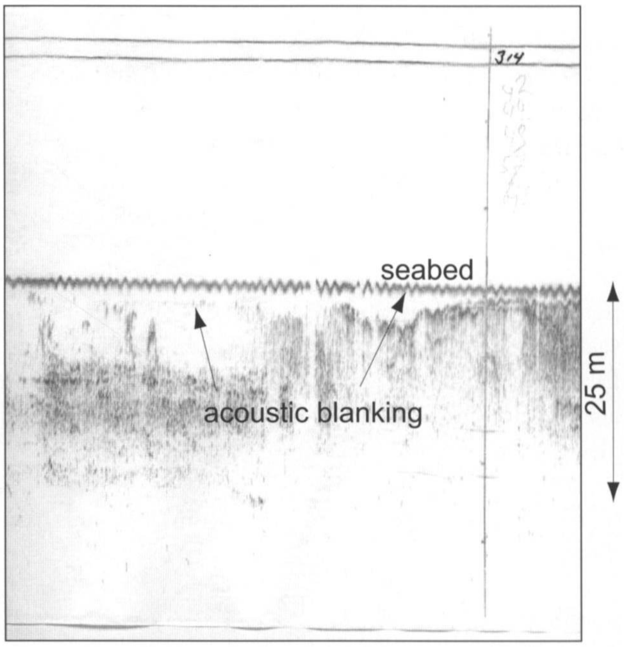

Fig. 5. Acoustic blanking in Holocene surface sediments (right hand side) and in Wechselian sediments (left hand side) on a 1972 SONIA 3.5 KHz record from block F3.

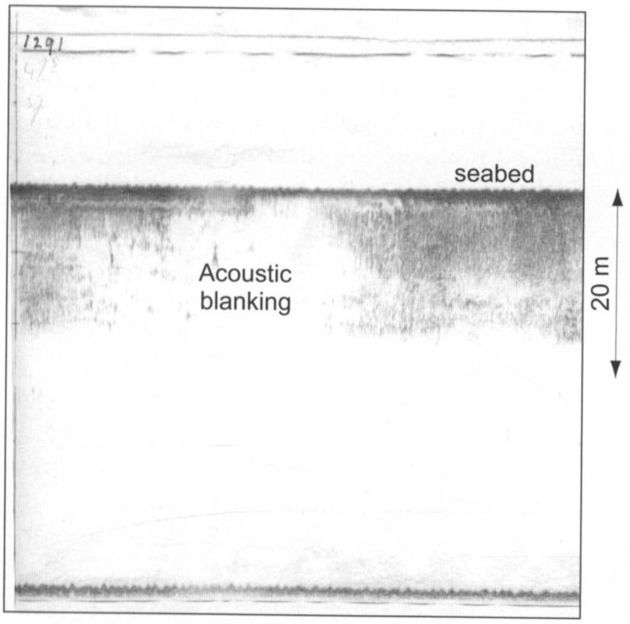

Fig. 6. Strong localised acoustic blanking of thin Holocene surface sediments and of underlying Wechselian and Eemian sediments on a 1972 SONIA 3.5 KHz record from block F3.

map (Cameron et al., 1986) do not show such conspicuous acoustic blanking.

*Enhanced reflections*

Enhanced reflections are coherent seismic reflections with increased amplitudes over part of their extent (equivalent to the bright spots summarised below). It is not uncommon for enhanced reflections to extend laterally from zones of acoustic turbidity. It is thought that, in very shallow sediments, gas may occur either as accumulations within porous (silt- and sand-rich) sediments, or finely disseminated within impervious (clay-rich) sediments. It would seem that acoustic turbidity characterises the latter situation, and enhanced reflections the former (Judd & Hovland, 1992). The rather steep flanks of glacial valleys, which may be up to 400 m deep in the Netherlands sector, show in places high-amplitude reflectors suggesting pathways in which dispersed gas is in transit to the seabed. We have observed this in blocks M2 and L4 in Elsterian channels. Some enhanced reflections may also be present in the middle, laminated, part of the glacial-channel infill.

