Princetonlaan 6
3584 CB Utrecht
P.O. Box 80015
3508 TA Utrecht
The Netherlands

www.tno.nl

T +31 88 866 42 56
F +31 88 866 44 75

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Inventory of wells through shallow gas layers in the Dutch North Sea

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Author(s)	M. Wilpshaar, G. de Bruin and N. Versteijlen
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Samenvatting

Tijdens een dertigledendebat op 14 november 2017 over een nieuwe gasvondst ten noorden van Schiermonnikoog heeft de Tweede Kamer ook aandacht gevraagd voor methaan-emissie bij gaswinning. In dit debat werd gerefereerd aan recente publicaties van Vielstädte et al. (2015, 2017). Deze publicaties stellen dat putten die lagen met biogeen ondiep gas penetreren, achter de verbuizing van de boorput kunnen lekken. Hierbij is berekend dat 3.000 tot 17.000 ton (1 ton=1.000 kg) methaan per jaar vrijkomt in de Noordzee. Los hiervan heeft SodM op 21 en 22 maart 2018 een symposium bijgewoond van de EUOAG (EU Offshore Authorities Group) met een technisch workshop met onder meer een presentatie over de publicaties van Vielstädte[1].
SodM heeft vervolgens op 18 juni 2018 TNO-AGE opdracht gegeven om nader onderzoek te doen specifiek voor het Nederlandse deel van de Noordzee. De specificaties van de opdracht zijn terug te vinden in de beantwoording van de minister op de Kamervraag (11 oktober 2018) naar aanleiding van het voorgenoemde dertigledendebat. SodM heeft daarbij TNO-AGE gevraagd om vast te stellen of de genoemde geologische condities zich ook op het Nederlandse Continentaal Plat kunnen voordoen en welke putten 'ondiep gas' doorboren.

TNO-AGE heeft met behulp van seismische interpretatie en put data een lijst met putten in de Nederlandse Noordzee opgesteld die ondiep gas doorboren. De aanwezigheid van gas in ondiepe sedimenten veroorzaakt anomalieën (bright spots) in seismische data. Daarnaast kan gas worden waargenomen tijdens het boren. De analyse van bright spots en boorgegevens laat zien dat ongeveer 10% van de putten ondiep gas doorboort (216 van de 2027 offshore putten).

Ook heeft TNO-AGE een literatuurstudie naar methaanemissie, ondiepe gasvoorkomens en methaanlekkage uitgevoerd. Hierbij zijn ook de recente publicaties van Vielstädte et al. (2015, 2017) beoordeeld om tot een eindconclusie te komen. Uit de literatuurstudie is gebleken dat de bandbreedte voor schattingen van de natuurlijke en antropogene methaan emissies enorm is. Voor het Noordzeegebied varieert deze voor bijvoorbeeld natuurlijke methaan emissie van enkele honderden tot miljoenen ton per jaar. Daarnaast laat de literatuurstudie zien dat veel ondiepe gasvoorkomens van nature lek zijn en daarbij methaan uitstoten.

De review van Vielstädte et al. (2015, 2017) heeft geresulteerd in kanttekeningen bij de aannames en getallen die gebruikt zijn om de totale gas lekkage van de gehele Noordzee te berekenen. Vielstädte et al. (2015, 2017) berekent de methaanlekkage als volgt: het totaal aantal putten in de gehele Noordzee (11.122) vermenigvuldigd met de kans dat ondiep gas doorboord wordt (33%± 6%), vermenigvuldigd met de kans op lekkage (100%), vermenigvuldigd met een methaan lekkage van 1 tot 4 ton per put per jaar. Dit resulteert in een schatting van de totale methaanlekkage naar de waterkolom van de gehele Noordzee van 3.000 tot 17.000 ton per jaar. TNO-AGE is van mening dat belangrijke aannames onzeker zijn en/of te hoog zijn. Hierdoor hebben de berekeningen een grote onnauwkeurigheid en is er sprake van een overschatting.

- Een belangrijke aanname is dat álle putten die ondiep gas doorboren achter de verbuizing lekken (100%). Dit is onvoldoende onderbouwd;
  - Onderzoek van Cardon de Lichtbuer (2017) laat zien dat 2% tot 11% van

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[1] https://euoag.jrc.ec.europa.eu/node/157

    de geabandonneerde Nederlandse onshore putten mogelijk lekken.
  - Vielstädte et al. stelt dat het boorproces het sediment rond de boorput mechanisch verstoort en breekt, waardoor zeer permeabele paden worden gecreëerde voor migratie van het gas. TNO herkent dit niet als een voor de hand liggend mechanisme van methaanlekkage. Ondiep gas kan ontsnappen tijdens het boren, maar voor verlaten putten zijn put-integriteitsproblemen zoals 'bad cement' een meer voor de hand liggende oorzaken van lekkage (Gasda etal., 2004).
- De dataset van drie putten is ontoereikend en niet representatief voor de gehele Noordzee (11.112 putten).
- Het percentage putten dat bright spots doorboort is bepaald op 33± 6% aan de hand van een klein gebied in de Centrale Noordzee waar 18 op 55 putten een bright spot doorboren. Deze (uitgebreidere) studie laat zien dat dit percentage voor de gehele Nederlandse offshore ongeveer 10% is (216 op 2027).
- Bij twee van de drie gemeten putten is de relatie tussen de methaan lekkage en het doorboren van een bright spot onvoldoende aangetoond:
  - Eén put (16/4-2) doorboort geen bright spot terwijl er wel methaanlekkage is gemeten (4 ton per jaar). De oorzaak van de methaanemissie is niet onderzocht, maar is niet gerelateerd aan bright spots. Vielstädte et al. gebruikt deze meting wel om de hoogste methaanlekkage mee te bereken voor putten die bright spots doorboren.
  - Eén put (16/7-2) met de allerhoogste methaanemissie (19 ton per jaar) wordt niet gebruikt omdat deze niet representatief zou zijn. De locatie van deze boring gaat door een zogeheten ‘gas chimney’. TNO-AGE merkt op dat gas chimneys veelvoorkomende natuurlijke, huidige dan wel historische, lekpaden naar het oppervlakte zijn van (on)diepere gasophopingen. De carbonaat afzettingen op de zeebodem bij deze put wordt door Vielstädte et al. (2015) gezien als meest waarschijnlijk bewijs van natuurlijke methaan lekkage.
  - Vielstädte et al. heeft geen gebruik gemaakt van meetgegevens vóór de boring waardoor ook geen onderscheid gemaakt kan worden tussen natuurlijke en antropogene lekkage.
- Vielstädte et al. refereren aan een onwerkelijk lage natuurlijke methaan emissie van maar 200 ton per jaar voor de gehele Noordzee. Deze schatting is zeer laag, aangezien de meting van 19 ton per jaar van slechts één locatie (bij put 16/7-2) waarschijnlijk een natuurlijke oorzaak heeft. Schattingen van totale emissie uit andere publicaties (tot 6 miljoen ton per jaar) worden niet in ogenschouw genomen. Ook niet de hoge natuurlijke methaan emissies (478 ton per jaar, Römer et al., 2017) boven één enkel ondiep gas voorkomen (Schroot et al., 2015).
- Vielstädte et al. 2017 gebruikt ongeveer 42% om de fractie methaan te berekenen die de atmosfeer bereikt vanaf de zeebodem. Daarentegen gebruikt Römer et al. 2017 een veel kleinere fractie van minder dan 5%.

TNO-AGE concludeert in antwoord op de Kamervraag dat ondiepe gasvoorkomens ook aanwezig zijn op het Nederlands Continentaal Plat. De antropogene methaanlekkage zoals beschreven in Vielstädte et al. (2015, 2017) is onvoldoende onderbouwd en een overschatting.
In het algemeen is nader onderzoek gewenst naar natuurlijke en antropogene methaanlekkage alvorens er gerichte maatregelen in de buurt van boorputten worden geformuleerd. TNO-AGE concludeert tevens dat voor het bepalen van mogelijke methaanlekkage van boorputten het enkel bestuderen van putten die ‘ondiep gas’ doorboren niet voldoende is.

Abstract

During a *dertigledendebat* on the 14th of November 2017 regarding a new gas discovery to the North of Schiermonnikoog, the House of Representatives called attention, amongst others, to methane emissions related to gas production. This debate referred to recent publications by Vielstädte et al. (2015, 2017). These publications state that wells penetrating sediments containing biogenic shallow gas leak behind the casing of the borehole, thereby releasing 3,000 to 17,000 tons (= 1,000 kg) of methane per year into the North Sea. Apart from this, SodM visited a symposium (on 21 and 22 March 2018) of the EUOAG (EU Offshore Authorities Group) with a technical workshop and amongst others a presentation of the Vielstädte publications.
Subsequently, SodM decided on the 18th of June 2018 to assign TNO-AGE for a study specifically for the Dutch part of the North Sea. The details of the assignment can be found in the Minister's response (11 October 2018) to the earlier parliamentary question of the *dertigledendebat*. SodM requested TNO-AGE to determine whether the above-mentioned geological conditions can also occur on the Dutch Continental Shelf and which wells are drilled through 'shallow gas'.

Using seismic interpretation and well data, TNO-AGE compiled a list of wells in the Dutch North Sea that pierce through shallow gas. The presence of gas in shallow sediments causes anomalies (bright spots) in seismic data. In addition, gas can be observed during drilling. The analysis of bright spots and drilling data shows that about 10% of the wells pierce through shallow gas (216 of the 2027 offshore wells).

TNO-AGE has also carried out a literature study on methane emissions, shallow gas accumulations and methane leakage. Finally, the recent publications of Vielstädte et al. (2015, 2017) were reviewed in order to draw a conclusion. The literature study has shown that the uncertainty range for estimating natural and anthropogenic methane emissions is enormous. For example, the natural methane emissions for the North Sea, varies from a few hundreds to millions of tons per year. In addition, the literature study shows that many shallow gas accumulations are leaking and naturally emitting methane.

The review of Vielstädte et al. (2015, 2017) has resulted in comments on the assumptions and values used to calculate the total gas leakage estimations of the entire North Sea. Vielstädte et al. (2015, 2017) calculates the methane leakage as follows: the total number of wells in the entire North Sea (11,122) multiplied by the probability that shallow gas is penetrated (33% ± 6%), multiplied by the probability of leakage (100%), multiplied by a methane leakage of 1 to 4 tons per well per year. This results in a total methane leakage to the water column of 3,000 to 17,000 ton per year. TNO-AGE believes that important assumptions are uncertain and/or too high. As a result, the calculations have great inaccuracy and result in an overestimation.

- An important assumption is that all wells that penetrate shallow gas leak behind the casing (100%). This is insufficiently substantiated.
  - Research by Cardon de Lichtbuer (2017) shows that 2% to 11% of the abandoned Dutch onshore wells may leak.
  - Vielstädte et al. states that drilling disturbs and fractures the sediment around the wellbore mechanically, thereby creating highly permeable pathways for the buoyancy driven migration of the gas. TNO does not

recognize this as an obvious mechanism of methane leakage. Shallow gas can escape during drilling, but for abandoned wells, well integrity problems such as 'bad cement' are more obvious causes of leaks (Gasda et al., 2004).

- The data set of three wells is inadequate and not representative for the entire North Sea (11,122 wells).
- The percentage of wells that penetrate bright spots has been determined at 33 ± 6%, based on a small area in the Central North Sea where 18 out of 55 wells penetrate a bright spot. This (more extensive) study shows that this percentage is around 10% for the entire Dutch offshore (216 out of 2027).
- At two out of three measured wells, the relationship between methane leakage and the penetration of a seismic bright spot has not been sufficiently demonstrated:
    - One well (16/4-2) does not penetrate a seismic bright spot while methane leakage has been measured (4 tons per year). The cause of the methane emission has not been investigated but is not related to bright spots. Nevertheless, Vielstädte et al. do use this measurement to calculate the highest methane leakage for wells that pierce bright spots.
    - One well (16/7-2) with the highest methane emissions (19 tons per year) is not used because it was not considered representative. The location of this borehole goes through a so-called 'gas chimney'. TNO-AGE notes that gas chimneys are common natural, current or historical, leak paths to the surface for shallow and deeper gas accumulations. Vielstädte et al. (2015) confirms that the specific carbonate accumulation on the seabed at this well is most likely evidence of natural methane leakage.
    - Vielstädte et al. did not make use of pre-drilling measurement data, so no distinction can be made between natural and/or anthropogenic leakage of shallow gas areas.
- Vielstädte et al. refer to an unreal low natural methane emission of only 200 tons per year for the entire North Sea. This estimate is very low, since the measurement of 19 tons per year from only one location (at well 16/7-2) probably has a natural cause. Estimates of total emissions from other publications (up to 6 million tons per year) are not considered. Moreover, the high natural methane emissions (478 ton per year, Römer et al., 2017) above a single shallow gas field in the Netherlands (Schroot et al., 2015) is not discussed.
- Vielstädte et al. 2017 uses around 42% to calculate the fraction of methane reaching the atmosphere from sea bottom. In contrast Römer et al. 2017 uses a much smaller fraction of less than 5%.

TNO-AGE concludes, in response to the parliamentary question, that shallow gas accumulations are also present on the Dutch Continental Shelf. The anthropogenic methane leakage as described in Vielstädte et al. (2015, 2017) is insufficiently validated and overestimated.

In general, further research is required into natural and anthropogenic methane leakage before defining targeted measures against methane leakage near wells. TNO-AGE concludes that for determining possible methane leakage from wells, just studying wells that penetrate 'shallow gas' is not enough.

Methaan lekkage bij put 16/7-2 (Vielstädte, 2015) van 19 ton per jaar in de buurt van carbonaat afzettingen op de zeebodem boven een dieptezone van (natuurlijke) hoge doorlatendheid, een 'gas chimney'.

Methane leakage at well 16/7-2 (Vielstädte, 2015) of 19 ton per year nearby carbonate deposits on the seabed above a depth zone of (natural) high permeability, a 'gas chimney'.

Contents

1 Introduction

During a ‘*dertigledendebat*’ (formerly *‘spoeddebat’*) on the 14th of November 2017 about a new gas discovery above Schiermonnikoog, the House of Representatives also called attention to methane emissions related to gas production. One member of parliament (Mr. Wassenberg, PvdD) noted the following*: “German researchers published a study at the end of August on methane leakages at boreholes in the North Sea: 3,000 to 17,000 tons of methane leaks away every year. This also happens with boreholes that are no longer used. What can the Minister do to combat methane leakage at those wells in the sea?”*[1] (shorthand report).
Reference was made to recent publications by Vielstädte et al. (2015, 2017). These publications state that wells penetrating "biogenic shallow gas" areas leak behind the casing of the borehole. The above-mentioned parliamentary question was officially submitted on 7 August 2018 and stated: “*Are direct measures being taken to prevent yearly methane leakages of 3,000 to 17,000 tons from boreholes in the North Sea?”*[2]*.*

In the meantime on 21 and 22 March 2018 SodM visited a symposium of the EUOAG (EU Offshore Authorities Group) with a technical workshop and amongst others a presentation of the Vielstädte publications. Subsequently, SodM decided on 18 June 2018 to assign TNO-AGE for a study specifically for the Dutch part of the North Sea.

The details of the assignment can be found in the Minister's response (11 October 2018) to the earlier parliamentary question of the *‘dertigledendebat’*. SodM, on behalf of the Minister of Economic Affairs & Climate, requested TNO to study whether methane leakage may occur on the Dutch part of the North Sea and which wells penetrate shallow gas accumulations. Accordingly, SodM will decide whether to require the owners of the wells (oil- and gas operators) to take measurements in order to assess potential methane leakage.

TNO-AGE used the following steps for this research
1) Literature study of methane emission, shallow gas and methane leakage (Ch 2)
2) Mapping "bright spots" in the Dutch North Sea area through seismic interpretation, indicative for shallow gas (Ch 3)
3) Well analysis of wells that pierce a bright spot (Ch 4)
4) Review of Vielstädte et al. 2015, 2017 (Ch 5)
5) Discussion and conclusions (Ch. 6)

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[1] https://zoek.officielebekendmakingen.nl/kv-tk-2018Z14543.html

[2] Kamerbrief over methaanemissie bij gaswinning en beantwoording Kamervragen (11-10-2018) https://www.rijksoverheid.nl/documenten/kamerstukken/2018/10/11/kamerbrief-over-methaanemissie-bij-gaswinning-en-beantwoording-kamervragen

2 Methane and shallow gas

In this chapter methane as a greenhouse gas and its shallow occurrence (in the North Sea) is discussed.

2.1 Introduction to methane

Methane (CH_4) emissions play a significant role in climate change. As a greenhouse gas, methane has a stronger effect per unit weight than carbon dioxide (CO_2). This is expressed in the Global Warming Potential (GWP), where methane is expressed in carbon dioxide equivalent emissions. Under the Kyoto protocol of the United Nations (United Nations Framework Convention on Climate Change (UNFCCC) methane has a GWP of 28 on a 100-year time scale. This means that over a 100-year period, 1 kg of methane contributes 28 times more to the greenhouse effect than 1 kg of carbon dioxide (IPCC AR5, 2013). According to the United States Environmental Protection Agency (EPA), the GWP of methane could be even higher, namely 28-36 over 100 years[3]. Although, methane has a large GWP, it has a much shorter lifetime than CO_2. Methane is removed from the atmosphere by chemical reactions (e.g. oxidation) within ~ 12 years, producing CO_2 and H_2O. Reducing methane emissions is a major part of the global initiative to mitigate global warming.

There are three ways in which methane can be formed:

1) Biogenic: in the event of degradation (fermentation) of biogenic material under low-oxygen conditions and comparatively lower-temperature formational environments (<50°C) Only CH_4 is formed (Figure 2-1).
2) Thermogenic: when vegetable and animal material residues are compressed in the earth's crust under high pressure and formation temperatures between 157° and 221°C. This process also generates higher alkane chains (e.g. ethane, propane, butane) beside methane (Figure 2-1)
3) Pyrogenic: In the event of incomplete combustion of biomass and biofuels.

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[3] https://www.epa.gov/ghgemissions/understanding-global-warming-potentials#Learn why

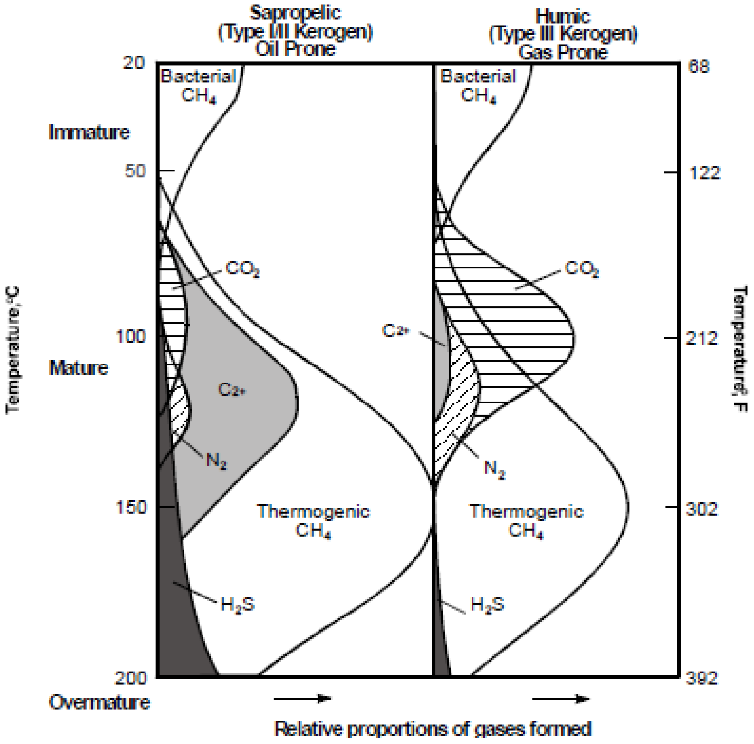

Figure 2-1 Relative proportions of natural gas generated from different types of organic matter (Hunt, 1996)

The sources for methane are categorized in two main groups:

1) anthropogenic sources: e.g. agriculture, waste dumps and the exploration and production of fossil fuels.
2) natural sources: e.g. swamps (wetlands) and leakages (seeps) from geological formations.

There are also several removal mechanisms ("sinks") for methane, including degradation of methane in the atmosphere, water and absorption of methane in soils by bacterial degradation (Saunois et al. 2016).

The uncertainty and size of formation and sinks of methane are discussed in Saunois et al., 2016, by a consortium of scientist organized around The Global Carbon Project (GCP). For the 2003–2012 decade, global methane emissions are estimated by top-down inversion at 558 million t/yr. (t=ton=1,000 kg). About 60 % of global emissions are anthropogenic (range 50–65 %). Sinks (only natural) are estimated at 548 million t/yr. resulting in an annual methane growth of 10 million t/yr. (Figure 2-2). Figure 2-3 shows global methane emission in CO_2 equivalent compared to other greenhouse gasses. In 2016, total global greenhouse gas emissions were about 49.3 gigatons in CO_2 equivalent (Gt CO_2 eq). Most of the emissions (about 72%) consist of CO_2, methane (CH_4) has a share of 19% (9.4 Gt CO_2-eq).

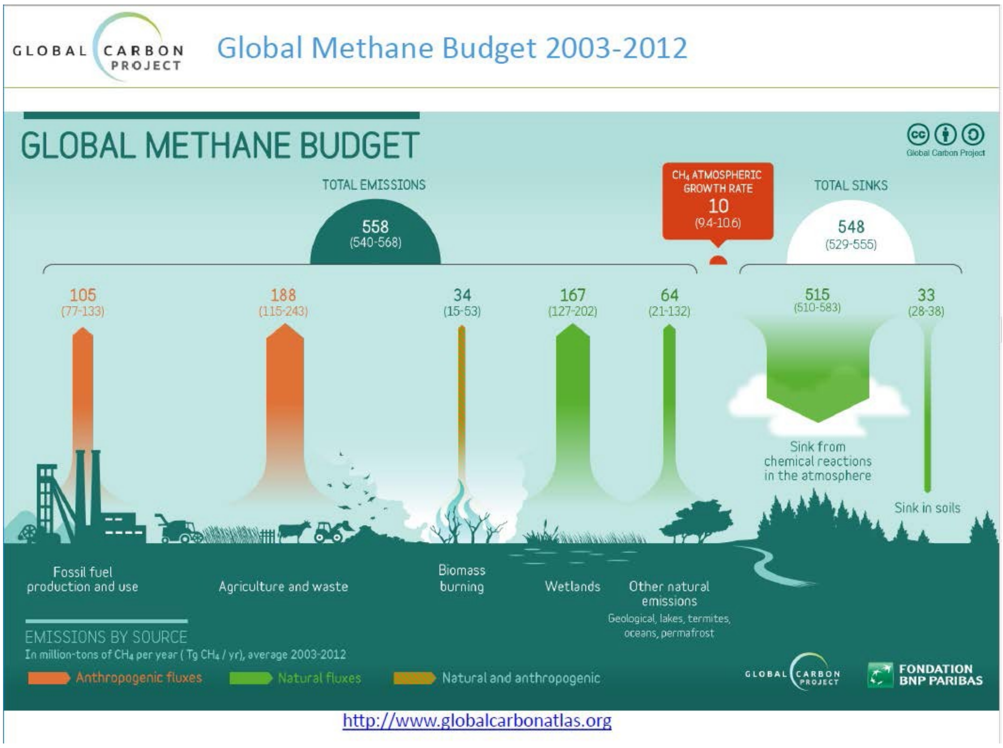

Figure 2-2 Global "top-down" methane budget (Saunois et al. 2016)

Methane levels are 1866 ppb in 2019[4]. The total mass of methane is estimated to be 5,187 million tons when using the conversion factor of the "Global Carbon Project" of 2.78 million tons per ppb[5]. A yearly increase of 10 million tons (Figure 2-2) gives (10/2.78=3.6) almost 4 ppb increase of methane.

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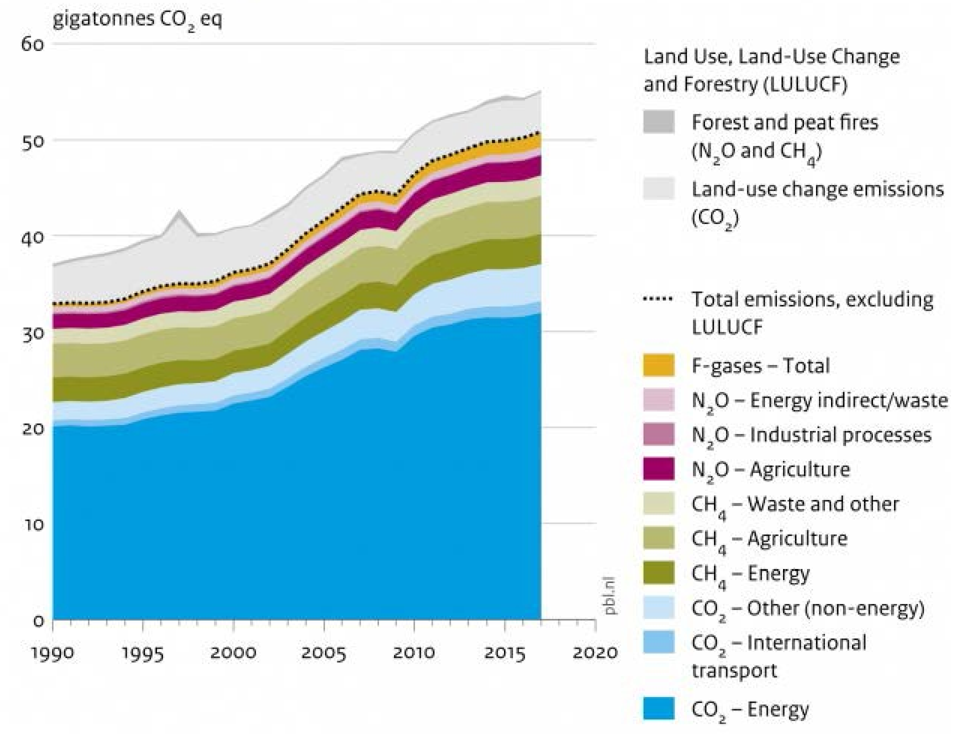
[4] https://esrl.noaa.gov/gmd/ccgg/trends_ch4/

[5] https://www.globalcarbonproject.org/methanebudget/16/files/GCP_MethaneBudget_2016.pdf

Global greenhouse gas emissions, per type of gas and source, including LULUCF



Source: EDGAR v5.0/v4.3.2 FT 2017 (EC-JRC/PBL, 2018); Houghton and Nassikas (2017)

Figure 2-3: In 2016, total global greenhouse gas emissions were about 49.3 gigatons in CO_2 equivalent (Gt CO_2 eq). Most of the emissions (about 72%) consist of CO_2, methane (CH_4) has a share of 19% (9.37 Gt CO_2-eq).