## Sub-surface expressions on standard seismic data

Standard E&P seismic surveys can also reveal expressions of shallow gas. This has already been demonstrated (e.g. by Heggland, 1994 and 1997). However, given the facts that the water-depth in the Netherlands sector of the North Sea is less than 50 m, and that the reflections from about the first 100 msec are lost in the mute of standard surveys, there is no meaningful seismic imaging of at least the shallowest 30 – 40 m of the sediments. Depending on the quality and characteristics of a particular survey one can start seeing reflectors in the Netherlands sector at levels deeper than about 40 – 50 m below seabed. For the same reason it is impossible to map a seabed reflector in this area. In deeper water areas an automatically tracked seabed reflector sometimes reveals surface features like pockmarks. Below an overview is presented of the sub-surface expressions of shallow gas that we do see in the Netherlands sector. Some of these features are indications for gas accumulations that are trapped in a sandy reservoir unit, overlain by an apparently efficient seal, whereas other features are indications for leakage or seepage of gas to the seabed.

*Shallow enhanced reflections*

Many of the 2D seismic lines of the 1987 regional survey (Fig. 1) contain localised occurrences of enhanced reflections in the shallowest part of the sections (i.e. between 100 – 400 msec TWT, corresponding to 70 - 350 m below MSL). Within these occurrences the seismic amplitudes can be extremely high compared to the immediately surrounding sediments. This is a strong indication for the presence of gas. Fig. 7 shows two examples close together on a seismic section across block F7. Apart from the clear increase in seismic amplitudes in the shallowest zone, another remarkable feature is the reflector-dimming underneath. The low-amplitude shadow zones are probably the result of the fact that very little acoustic energy is transmitted through the shallow high reflectivity zone to the deeper levels. Although the reflections within the shadow zone are very weak, the reflection pattern is not chaotic, indicating that the cause of the dimming is probably not within the zone itself. The observation that adjacent to many of these features faults can be interpreted cutting all the way to the seabed, indicates that gas may have migrated along these faults from deeper down, and thus that the gas would be primarily thermogenic in origin. When taking a close look at these features in Fig. 7 the possibility should also be considered that in fact only the shallowest of these strong reflections represents a true gas-charged layer, and that the ones underneath represent multiples from the first one. In any case the feature would still be a shallow gas indicator.