2.2 The shallow gas system in the North Sea

In the North Sea, including the Dutch continental shelf, natural methane accumulations occur in many geological formations. This study focusses on the topmost (max) 1000 m of sediments of the geological formations of the North Sea Group containing biogenic gas accumulations. Most gas accumulations occur in deeper geological structures therefore gas accumulations in the North Sea Group are named shallow gas accumulations. This natural gas mainly accumulated in unconsolidated marine to fluvio-deltaic deposits of the Plio-Pleistocene Eridanos delta (Overeem et al., 2001), in the Pleistocene tunnel-valley fill deposits and in a few volcanoclastics at the base of the Paleocene (e.g. Basal Dongen Tuffite). The gas is predominantly generated biogenically within the deltaic deposits, which contains organic land plant matter (Verweij et al., 2018) and thus the gas composition has a very high methane content (>99%). Gas generation started in early Pleistocene-Calabrian times in the delta and is still ongoing (Verweij et al., 2018).

The gas is structurally trapped in low-relief anticlinal structures above salt domes or occurs in stratigraphic or depositional traps. The clay to silt rich intervals between the silty to sandy reservoir layers function as seals, which traps the gas within the reservoirs.

Shallow gas accumulations are near hydrostatic pressure (Figure 2-4) which indicates that the seals cannot hold a large gas column and leakage, so called seal breach, occurs when the pressure exceeds a few bar above hydrostatic pressure, allowing the gas to migrate upwards. Furthermore, the accumulations are not filled to the spill point, and are sometimes found in multiple reservoirs layers stacked vertically (Verweij et al. 2018). These stacked reservoirs can be explained by a decreasing seal strength upward due to decreasing effect of compaction upwards and the increased buoyancy of gas upward. Ultimately natural methane leakage occurs when a portion of the gas reaches the seabed and is vented into the sea and atmosphere. Schroot et al. (2005) and Römer et al. (2017) showed high frequency sub-bottom profiler record running W–E across a shallow gas accumulation in the Dutch offshore block B13, showing natural gas plumes in the water column (Figure 2-5) leaking 478 tons a year from the seabed to the water column (Römer et al., 2017).

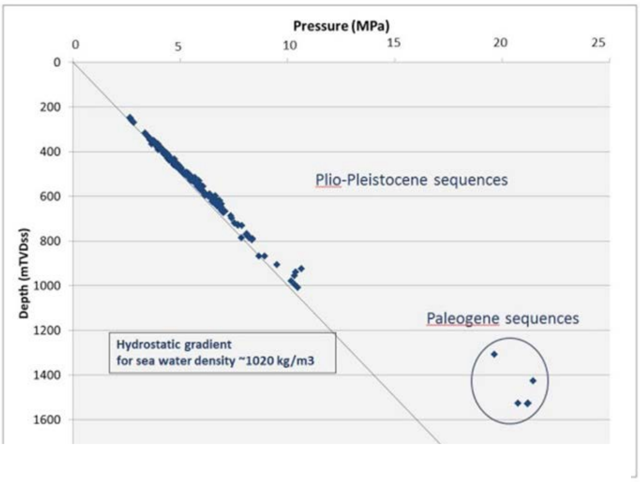


Figure 2-4: Cross plot of pore fluid pressure versus depth showing that the pressures in the Plio-Pleistocene Southern North Sea delta sequences (<1000m) are hydrostatic to close to hydro static (Verweij et al., 2018).

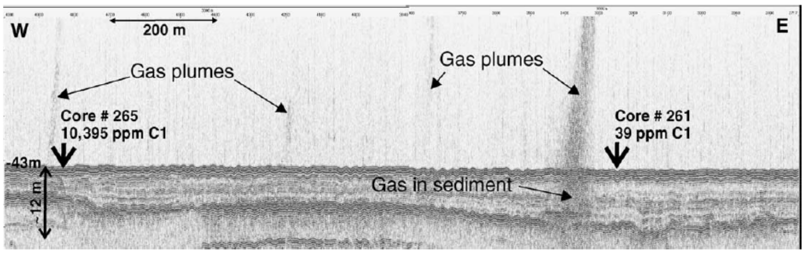


Figure 2-5 High frequency sub-bottom profiler record running W-E across the B13 shallow gas accumulation, showing gas plumes in the water column (Schroot et al., 2015)

2.3 Methane leakage in the North Sea

As methane leakage from wells penetrating shallow gas accumulations are suggested as a significant methane source it is important to understand their relative contribution in respect to natural emission.

As described in the previous chapter, methane leaks naturally from the seabed of the North Sea (e.g. Rehder et al., 1998). Depending on physical and chemical conditions, this methane can reach the sea surface and thus lead to natural atmospheric emission. It has also become clear that methane leakage from the North Sea seabed occurs through anthropogenic activities in relation to exploration and production of oil and gas. The UK22/4b blow-out on November 1990 is an example of (still ongoing) leakage due to anthropogenic (exploration) activities (Leifer, 2015).

Natural leakage of methane occurs through seeps (Schroot et al., 2005; Judd & Hovland, 2007; Hovland et al., 2012, Römer et al. 2017). A seep is a general term for a place where gas (bubbles) escape from the subsurface. The terms micro-seep and macro-seep are also used: a macro-seep is a location where leakage of gas bubbles can be observed acoustically (seismic data) or visually in the above water-column (Figure 2-5). Several macro-seeps in the North Sea (Dutch Dogger Bank above B13 shallow gas field, Tommeliten, Scanner and Gullfaks) (Figure 2-6) are reported to have a relatively large methane flux (Römer et al., 2017, Hovland et al., 2012). High methane fluxes are reported above the shallow gas fields in the northern Dutch offshore (Schroot et al., 2015, Römer et al., 2017). The hydrocarbon seeps release methane dissolved in pore waters or in the form of gas bubbles into the seawater in case of oversaturation (Di et al, 2019).
When methane is released as gas bubbles, a fraction of the methane in the bubbles dissolves into seawater via gas exchange during the transport to the seawater surface. The effective methane flux to the atmosphere depends on release depth, bubble diameter, and the buoyancy force of the plume (Di et al, 2019). The Dutch situation is unfavorable regarding leakage from the North Sea bottom towards the atmosphere since the southern North Sea is shallower, so that bubbling gas can easily reach the atmosphere.

Another source of natural (thermogenic) methane leakage are methane fluxes of deeper petroleum systems. Over geological time (millions of years), only a very small part of the hydrocarbons generated in a petroleum system is trapped while the larger part is lost (England, 1994, Magoon & Valin, 1994). Jager and Geluk (2008) state that for the petroleum systems in the Dutch subsurface: “probably 98% of the generated hydrocarbons escaped into the biosphere”. To distinguish natural from anthropogenic methane leakage, in prolific petroleum systems, is not easy since many wells are drilled in areas were methane leakage already occurs naturally.

Macro seeps are often recognized by the presence of a pockmark. A pockmark is a crater in the seabed, thought to be created by either sudden, periodical or semi-continuous (explosive) escape of gas (Schroot et al., 2005). A spectacular video image[6] of an explosive hydrocarbon release (gas and oil) at a natural seep is shown by a Nautilus expedition in 2015 in the Gulf of Mexico in the area where the

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[6] https://nautiluslive.org/video/2015/04/25/explosive-methane-burst-and-bubble-streams

Deepwater horizon sunk[7]. Pockmarks may contain coarser sediments or carbonate crusts and/or bacterial mats inside. The abundance and size of the pockmarks vary. Pockmarks have been found also in the northern part of the North Sea (Hovland et al., 2012) and recently an abrupt emergence (less than five months) of a large pockmark field (more than 300,000 pockmarks) in the German Bight, southeastern North Sea was discovered (Krämer et al., 2017). Pockmarks, as studied in blocks A5 and F10, are typically 40 m in diameter and 2 m deep (Schroot et al., 2005, Schroot and Schüttenhelm, 2003). It is not known whether the pockmarks have a biogenic of thermogenic source, or both. Moreover, macro seeps can occur without morphological expression of the seabed. This may be the case, for example, if the sediment on the seabed is coarse-grained.

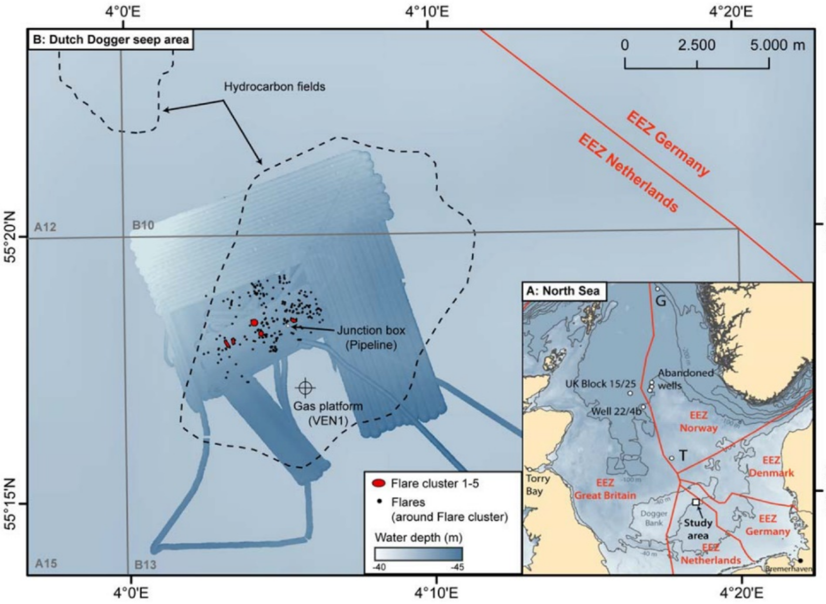

Figure 2-6 (A) Overview map of the North Sea including locations of the main seep areas and the study area located at the eastern edge of the Dogger Bank in the Netherlands EEZ. G, Gullfaks and T, Tommeliten. (B) Hundreds of flares were detected in the Dutch Dogger Bank seep area (from Römer et al., 2017) above the B13 shallow gas (production) field

2.4 Quantification of methane flux in the North Sea

TNO report TNO2018 R11080 presents a literature review quantifying various types of methane emission in the North Sea, among others Vielstädte et al. (2015, 2017). Since the 1980s, all kinds of studies estimated North Sea methane fluxes. Table 2-1 (modified from TNO report TNO2018 R11080) presents a compilation of the size in tons (1,000 kg) per year of methane flux types in the North Sea. Three types are distinguished:

1. From the North Sea seabed to the seawater.
2. Between the North Sea as a water body and other water bodies.
3. From the North Sea to the atmosphere.

TNO R11080 concludes that the wide range of estimations of methane flux indicates that, on the scale of the North Sea as a whole, there is considerable uncertainty on the magnitude of the total natural methane flux from the seabed to the North Sea versus the total flux due to leakage along the well as an anthropogenic source. The uncertainty in the emissions from the North Sea to the atmosphere is correspondingly uncertain. This is mostly due to upscaling from individual measurements at both natural and anthropogenic sources to regional flux which introduces a large uncertainty. This uncertainty concerns both the conceptual assumptions when scaling up and the spatial and temporal representativeness of the measurements.

Vielstädte et al. (2015, 2017) describes leakage near three wells in the Norwegian continental shelf. Their study concludes that all North Sea wells leak 3,000-17,000 t/year from the seabed to the water body of the North Sea, resulting in anthropogenic methane emission to the atmosphere of 1,000-7,000 t/yr (~42%). This study triggered questions in Dutch Parliament and was as such instrumental for the present research. A review on, amongst others, the assumptions and uncertainties of this publication is discussed in chapter 5.

To put the numbers of Table 2-1 into perspective; the total methane emissions of the Netherlands was 721,000 ton in 2017[8], 75% of which was emitted by agriculture, 15% by waste disposal, 3% by the energy sector (e.g. powerplants) and 7% by miscellaneous sources. For comparison the average methane emission by a single dairy cow[9] is 14 gr/hr (123 kg/yr.). There were 1.7 million dairy cows in 2017 in the Netherlands, accountable for a year emission of 208,500 ton methane (Figure 2-7).

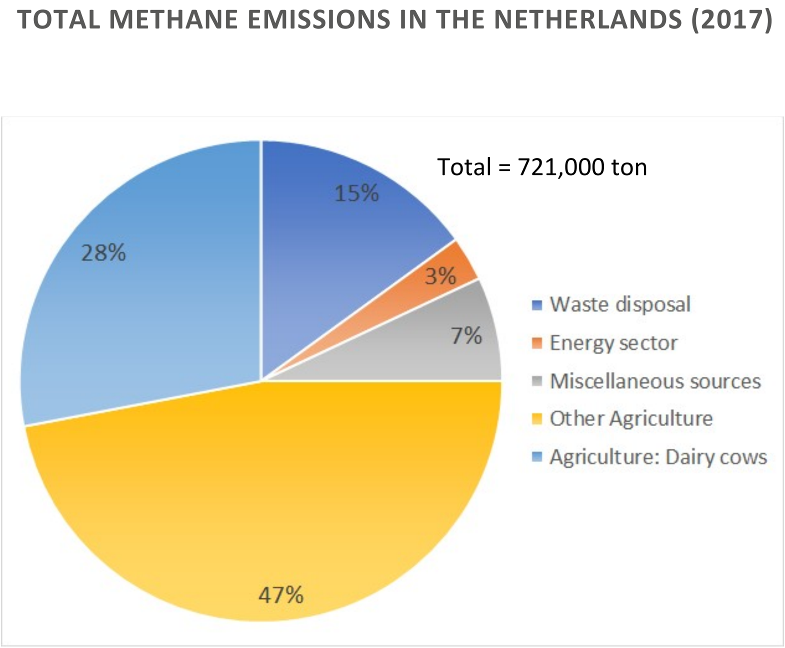

Figure 2-7 total methane emissions of the Netherlands was 721,000 ton in 2017 (after footnote 8 & 9)

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[8] www.clo.nl

[9] https://resource.wur.nl/nl/show/Koeien-stoten-meer-methaan-uit-dan-gedacht.htm

Situation	**Methane flux** (tons of methane a year)	**Reference**
1.- Flux from seabed to water		
Pockmark G11, off-shore Mid-Norway	0.151	Chen et al., 2010
Scanner pockmark macroseep	0.262	Hovland et al., 2012
Gas chimney at Tommeliten	26	Schneider von Deimling et al., 2015
Tommeliten wider seep area	5.64	Hovland et al., 1993
Seep at UK Block 15/25	17	Hovland et al., 1993
Average of individual seeps on continental shelf of U.K.	1.25 - 35.8	Judd et al., 1997
Major seeps at the Dutch Dogger bank	478	Römer et al., 2017
Seeps as a whole on the continental shelf of the U.K.	87,000 – 290,0000	Tizzard, 2008 in Judd, 2015
Seeps as a whole on the continental shelf of the U.K.	216,000 – 6,200,000	Judd et al., 1997
Total natural leakage from the seabed of the North Sea	200	Vielstädte et.al., 2017
Abrupt emergence pockmark field, southeastern North Sea	5,000	Krämer et.al., 2017
Blowout UK22/4b	15,000 – 41,000	Leifer, 2015
The range of leakage along 1 of 3 wells in the central North Sea (Norway)	1 – 19	Vielstädte et al., 2015
Total leakage along wells in the North Sea	3,000 – 17,000	Vielstädte et al., 2017
2.- Flux waterbodies		
Flux from North Sea to the Atlantic Ocean	7,569	Rehder et al., 1998
3.- Emission to the atmosphere		
Sea/air exchange at Tommeliten	< 1.04	Schneider von Deimling et al., 2015
At seeps of the Dutch Dogger bank	21.7	Römer et al., 2017
Associated with seeps on the continental shelf of the U.K.	10,000 – 480,000	Tizzard, 2008 in Judd, 2015
Associated with seeps on the continental shelf of the U.K.	119,000 – 3,400,000	Judd et al., 1997
Dutch part of the Southern Bight, North Sea	2,000 – 200,000	Scranton & McShane, 1991
North Sea as a whole - model 1	7,543	Bange et al., 1994
North Sea as a whole - model 2	5,803	Bange et al., 1994
North Sea as a whole	24,000 – 50,000	Rehder et al., 1998
Nearby blowout UK22/4b	7,008	Rehder et al., 1998
Nearby blowout UK22/4b from the seawater	< 5,000-7,500	Gerilowski et al., 2015
Bubble mediated emission nearby blowout UK22/4b	700 ± 300	Schneider von Deimling et al., 2015
North Sea as a whole by leakage along the wells	1,000 – 7,000	Vielstädte et al., 2017

Table 2-1 Methane fluxes in the North Sea for various, natural and anthropogenic sources in the North Sea as derived from combinations of measurements and calculations. Green cells correspond to references about natural methane gas fluxes, while red cells involve anthropogenic sources. Unlike in the TNO report, in this table the influence of the major rivers is not taken into account. Modified from TNO2018 R11080

2.5 Well integrity and leakage of methane onshore

Well integrity issues are the most likely cause of methane leakage from wells (Figure 2-8). However, there is little information in the public domain about well integrity issues and possible methane leakage for wells in the Dutch Offshore and the North Sea in general. In the Netherlands, some research has been done on methane leakage at plugged and abandoned wells on land. In a recent report on methane leakage in the Netherlands (TNO R11080, 2018) TNO concludes that onshore leakage of oil and gas wells to the surface can occur (Cardon de Lichtbuer, 2017; ECN, 2017). The leakages are shown by the unique blow-out event, which occurred at ‘t Haantje in Sleen and the leakage of thermogenic methane close to the surface at one abandoned well (MON-02) of the 29 abandoned wells that were studied (Cardon de Lichtbuer, 2017). Statistically, it is unlikely that these wells are the only (abandoned) wells that are leaking. Furthermore, an ECN study of 185 onshore wells concludes that: i) at several active wells, gas bubbles are found in the wellhead cellar, ii) there is an increased methane concentration in the air at two locations with one or more abandoned wells and iii) at most locations there is no “relevant” emission (ECN, 2017).

Based on Cardon de Lichtbuer (2017) an estimated range of 2% to 11% of wells lack full integrity out of the 1303 abandoned wells in Dutch onshore territory. This is based on a limited number of measured wells in the Netherlands (29 out of 1303).

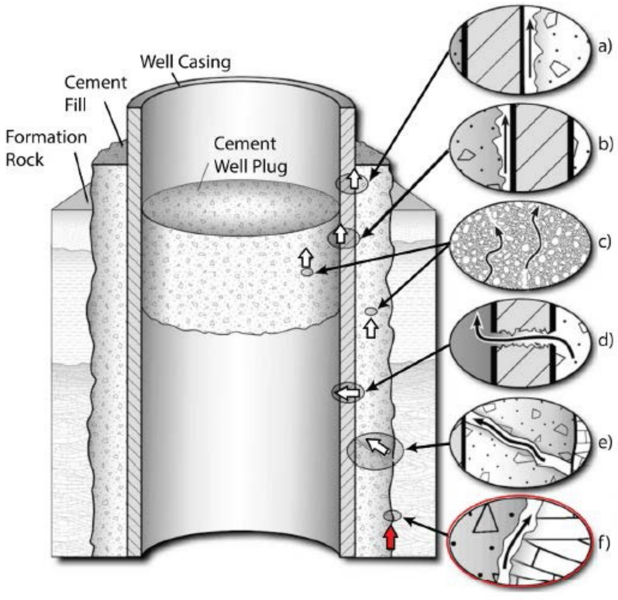


Figure 2-8 Scheme illustrating possible leakage pathways through (white arrows) and along (red arrow) an abandoned well: a) Between casing and cement; b) between cement plug and casing; c) through the cement pore space as a result of cement degradation; d) through casing as a result of corrosion; e) through fractures in cement; and f) between cement and rock along the outside of the well (from Vielstädte, 2015, modified after Gasda et al., 2004).

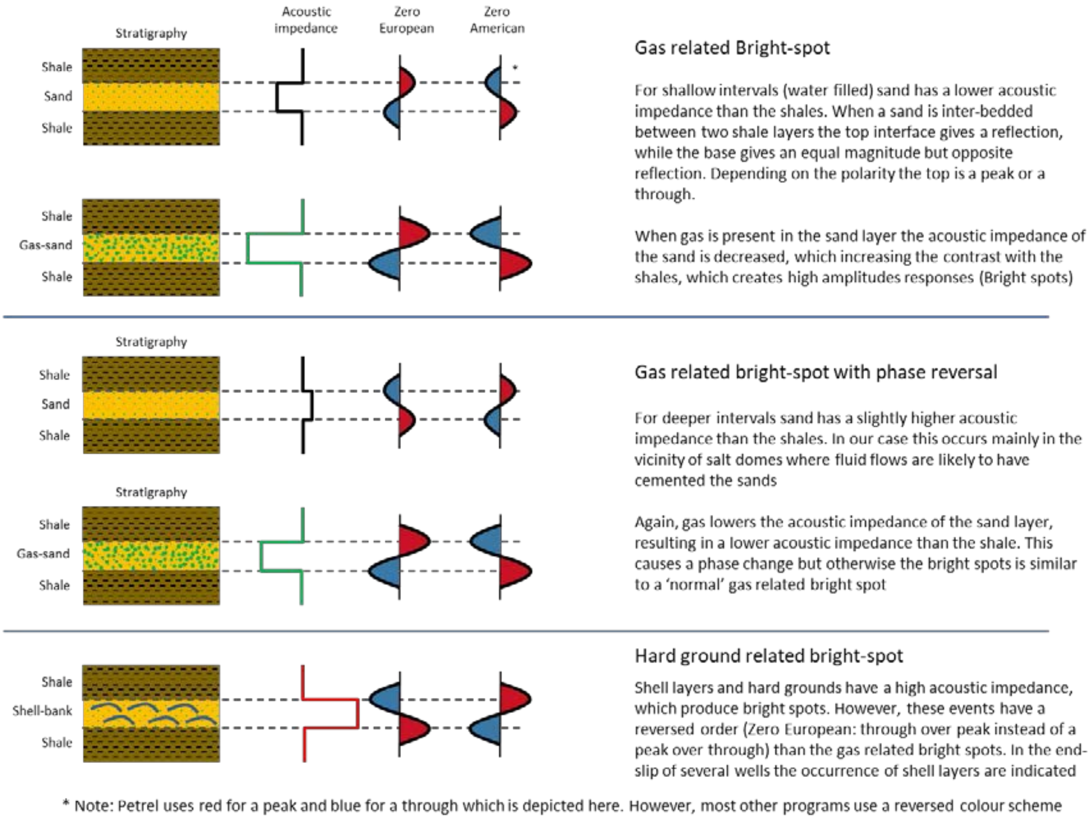
3 Seismic interpretation of shallow gas areas in the Dutch North Sea

When gas is present in the subsurface it may be seen as so-called bright spots on 3D seismic data. For this project almost two hundred 3D seismic surveys were used to detect bright spots in the shallow sub-surface (1,000m <). Based on this seismic interpretation polygons were created around these bright spots. Wells that lie within these polygons will possibly penetrate a shallow gas accumulation and are subsequently studied further. In this chapter, the seismic interpretation of the North Sea area is described. First the theory on identifying shallow gas accumulations in seismic data is described. This is followed by a description of the data availability, methodology and the results of the seismic interpretation study for mapping bright spots will be described.

3.1 Introduction to seismic characterization of shallow gas

3.1.1 Principles of seismic characterization of shallow gas

When gas is present in the subsurface it may be seen on seismic data. The gas (partially) replaces the pore fluids, which results in an anomalous seismic amplitude response. These anomalies are known as direct hydrocarbon indicators (DHI's).



Gas related Bright-spot

For shallow intervals (water filled) sand has a lower acoustic impedance than the shales. When a sand is inter-bedded between two shale layers the top interface gives a reflection, while the base gives an equal magnitude but opposite reflection. Depending on the polarity the top is a peak or a through.