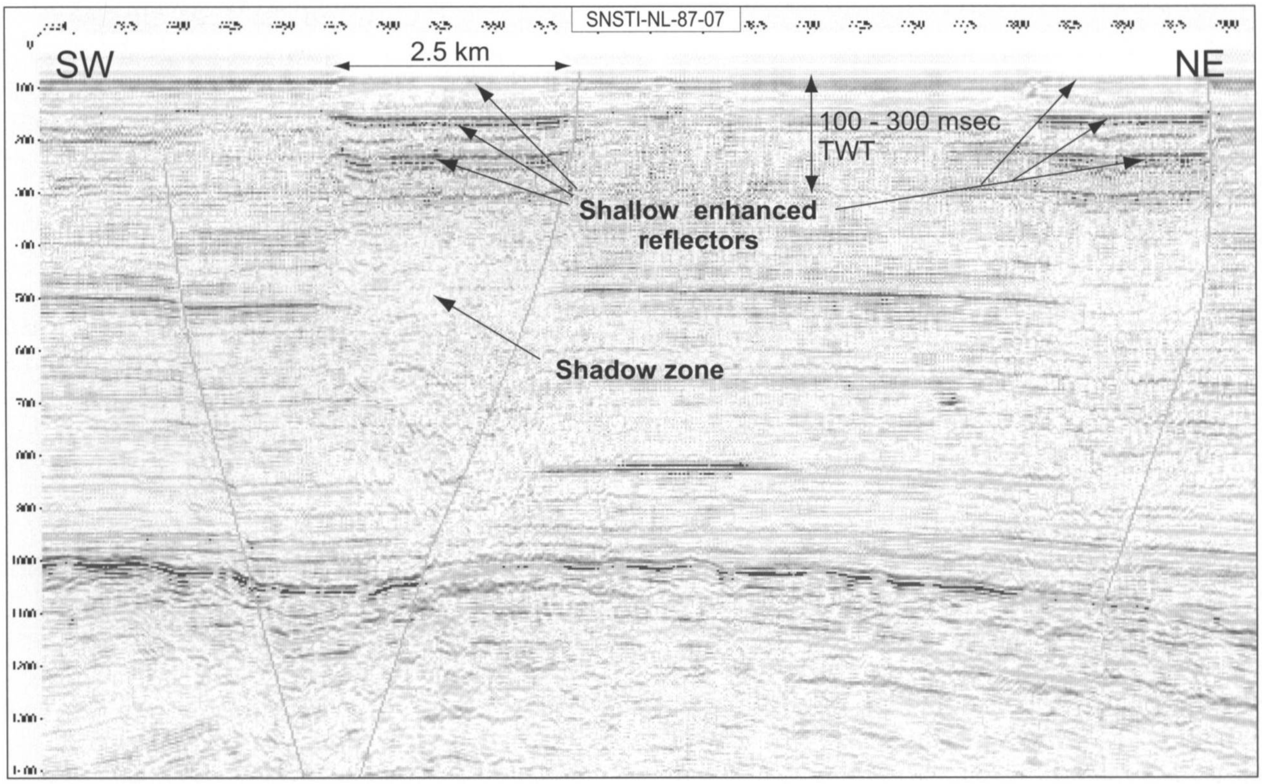

Fig. 7. Shallow enhanced reflectors adjacent to faults cutting to the seabed in the uppermost 300 msec of regional 2D seismic from 1987. This example is from license block F7. Similar features are abundant in the northern Netherlands offshore. The deeper anomalies might be multiples (processing artefacts) of the shallowest.

*Bright spots*

One of the best-known direct hydrocarbon indicators on seismic data is the bright spot. It is a high amplitude anomaly caused by the strong decrease in acoustic impedance at the top of a reservoir charged with hydrocarbons. The bright spot effect diminishes with greater depth, and is much stronger with gas than with oil, thus most examples of bright spots relate to shallow gas-charged reservoirs. If the reservoir is thick enough, it is usually accompanied by underlying high amplitudes of opposite phase, caused by the impedance contrast at the gas-water interface (a flat spot). In case of thin reservoir units these two reflections cannot be distinguished. Fig. 8 shows an example from the 3D survey in block F3 of such a bright spot over a flat spot.

In the northern part of the Netherlands North Sea sector abundant bright spots can be seen in the Upper Pliocene – Pleistocene sections, usually corresponding to low-relief structural highs (anticlines) above salt structures. Some of these gas accumulations are large enough (bright spots with diameters up to 10 kms) to be of economic interest, many others are smaller, like the one shown in Fig. 8. In fact, this figure taken from the 3D survey in block F3 is a good example of a shallow bright spot over a flat spot. At the level of the bright spot a possible polarity inversiopn of the seismic signal can been seen. What these accumulations all have in common is their typical depth of about 500 - 800 msec TWT, which corresponds to about 450 – 800 metres below MSL. In comparison to the shallow enhanced reflections that occur at shallower levels, the bright spot accumulations are more clearly related to certain stratigraphic levels, and to closed structural traps. This implies that the gas occurrences causing bright spots are more similar to efficiently trapped and sealed hydrocarbon accumulations, while the enhanced reflections may be more the result of unsealed gas-saturated unconsolidated sediments, through which the gas passes to the seabed.

*Buried gas-filled ice-scours*

Time-slices from 3D seismic surveys can reveal buried iceberg scour-marks. Gallagher et al. (1991) showed examples from the mid-Norwegian shelf. The ice-scours within Upper Pliocene sediments are visible because they are filled with sand, which hosts shallow gas. The resulting display in the horizontal plan is a very typical pattern of straight and narrow lineaments in different directions. In the 3D survey from the Dutch block F3 we have found similar ex-

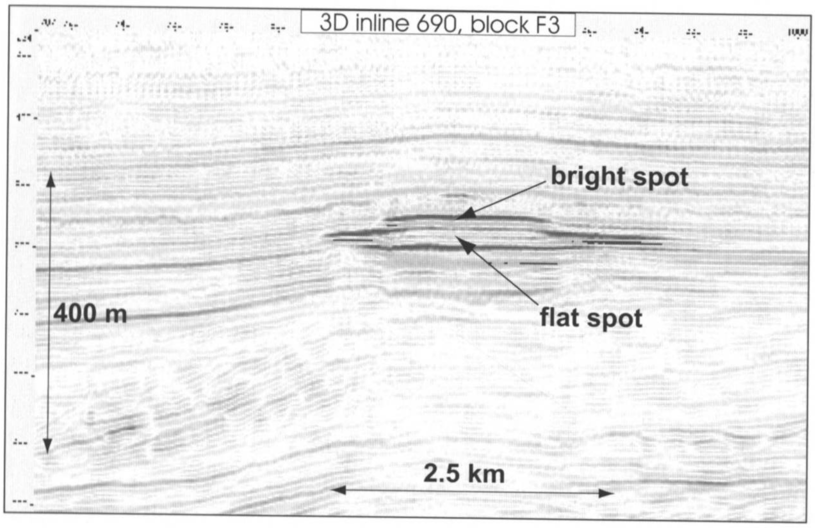

Fig. 8. A shallow bright spot overlying a flat spot which corresponds to the gas-water-contact in the Upper Pliocene sediments of license block F3. This expression is indicative for effective structural trapping of shallow gas in high porous stratigraphic intervals.