When gas is present in the sand layer the acoustic impedance of the sand is decreased, which increasing the contrast with the shales, which creates high amplitudes responses (Bright spots)

Gas related bright-spot with phase reversal

For deeper intervals sand has a slightly higher acoustic impedance than the shales. In our case this occurs mainly in the vicinity of salt domes where fluid flows are likely to have cemented the sands

Again, gas lowers the acoustic impedance of the sand layer, resulting in a lower acoustic impedance than the shale. This causes a phase change but otherwise the bright spots is similar to a 'normal' gas related bright spot

Hard ground related bright-spot

Shell layers and hard grounds have a high acoustic impedance, which produce bright spots. However, these events have a reversed order (Zero European: through over peak instead of a peak over through) than the gas related bright spots. In the end-slip of several wells the occurrence of shell layers are indicated

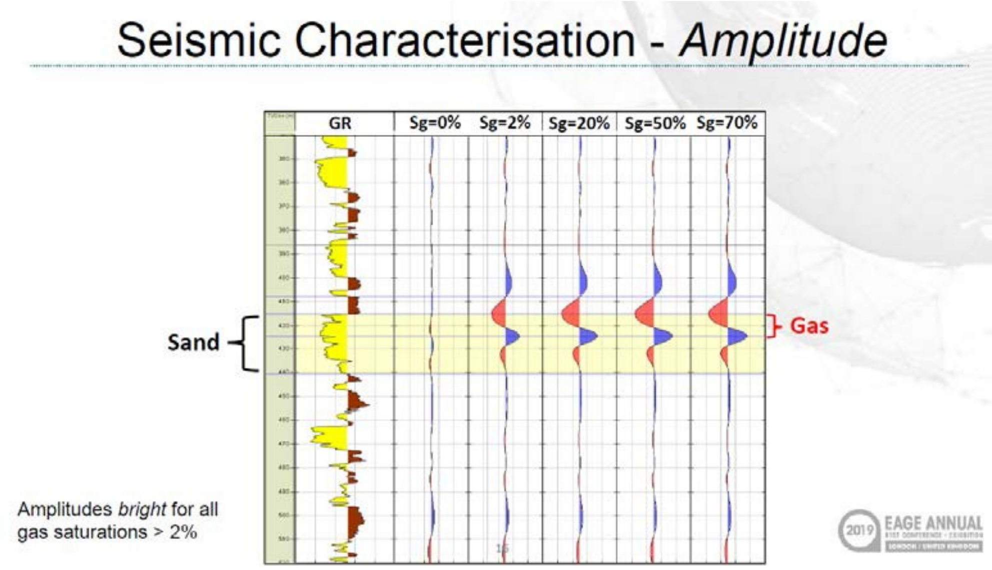
* Note: Petrel uses red for a peak and blue for a through which is depicted here. However, most other programs use a reversed colour scheme

Figure 3-1: Seismic character of shallow gas.

Especially, shallow gas is known to produce these DHI’s, since a small amount (>2%) of gas leads generally to a strong decrease in propagation velocity and to a higher attenuation of the seismic waves (Figure 3-2, Hoetz. & Boogaard van den., 2019). There are various DHI’s associated with shallow gas. Bright spots occur at shallow intervals, phase reversals at slightly deeper intervals, and flat-spots can be found throughout these intervals (Figure 3-1).

However, not all bright spots are related to gas. There are other phenomena that cause anomalous seismic amplitudes. Shell layers, boulder clay and hard grounds can produce bright spots. These bright spots can be differentiated from gas related bright spots since they have a reversed order of events. Where gas filled sands have a lower acoustic impedance in respect to the overlying and underlying sediments, these phenomena have a higher acoustic impedance (AI) relative to the surrounding sediments. Consequently, it is very important to determine whether the bright spot is low AI layer or a high AI layer. This can be done by identifying well known high acoustic impedance layers (Figure 3-3); Zechstein Z1 Carbonate member, floaters in the Zechstein salt, and the Chalk Formation (i.e. shallow gas related bright spots has the reversed order of seismic events in respect to these layers).

Figure 3-4 shows a textbook example of the various layers that are taken into account during the seismic interpretation phase. The Zechstein Z1 carbonates and floaters are clearly visible and a blue over red reflector set. Consequently, shallow gas must be a red reflector over a blue reflector (zero phase European seismic data). In this example the shallow gas is not only bright, but the base is also a flat spot. Please note that the tunnel valley (glacial channels that occur beneath glaciers), has a bright red reflector at the base and not a blue reflector like the shallow gas. Based on this we conclude that the tunnel valley bright events are caused by a hard layer, probably boulder clay.



Seismic Characterisation - *Amplitude*

Amplitudes *bright* for all gas saturations > 2%

Figure 3-2 Bright seismic amplitude for shallow gas in unconsolidated sediments for all gas saturations >2%. From Hoetz, G. & Boogaard van den M. (2019).

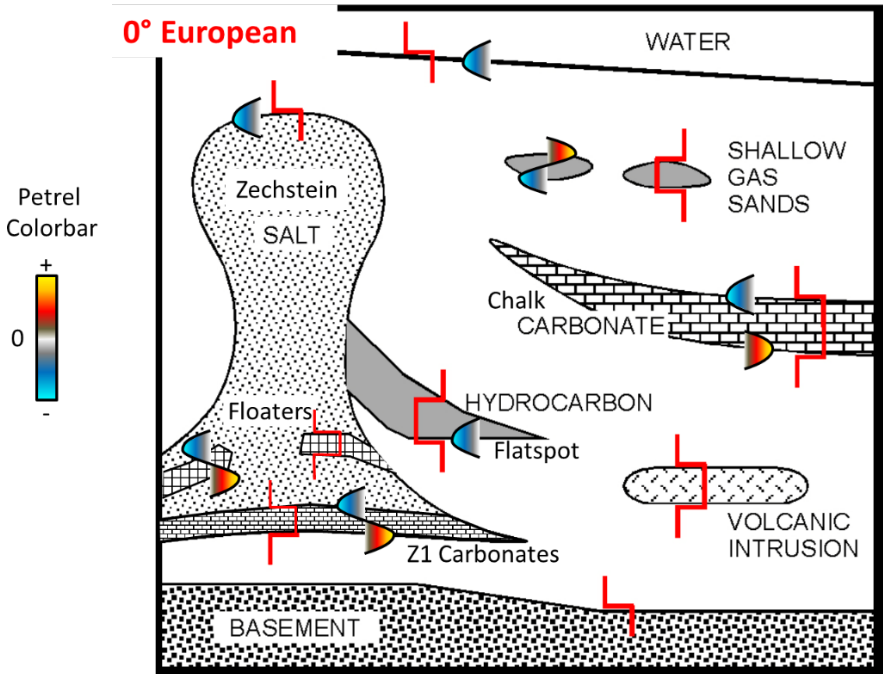


Figure 3-3: Seismic response of different geological elements that are present in the North Sea. Please note, that the seismic response is only valid for zero phase European seismic data, displayed with a Petrel colour bar. Figure after Brown (2011).

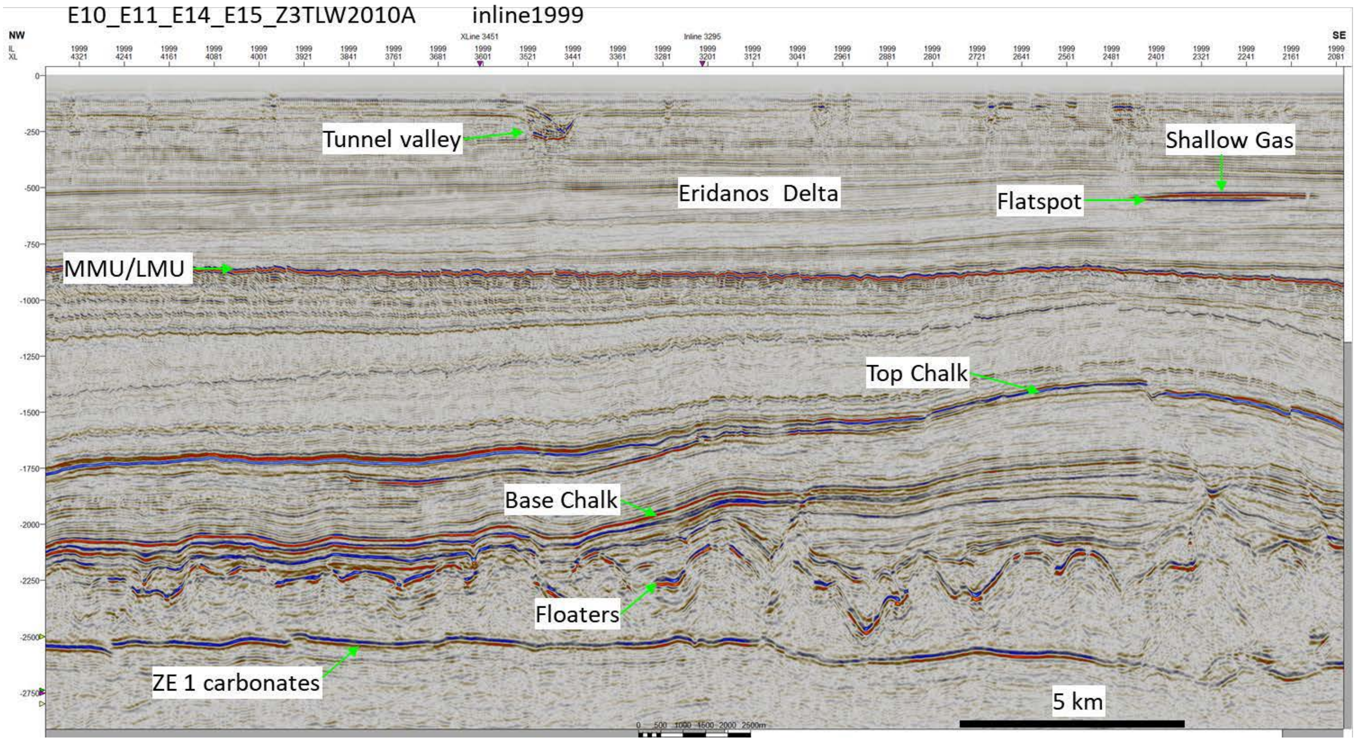


Figure 3-4: Seismic line through the E-blocks, showing all the geological elements that help with the identification of the phase of the data, and the differentiation off shallow gas from other features that produce bright reflectors.

3.1.2 Known trap types containing shallow gas in the Netherlands

Gas is known to be present in 4-way dip closures and in sedimentary structures. 4-way dip closures are mainly found above salt domes. Sedimentary structures that are known to contain gas are sediment waves, glacial plough marks, and slumps.

Sediment waves (Figure 3-5) are elongated features formed by strong bottom currents. They are present in several areas of the North Sea and at multiple stratigraphic levels. The sediment waves studied in the A15 block (TNO-060-UT-2011-01184/C) contained residual gas and therefore it was concluded that the seals are probably leaking (naturally).

Slumps (Figure 3-6) and other mass transport deposits are present in the eastern part of the Dutch offshore (G an M blocks) and were studied by Benvenuti et al. (2012).

When floating icebergs make contact with the seafloor, they can produce iceberg plough marks or scour marks (Figure 3-7). These plough marks are buried subsequently, and are occasionally associated with shallow gas (Haavik and Landrø, 2014).

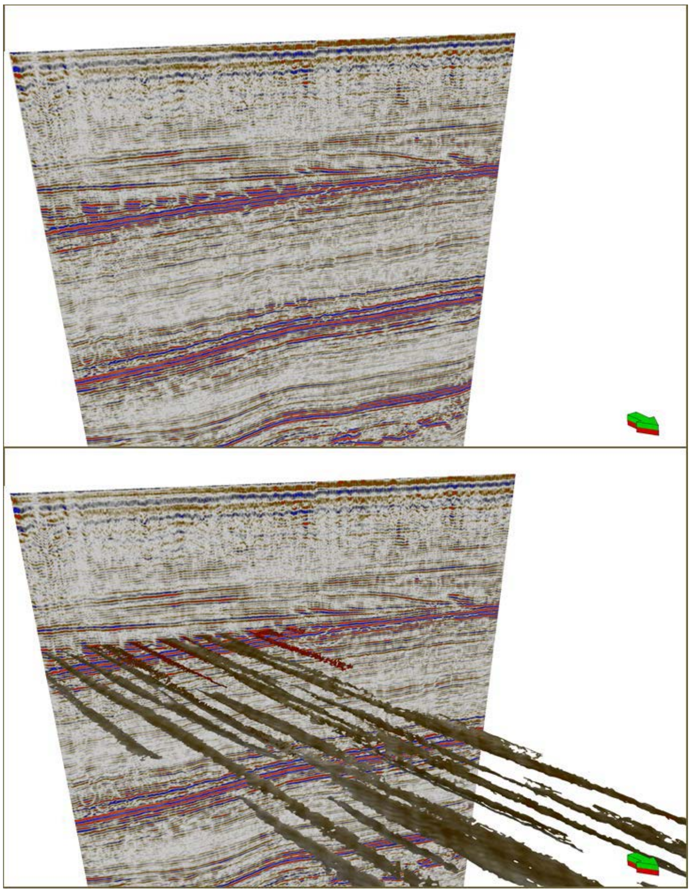


Figure 3-5: Sediment waves with bright spots. Cross section shown above, below a combination of cross section and the interpreted sediment wave bodies in 3D.

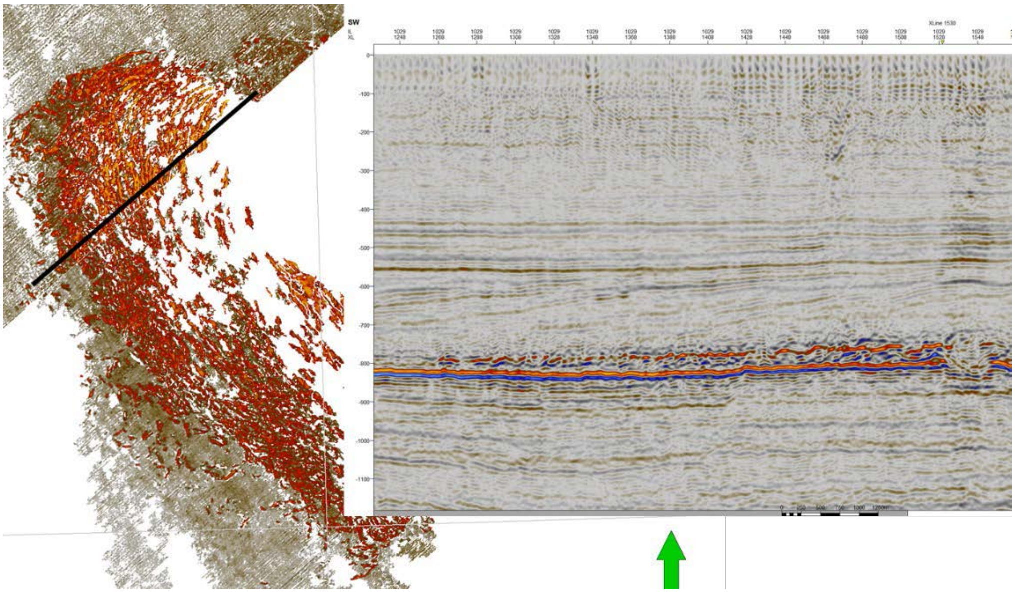


Figure 3-6: Example of slump deposits containing natural shallow gas. Top view/time slice on the left, cross section on the right.

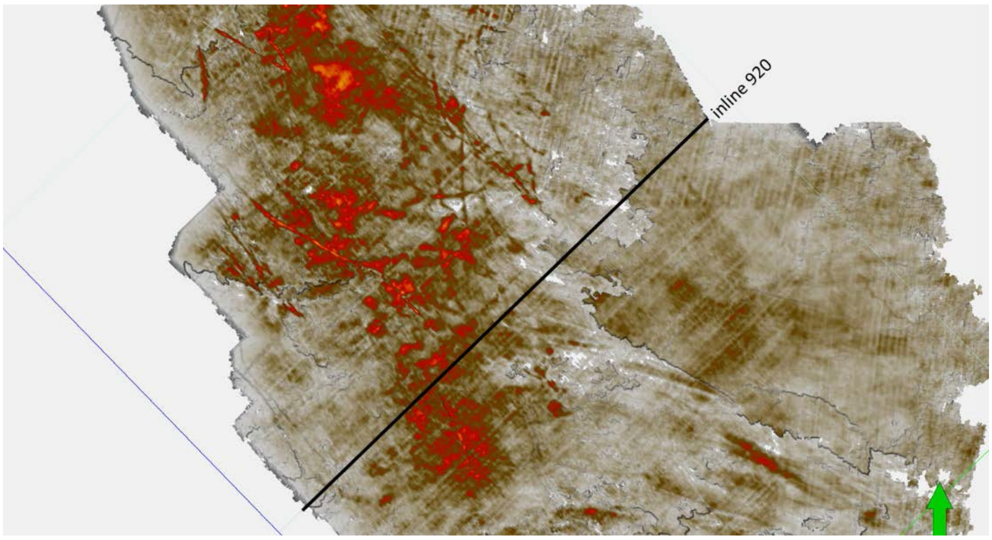


Figure 3-7: Example of iceberg plough marks containing shallow gas

3.1.3 Miocene Unconformities

The base of the Dutch Eridanos delta is a complex boundary that is a culmination of up-to four unconformities and a downlap surface and often a seismic bright event (see Figure 3-4 and Figure 3-8).

The four unconformities are the Savian Unconformity, early Miocene Unconformity (EMU), Mid-Miocene Unconformity (MMU) and the Late Miocene

Unconformity (LMU) (TNO 2017 R10425) merge westward into one single erosional event. Above, the Eridanos delta prograde westwards and downlaps onto this amalgamation of unconformities. This downlap surface is a condensed section.

The resulting boundary is often called the “MMU”, but strictly speaking this is incorrect. Due to the laterally changing sediments above and below these unconformities the seismic response varies laterally. Moreover, the downlapping and erosion causes lateral thinning, which results in seismic tuning. This effect adds to the lateral change in seismic character of this event. Consequently, it is difficult to determine if brightening is the result of the presence of gas, or a lateral change of sediments along the ‘MMU/LMU’ itself (see Figure 3-9).

TNO (2017; report R10425) found an abrupt change in gas composition at the MMU/LMU. Gas below the MMU/LMU is predominant thermogenic and above it is predominant microbial. Since this study focusses on the presence of shallow gas, bright events at the MMU/LMU are not taken into account. Which means that this study in general has interpreted shallow gas of the Upper North Sea Group.

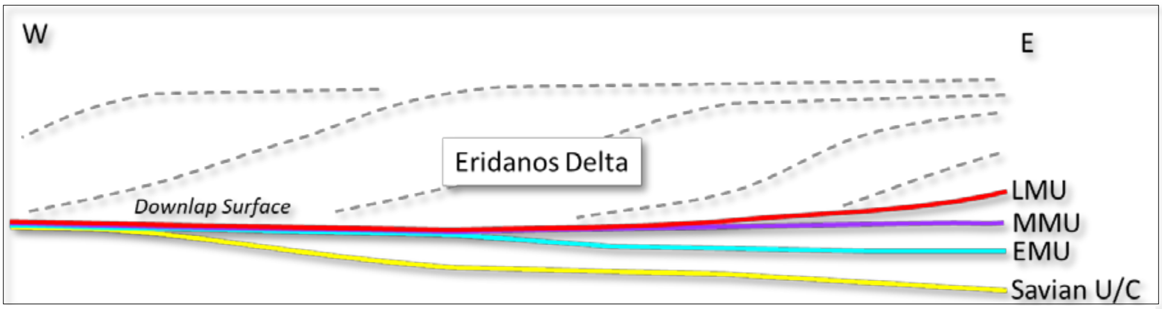


Figure 3-8: The base Eridanos delta comprises of up-to four unconformities. The four unconformities are the Savian Unconformity, early Miocene Unconformity (EMU), Mid-Miocene Unconformity (MMU) and the Late Miocene Unconformity (LMU) (TNO 2017 R10425).

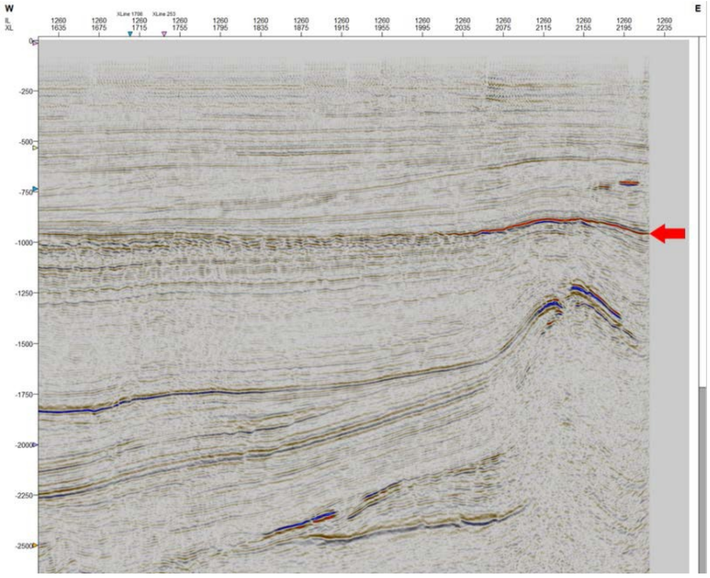


Figure 3-9: Example of a bright spot on the MMU/LMU.

3.2 Data availability

A large part (82.6%) of the Netherlands Continental Shelf is covered with 3D seismic data (Figure 3-10). Some of the area is covered by multiple surveys. Areas not covered with 3D seismic data have a small number of wells. The areas not covered by 3D seismic data have not been considered in this project. Almost 200 different 3D seismic surveys were interpreted for this study.

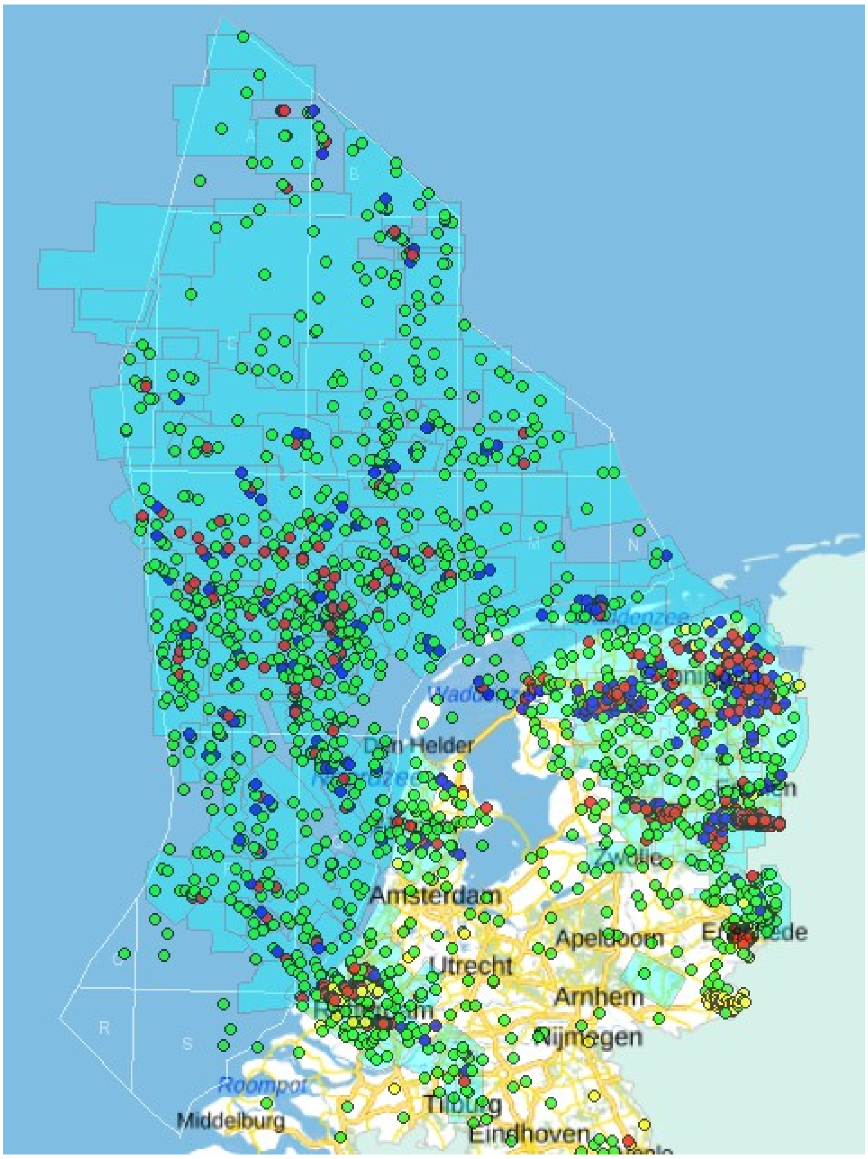


Figure 3-10: map showing the area covered with 3D seismic data (light blue areas) and well locations (source: www.nlog.nl). Red dot: development well, blue dot: appraisal well and green dot: exploration well.

3.2.1 Methodology

Seismic surveys have different phases and polarities. In theory, they should all be zero phase, but in practice different phases are present. Figure 3-11 shows the seismic reflection pattern of shallow gas with different phases and polarities.

Figure 3-12 shows an example of a non-zero phase seismic volume with bright events that have an unclear origin. In this case, the absence of other clear indicative reflectors (such as Chalk, floaters, etc.) impedes phase discrimination. Consequently, shallow gas identification is non-trivial in many seismic cubes.