amples on several time-slices. Fig. 9 is from a time-slice taken at 528 msec. Also in this case the age of the marks would be approximately around the Pliocene-Pleistocene boundary of 1.8 Ma. At this time ice-bergs could have drifted into the North Sea area from the north. These features are known drilling hazards. The last major blow-out off Mid Norway was reported to have occurred in a dense grid of such gas-filled sands related to ice-scours.

### *Seismic anomalies indicating leakage*

We use the term *seismic anomalies indicating leakage* to describe the sub-surface expressions that might be related to leakage or seepage. This is an objective and descriptive term, which would include the more interpretative term gas-chimney, that is often found in literature on hydrocarbon migration. Also included are phenomena like direct indications of leakage along fault trajectories, and smaller local gas accumulations indicated by high amplitudes located along flanks of glacial valleys.

### *Gas chimneys*

One type of seismic anomaly that is indicative for leakage of hydrocarbons is the so-called gas chimney. Gas chimneys or seismic chimneys are vertical disturbances in seismic data that are interpreted to be associated with the upward movement of fluids or free gas. Heggland et al. (2000) and Meldahl et al. (2001) have reported on examples of seismic chimneys, and have also demonstrated the added value of automated systems for the detection and analysis of these features in 3D seismic data-cubes. They mention that most of these vertical disturbances are characterised by low seismic amplitudes, and low coherency. Different mechanisms can explain such characteristics. Gas residing in the pores changes the acoustic properties of the rock. Because of this, it may be that locally the seismic processing has not been adequate, using the wrong processing velocities, and as a result seismic imaging is poor. An alternative explanation, relating more to the physical mechanisms of the fluid flow involved, would be that the over-pressured fluids or gasses have cracked the rocks (or disturbed the sedimentary bedding in the case of unconsolidated sediments) resulting in a scattering of seismic waves, and very little focussed reflected energy. Depending on the particular case, either of the two mechanisms or the combination of both may be responsible.

Fig. 10 shows a chimney we have found in the 1989 3D survey of block F3. It is visible both on the vertical sections and on time-slices, and is related to a

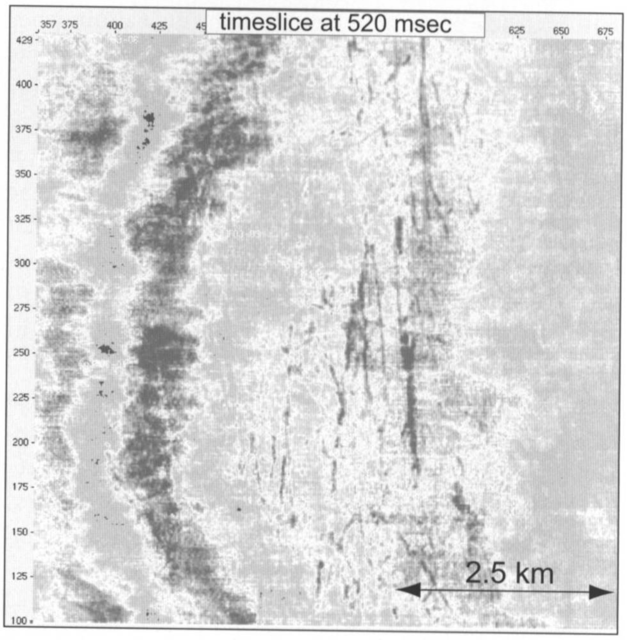

Fig. 9. Scour marks left behind by icebergs scratching the seabed visible on a time-slice from the 3D seismic cube in block F3 taken at 520 msec TWT.

fault running from an associated underlying salt dome up to the seabed. Also associated are bright spots in Upper Pliocene intervals, indicative of the presence of gas, immediately underneath the chimney. This chimney is characterised by increased seismic amplitudes within the chimney, and by the preservation of reflector continuity, and therefore of sedimentary bedding within the chimney. In this respect it contrasts with the examples of seismic chimneys published by e.g. Heggland et al. (2000) and Meldahl et al. (2001). This difference could imply a difference in migration mechanisms. One hypothesis is that the type of high amplitude / preserved reflector continuity seismic chimney relates to a gas migration mechanism which has been slow and moderate enough not to disturb the original sedimentary bedding too much (Schroot, 2002).

Our example more resembles the gas chimney above the Machar salt dome in the Central North Sea (UK quadrant 23) presented by Thrasher et al. (1996). They interpret the Machar dome chimney to represent smaller and localised seepage. Smaller and localised seepage would be one particular seepage style in a range of possible styles, ranging from spectacular to weak but highly focussed. Spectacular seepage appears to result from high rates of sedimentation and from active tectonism, while weaker localised seepage is often related to mud or salt diapirs. Gas chimneys and high gas concentrations in mud logs have been recognised over many Central North Sea salt structures. The salt structures seem to act as foci for hydrocarbon migration. With respect to the migra-

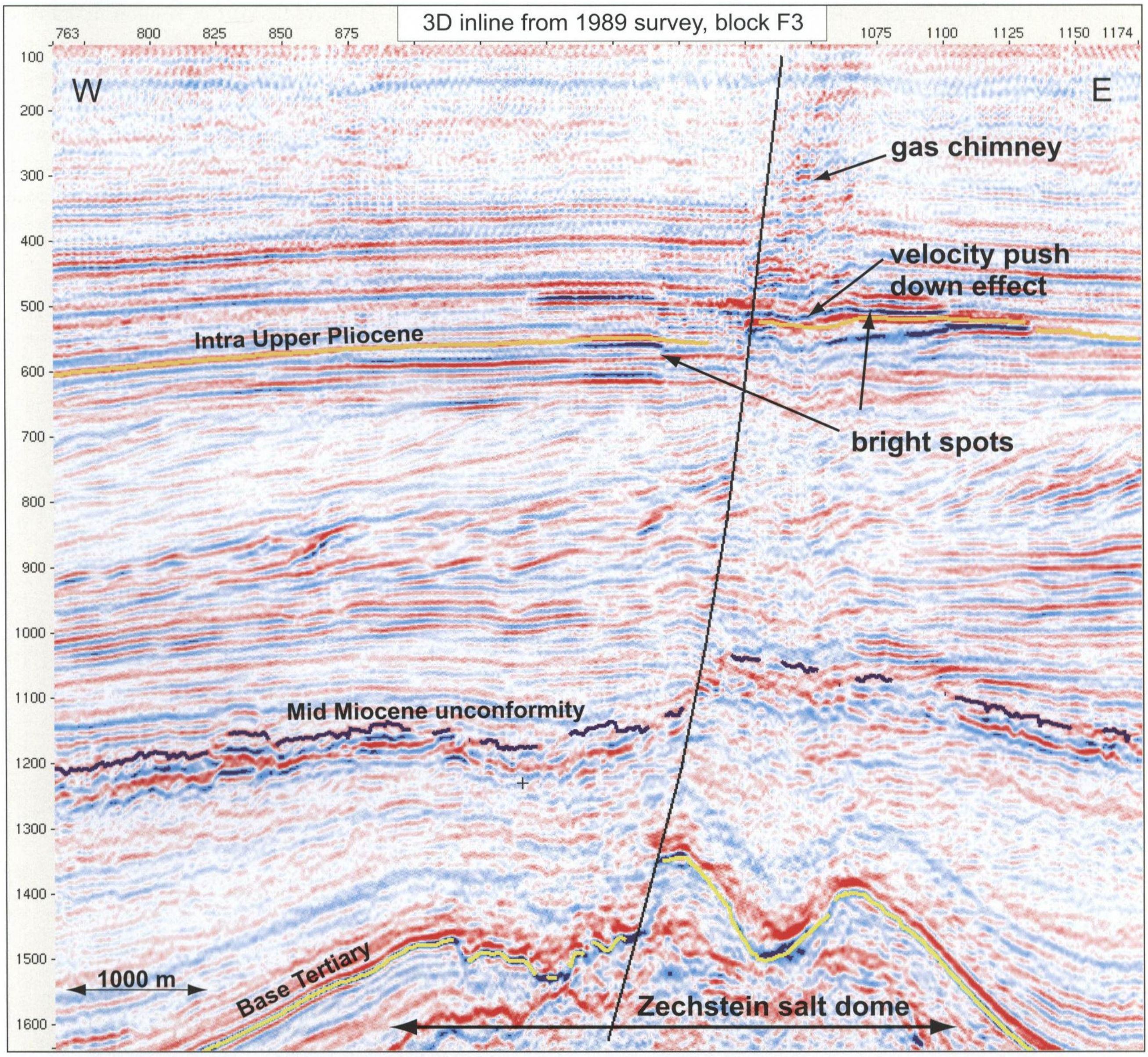

Fig. 10. A gas chimney adjacent to a fault and immediately overlying an apparently leaking bright spot at reservoir levels similar to the example in Fig. 8. A velocity push down effect can be seen underneath the chimney.