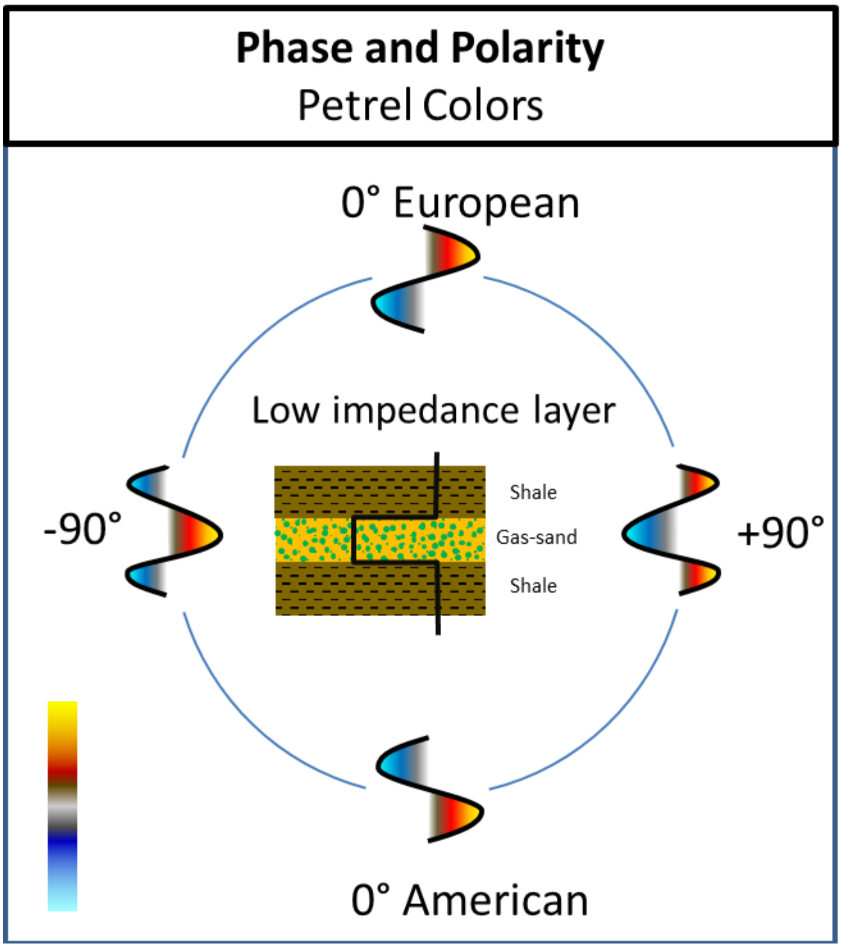


Figure 3-11: The seismic character of shallow gas depends on the polarity and phase (after Brown, 2011)

Therefore, all bright amplitude events which potentially could be caused by gas are interpreted and marked. These events are auto-tracked and the amplitude map is analysed. If the brightening is clearly linked to structures, such as 4-way dip closures, it is likely caused by the presence of gas. Similarly, when bright events are found in known sedimentary structures (see above) it is also likely that it is caused by gas. If a structure is present the area is marked as “likely shallow gas”. When the bright event is not clearly linked to these structural or stratigraphic features, the bright spot is discarded as potential shallow gas and the polygon is not used in the subsequent analysis.

Since this study uses many seismic vintages that have various polarities and phases, it proved to be inefficient to automate the detection of bright spots. Therefore, detection was done manually.

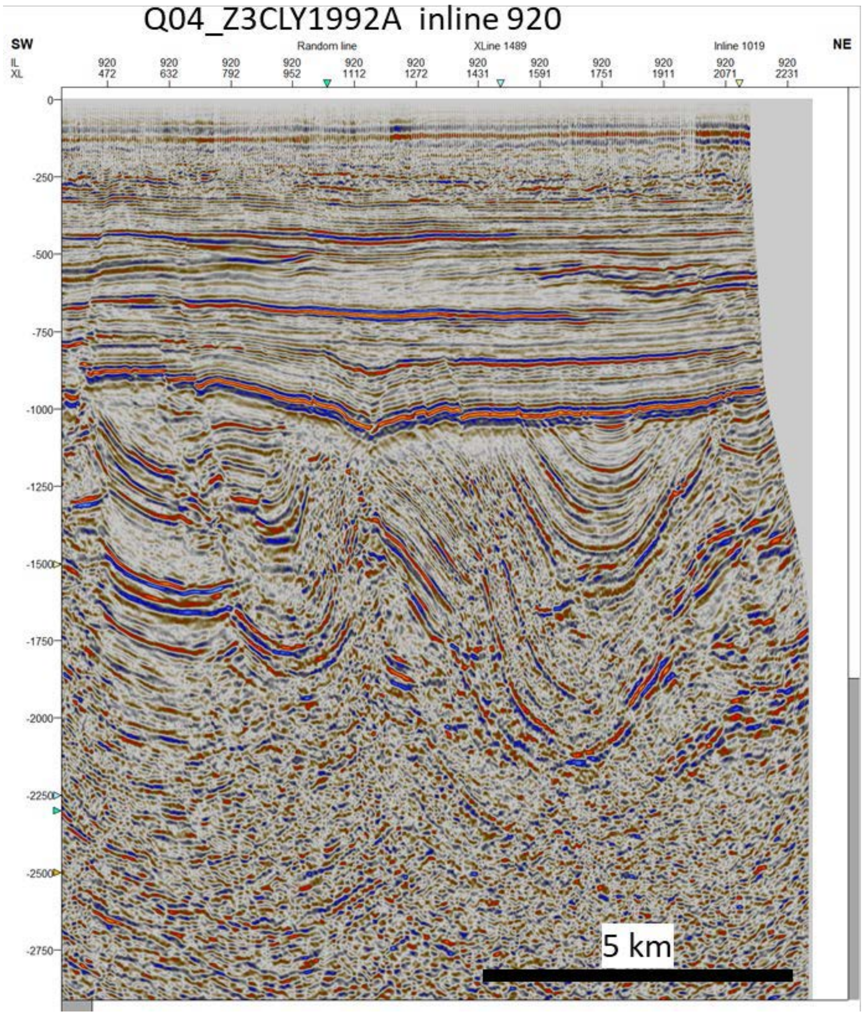


Figure 3-12: Example of a cross section of a non-zero phase seismic volume in the Q blocks.

3.3 Results (polygons)

The A, B, and F blocks were mapped and studied for shallow gas by TNO (TNO 2013 R10060) and EBN (2016), using the same methodology. All remaining blocks were studied and the bright spots mapped. Figure 3-13 shows the polygons surrounding the mapped bright spots of this study for the Dutch offshore.

All wells that lie within one or more polygon(s) are marked as potentially penetrating shallow gas accumulations. This overlay resulted in a total of 216 wells including side tracks. Please note that this is a high-end estimate since wells are normally side tracked below the North Sea Group and share the same top-hole section. Further analysis of the likelihood of shallow gas presence in these wells is described in Chapter 4.

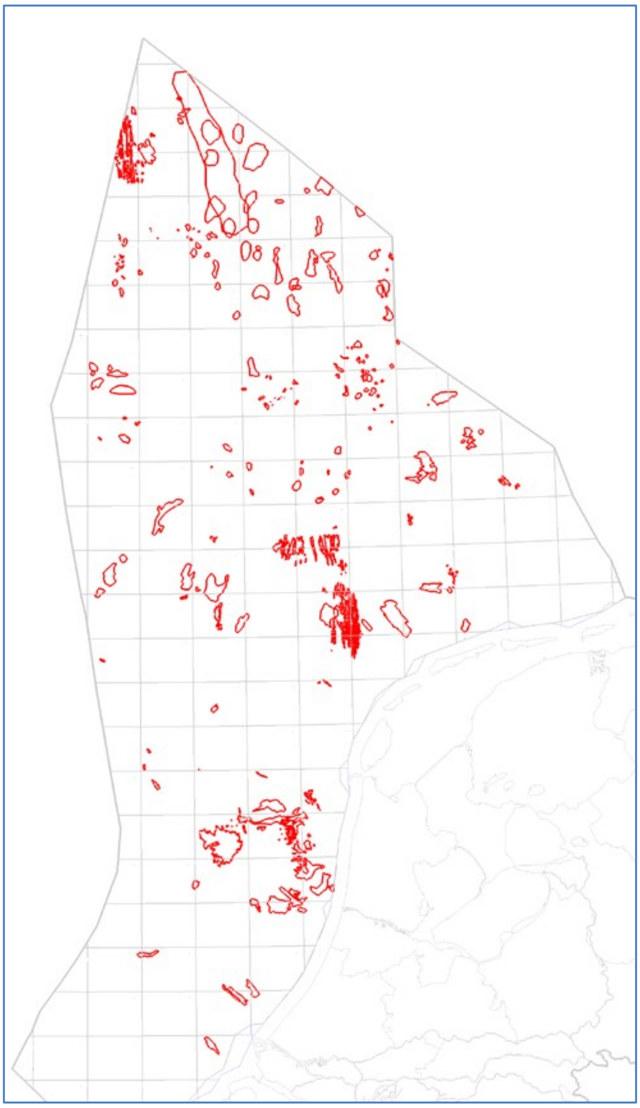


Figure 3-13: Shallow gas related bright spots in the Dutch Offshore present in the Eridanos delta (above MMU-LMU, Upper North Sea Group).

4 Well analysis

4.1 Introduction

The seismic interpretation of the Dutch offshore of this study resulted in a set of polygons around bright spots and a list of wells that penetrate these bright spots. As explained in section 3.1 and 3.2, bright spots can be caused by several phenomena, and are not necessarily indicative of a high gas saturation. Well data is essential to check whether a well penetrates significant concentrations of shallow gas. In this chapter, data from wells that penetrate the interpreted bright spots (chapter 3) are further investigated to assess the likelihood of the presence of shallow gas.

Please note that not all wells were logged for (shallow) gas within the Upper North Sea Group (no data). In the past there was no or little economic interest for an operator to use a full logging set when drilling this interval. Only when the well data (e.g. composite log, well report) indicates that gas was sufficiently (directly or indirectly) measured within the (Upper) North Sea Group, has the conclusion been drawn on the presence of gas shows. Thus, the lack of gas data (no data) does not necessarily indicate that there is “no gas show”.

4.2 Data and methods

The seismic interpretation of the Dutch offshore (Chapter 3) resulted in a list of wells located within the various bright spot polygons. All wells which penetrate one of the shallow gas production fields (mostly A and B blocks) have obviously high gas saturation. The remainder of the wells are compared with the Hydrocarbon show database of EBN [10]. Finally, TNO used a quick petrophysical scan with mostly data from the nlog.nl website for wells not present in the shallow gas fields and EBN database.

4.2.1 Shallow gas fields

Since the early 1970s large shallow gas occurrence in the northern part of the Dutch offshore (mainly A and B blocks) triggered economical interest and were proven by wells in the 1980s and several have been taken in production from 2007 onwards. The traps are generally low relief 4-way dip closures related to salt domes, with stacked reservoir sands containing a stack of separate gas columns. Accordingly, these shallow gas fields have good gas shows.

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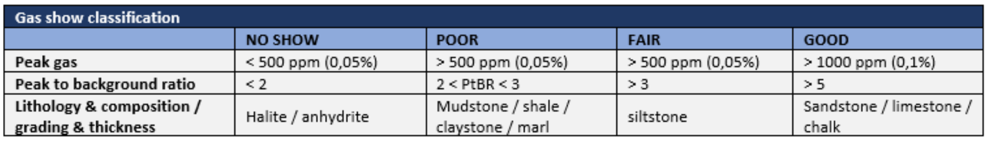
[10] EBN HC show database (Release: 01-06-2019_v2.0). This database is not yet complete, EBN aims to incorporate all Dutch wells in the near future. 724 Wells out of around 6000 wells have been analyzed to date. This database is made freely available. More details and information on how to request access to the databases can be found at www.ebn.nl.

4.2.2 EBN HC show data base

This database provides an overview of hydrocarbon (HC) shows based on public data (nlog.nl) at different stratigraphic intervals along a borehole trajectory. Three types of data are incorporated by EBN: mud log, test- and core data. Each of these data types is classified as *good*, *fair*, *poor*, *no show*, or *no data* based on the information in gas logs, mud logs, core data, test data, cutting descriptions and well reports. Finally, the classifications for each stratigraphic interval are combined into a 'concatenated HC show classification', which represents the best classification from all available data. In the EBN HC show database, the most important classifications are the gas and oil shows observed in the mud log data, while (SW-)core and test results provide additional information (Figure 4-1). In this case, the gas shows within the Upper North Sea Group (NU) and for those wells where no differentiation of North Sea Group (N) was made the North Sea Group as a whole was used. The well data at Mid and Lower North Sea Group is not taken into account, because these stratigraphic levels lie underneath the so-called Mid-Miocene unconformity (Chapter 3.1) and are outside the scope of this project.

Only a few wells (Appendix A: Table A2) of the EBN HC database with a *good show* lie outside a bright spot polygon of this study while some other wells with a *fair*, *poor* or *no show* lie inside a bright spot polygon of this study. This can be explained since 2% gas (fizz gas) in the (formation) water gives exactly the same seismic bright spot as 80% gas (Figure 3-2, Hoetz & Boogaard van den, 2019), while *fair*, *poor* or *good show* well data only gives an indication of the presence of gas, rather than an exact percentage.