tion mechanism in case of the Machar dome, Thrasher et al. (1996) comment that overpressure in the Machar reservoir is insufficient for fluid induced fracturing, and that therefore the primary leakage mechanism must have been capillary failure of the top seal. Salisbury (1990), who described high resolution seismic data from the same area, concluded that for the vertical gas migration in this setting there are two different types of pathways: either along Tertiary fault planes, or through gassified sediment columns (seismic chimneys). He also pointed out that horizontal migration takes place via the sandy/silty layers within the otherwise clay sequence. It is thus clear how the salt structures focus the migration.

*Fault related amplitude anomalies*

An additional observation made elsewhere in the 3D survey in block F3 is shown in Fig. 11. Again seepage of gasses or fluids can be interpreted right over a salt dome.

Some extensional faults related to the salt structure are providing the migration path up to the seabed. Relatively small patches of high seismic amplitudes can be followed upward along the faults (most clearly visible at the westernmost fault). The interpretation is that wherever the fault intersects favourable stratigraphic levels (i.e. sandy layers with good reservoir properties overlain by some sealing shaly beds) migrating gas is temporarily stored, giving rise to the small bright spots. These 'seismic anomalies indicating leakage' are clearly related to the presence of a fault system. When dealing with gas chimneys, such as described above, this may not always necessarily be the case.

*Shallow disturbed zones*

A last example of 'seismic anomalies indicating leakage' is the noise present in localised patches at shallow levels shown in Fig. 12. The profile in this Fig. is from a 1990 3D survey in block Q13 a few kilometres off the coast of Holland. Like the shallow enhanced reflectors, these features also seem to indicate the presence of shallow gas between the seabed and a depth of about 500 m. They differ from the 'shallow enhanced reflectors' because of the total lack of seismic coherency. In a way they are somewhat similar to low-coherency seismic chimneys, but a difference is that we see these shallow disturbed zones mainly in

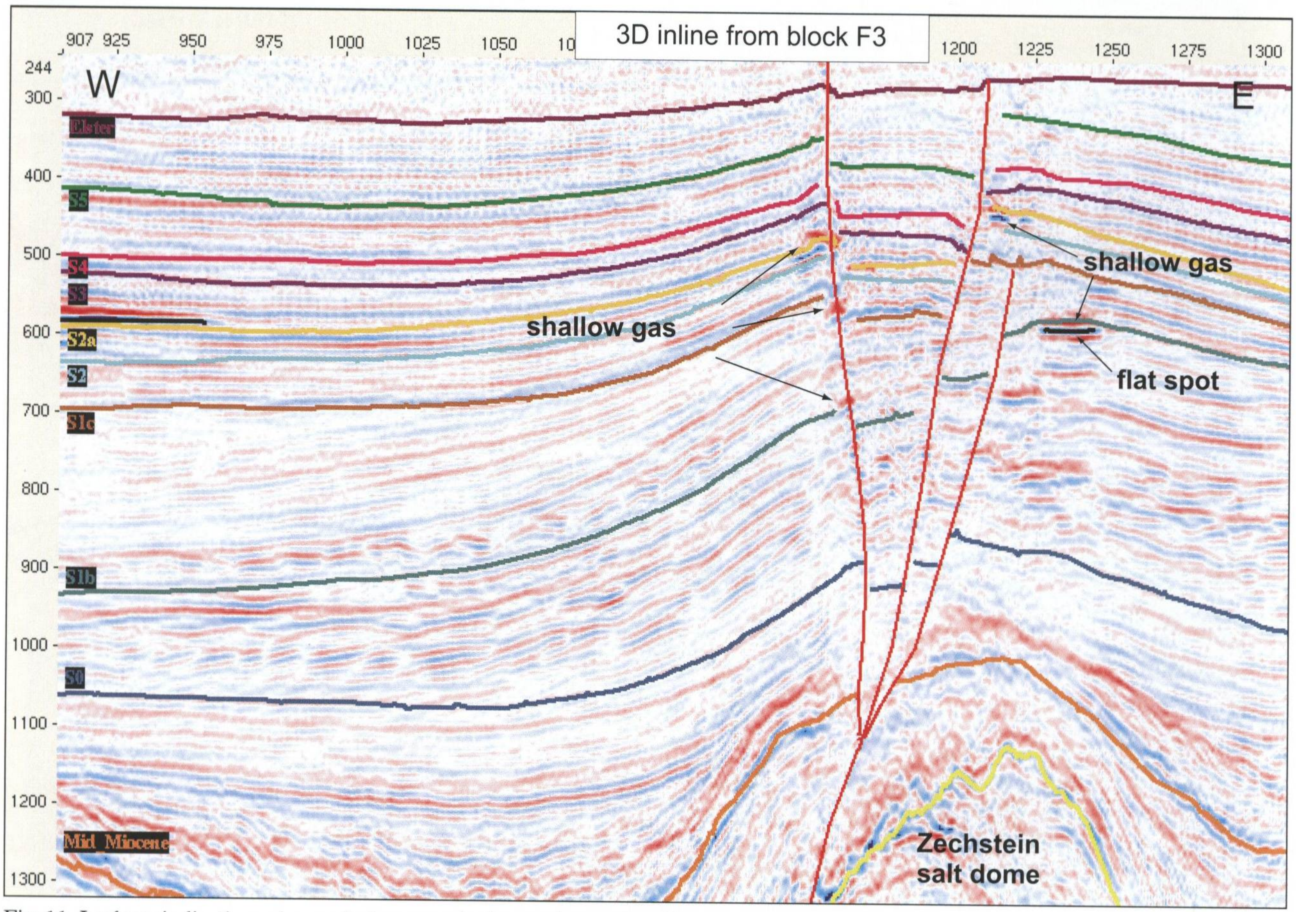

Fig. 11. Leakage indications along a fault system in the northern part of block F3. Wherever the fault, which provides the migration path, intersects a sandy or silty layer small localised bright spots indicate the accumulation of gas.

the uppermost couple of hundred metres. An interpretation of these features could be that the noisy zones are the result the failure of seismic processing to properly image localised areas with anomalously low seismic velocities. Again the low velocities themselves may be related to gas-saturation.

## Discussion and conclusions

A closer look at indications for shallow gas in the Netherlands North Sea shows that numerous gas-related phenomena occur. Some features (such as bright spots) indicate gas accumulations which are efficiently trapped and sealed in shallow reservoirs, whereas a whole range of other features point at frequently occurring leakage and migration of gas to the seabed. There is indirect evidence for actual gas venting, e.g. by the observation of pockmarks. There also appear to be more cases of gas-induced carbonate-cemented sediments than previously thought.

Although biogenic generation also plays a role, and there will certainly be admixture of such gas, most of the phenomena observed in the Netherlands offshore relate to the migration of thermogenic gas from deeper sources to the near-surface environment. From our observations we conclude that many of the seismic anomalies indicating leakage found in the area correlate with the positions of salt structures, and that the normal faults which are very often present over the crests of these structures, provide migration pathways to the shallow realm for the thermogenic gas.

In terms of seepage styles, the gas chimney found in block F3 best fits the 'weak and localised seepage style', often related to focussed seepage over salt structures, defined by Thrasher et al. (1996). In the same area indications on seismic profiles of gas migration along fault systems subscribe to this point of view.

At near-seabed depths major gas retention media are sheet-like plastic clays or muddy sediments, not (yet) affected by appreciable compaction and by faulting. Glaciations with associated low-stands and high-stands have apparently played a major role in the present abundance of gas-related phenomena such as acoustic blanking in glacial and low-stand channels, enhanced reflectors in glacial valleys and gas-charged

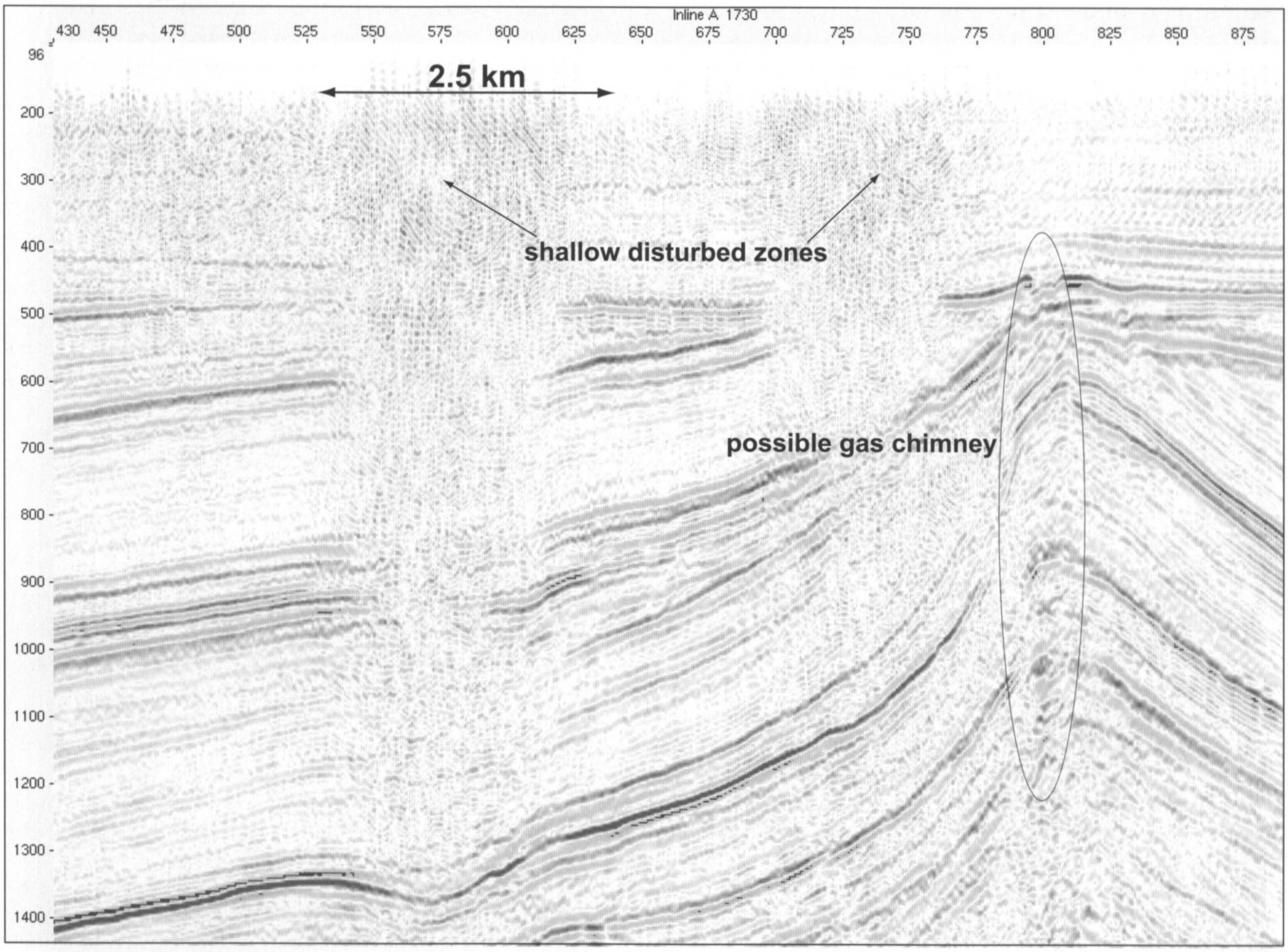

Fig. 12. Shallow disturbed zones indicating the presence of gas in the shallowest sediments which results in inadequate seismic processing for the underlying part of the section. A possible gas chimney is visible at crossline location 800. Example from a 1990 3D survey in block Q13.

ice-scours. Permafrost, a different preservation potential of organic matter, sub-glacial channel formation and glacially reactivated salt tectonics and faulting may all have contributed to the present situation. This however falls outside the scope of this paper.

The apparent abundance of shallow gas in the Netherlands North Sea sector and its significance both as a resource and as a hazard, merit a detailed search in the Netherlands sector for significant gas-related phenomena and pathways. One of the aims of future work will be to better reconcile the observations made in the shallowest realm (using very high frequency methods) on the one hand with the observations made on standard E&P seismic data on the other. Another objective will be to describe the time-dependency of the features found so far, e.g. investigate how gas chimneys possibly change with time. A better understanding of the dynamics of the gas migration systems is also needed. A more complete classification in the future of the features indicating leakage and an understanding of the different mechanisms related to the different classes and the seepage styles is needed. Once adequate models exist, tools like seismic and geochemical monitoring will directly yield a description of the migration processes if they take place. This would be highly relevant when the geological boundary conditions for safe and efficient storage of $CO_2$ have to be formulated, and when monitoring systems will be used in the event of actual storage.

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