The EBN gas show database wants to incorporate all Dutch wells but at present not yet complete. TNO-AGE therefore performed a quick scan for those wells inside a bright spot polygon of this study that were not present in the EBN HC show database.



Gas show classification

	NO SHOW	POOR	FAIR	GOOD
Peak gas	< 500 ppm (0,05%)	> 500 ppm (0,05%)	> 500 ppm (0,05%)	> 1000 ppm (0,1%)
Peak to background ratio	< 2	2 < PtBR < 3	> 3	> 5
Lithology & composition / grading & thickness	Halite / anhydrite	Mudstone / shale / claystone / marl	siltstone	Sandstone / limestone / chalk

Figure 4-1 Gas show classification scheme of EBN HC show database, where a peak is considered the absolute difference between the maximum accumulated gas and the background level. Gas shows in halite or anhydrite are classified as NO SHOW due to the low porosity and permeability of this lithology.

4.2.3 TNO quick scan

When the well is not available in the EBN HC show data base, a quick scan based on the available in-house well data (mainly www.nlog.nl) was performed. This petrophysical quick scan is mostly based on composite logs and well reports and give insight on gas shows/no shows or no data in Upper North Sea Group (NU). Where total gas indicates a peak in the measurements (>500 ppm), the data is classified as *'Gas show'*.

4.3 **Results of well analysis**

The interpretation of seismic bright spot polygons of Chapter 3 resulted in a total of 216 wells (incl. side tracks) summarized as 98 well location points (Appendix A-1). A well location point can be a single well or multiple wells at a (production) platform. We summarized individual wells of a production platform since they are located relatively close at their top-hole segment. Furthermore, the side track of a well is summarized in a single well location point since the top-hole location of a side track will (normally) be the same (or almost the same) as the original hole. Next paragraphs are wells according to the highest change of it penetrating a shallow-gas accumulation with a high gas saturation

4.3.1 Shallow Gas fields

In Table 4-1 the shallow gas fields in the Dutch offshore are indicated, including the corresponding 21 well location points. These wells, including production wells, penetrate a shallow gas accumulation with a high gas saturation (Appendix A: Table A1 named “Shallow gas field”).

Shallow gas fields	Well location points
A12-FA	A12-01, A12-03, A12-A-01 t/m A09
A15-A	A15-02, A15-03, A15-05
A18-FA	A18-02, A18-A-01 to A18-A-05
B10-FA	A12-02, B10-03, B10-04
B13-FA	B13-01, B13-03, B13-A-01 to B13-A-04
B16-FA	B16-01
B17-FA	B17-03, B17-05, B17-06
F02a-Pliocene	F02-A-02 t/m A-06, F02-06, F02-B-01

Table 4-1 Shallow gas fields with well location points.

4.3.2 EBN HC show data base

Note that the EBN HC show database classifies the wells in the shallow gas fields, if data is available, from poor (B13-01), fair (6 well location points) to good (5 well location points) gas shows.
Within the other interpreted bright spot polygons (outside the shallow gas fields) the EBN HC show database contains:

- 5 well location points with a “good” gas show (Table 4-2)
- 9 well location points with a “fair” gas show
- 7 well location points with a “poor” gas show
- 7 well location points with “no data”’

Furthermore, wells that penetrate a bright-spot polygon, but are classified as “no show” in EBN HC show database (Appendix A-3) were studied and the bright spot was discarded unless there was a good indication that the well information was insufficient or wrong. In the latter case two wells were not discarded and added to the wells potentially containing shallow gas.

Additionally, 14 wells (from the EBN HC database) have a “good” gas show, but not within a bright spot polygon of this study (appendix A-2). This shows that seismic interpretation of bright spots not necessarily indicates shallow gas.

Well location points with "good" gas show
B18-02
F01-01
F03-02
L02-08
L05-FA-103

Table 4-2 Well location point with "good" gas show (EBN HC show database) in N or NU and located within the bright spot (not in shallow gas fields)

4.3.3 TNO quick scan

A little more than half of the total of 98 well location points are within a shallow gas field or included in the EBN HC show database. TNO applied a quick scan for the other 47 well location points. TNO interpreted 17 well location points with a gas show, the other 31 well location points had no data to interpret gas shows.

5 Review of Vielstädte et al. (2015, 2017)

Vielstädte et al. (2015, 2017) concluded that large methane emission occurs behind the well casing in wells penetrating shallow gas pockets. These publications triggered a question in Dutch Parliament: “Are direct measures being taken to prevent methane leakages of between 3,000 and 17,000 tons of methane from boreholes in the North Sea each year?” and instrumental for instigating this study. Please note that 3,000 to 17,000 tons per year refers to methane leakage from seabed to water column and estimated by Vielstädte to be around 42% methane emission to the atmosphere resulting in 1,000 to 7,000 tons per year.
Although, Vielstädte et al. (2015, 2017) measurements at three abandoned wells are very valuable, we have concerns with several assumptions (uncertain and overestimated) and thus their conclusions. These are listed below

- Vielstädte et al. (2015, 2017) assume that all wells (100%) that penetrate bright spots are leaking. This assumption is not demonstrated and needs further research.
  - The actual causes of the measured leakage were not investigated. The proposed mechanism …*Drilling disturbs and fractures the sediment around the wellbore mechanically, thereby creating highly permeable pathways for the buoyancy driven migration of the gas*…. requires further research. Vielstädte et al. refers only to themselves and Gurevich et al. (1993) who describes mainly methane leakage at underground gas storages in depleted oilfields. These references may be considered to describe a different mechanism than those occurring in shallow gas accumulations at (near) hydrostatic pressure. Moreover, mechanical fracturing up to surface in unconsolidated sediments, where the shallow gas accumulations are found, is unknown. TNO does not recognizes this as an obvious mechanism of methane leakage. Shallow gas may escape during drilling in open hole conditions, but for abandoned wells (which were measured), well integrity issues such, as ‘bad cement’, are more known causes of leakage (Gasda et al., 2004).
  - No pre-drill data is used. Therefore, no distinction is possible between natural or anthropogenic methane leakage measurements. This is essential for shallow gas systems as these near hydrostatic pressured systems in unconsolidated sediments with thin top seals leak methane naturally (see chapter 2).

- The statistically very small data set of only three wells (Figure 5-1) and subsequent extrapolation to all wells in the entire North Sea is unrealistic. Additionally, two out of three wells have no clear direct relation with (anthropogenic) methane leakage as a result from drilling through shallow gas:
  - One well (16/4-2) has no clear relation with any seismic bright spot at all while methane leakage was measured near the well. The methane expulsion levels measured at this well was used to as the high-end methane leakage scenario (4 t/yr.) for the entire North Sea for leakage from wells penetrating bright spots (shallow gas). The well in question did not penetrate a bright

    spot and can therefore not be used to be typical for shallow gas penetrating wells.
    - Measurement at well 16/7-2 is discarded by Vielstädte et al. (2015, 2017) since that well was drilled through a seismically disturbed zone. These disturbed zones are interpreted as (pre-drill) natural gas escape structures, so called gas – or seismic chimneys. Vielstädte et al. (2015) describes this phenomenon as follows…*the seismic feature is also in good agreement with the evidence of carbonates found at the seafloor that may indicate a longer history of gas seepage in the area of the seismic chimney*... This well had the largest leakage (19 t/yr.) of the three wells studied and was drilled in an area were natural methane leakage already exists.
    - Only one well (15/9-3) with the lowest methane emission (1 t/yr.) penetrates a bright spot.

- Vielstädte et al. (2015, 2017) propose that as 33%± 6% of the wells in the study area penetrate bright spots the leakage probability of all wells in the larger North Sea area is the same. This assumption is based on a small and non-representative area in the Central North Sea where 18 of the 55 wells studied penetrate a seismic bright spot. First of all, as discussed in the previous chapters a bright spot is only an indication for shallow gas. Furthermore, in our research, 216 of 2027 wells penetrated a bright spot. This is approximately 10% of all Dutch Offshore wells. Using 33 ± 6% for all 11.122 wells in the North Sea seems an overestimation and requires more research.

- Vielstädte et al. 2017 referred to natural methane leakage of 200 t/yr. from seabed to waterbody for the entire North Sea. This number seems very low, as their own measurement of possible natural leakage was 19 t/yr. leakage measured at one location (well 16/7-2 located in a gas chimney). Gas chimneys are a natural phenomenon and not created by the well bore. This can easily be proven by interpreting the pre-drilling seismic (available at the NPD). Unfortunately, no pre-drill seismic or other data (*e.g.* methane emission) was used in the study of Vielstädte et al. (2015, 2017). If the extreme flux is considered natural it shows an enormous contrast between possible anthropogenic and natural methane leakage. Moreover, the reference to 200 t/yr, seems a significant underestimation when compared with the reference overview shown in Table 2-1, which ranges from 87.000 to 6.200.000 t/yr. for the North Sea. Finally, 478 t/yr of methane leakage has been observed above one single shallow gas field (Römer et al., 2017). The direct relation between high methane fluxes and shallow gas (Schroot et al., 2015) is not discussed. TNO therefore concludes that more research is necessary to distinguish natural from anthropogenic methane emission and their levels of magnitudes. The numbers of methane emission near wells leaking from shallow gas accumulations cannot be reliably extrapolated to the entire North Sea nor can they be related to accurate estimations for anthropogenic emissions.

- Emissions from the North Sea to the atmosphere is uncertain and dependent amongst others to the water depth and bubble sizes. Deeper water depth and smaller bubble sizes give less methane emission to the atmosphere. Vielstädte et al. 2017 uses around 42% to calculate the fraction of methane reaching the atmosphere from sea bottom. The approach to estimate atmospheric emissions is according to Vielstädte et al. 2017 (SI section 2.2.6), believed to be conservative. In contrast Römer et al. 2017 uses a much smaller fraction of less than 5% (Table 2-1: 21.7/478) of natural methane emission to the atmosphere with a water depth around 40 meters.

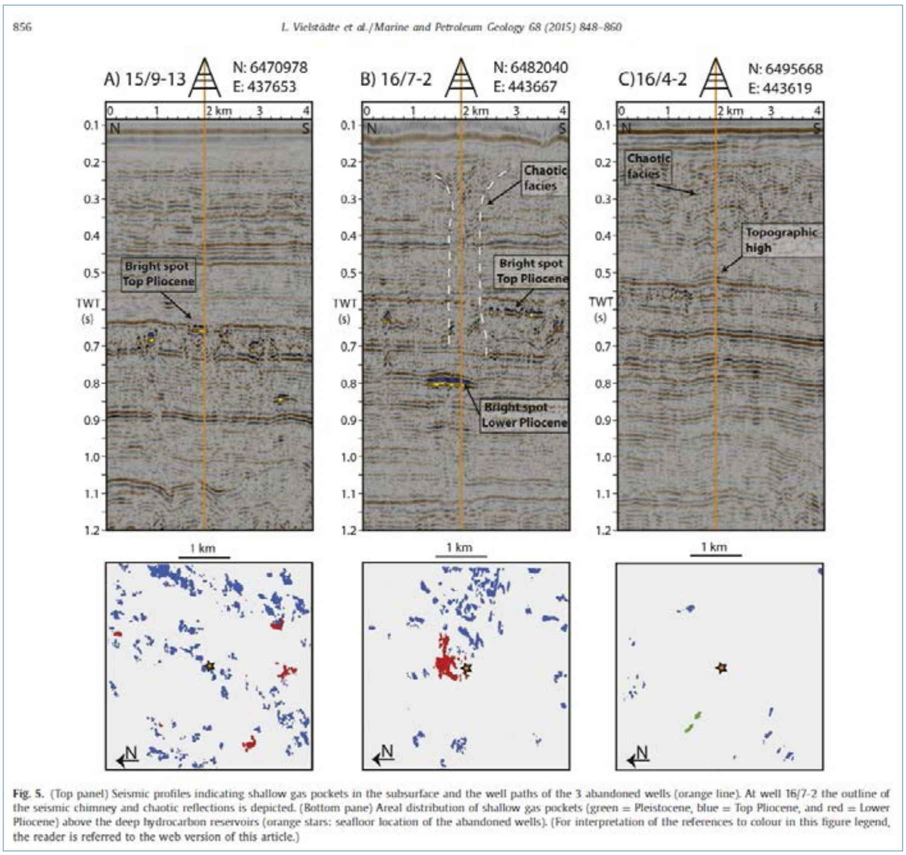


Fig. 5. (Top panel) Seismic profiles indicating shallow gas pockets in the subsurface and the well paths of the 3 abandoned wells (orange line). At well 16/7-2 the outline of the seismic chimney and chaotic reflections is depicted. (Bottom pane) Areal distribution of shallow gas pockets (green = Pleistocene, blue = Top Pliocene, and red = Lower Pliocene) above the deep hydrocarbon reservoirs (orange stars: seafloor location of the abandoned wells). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Figure 5-1: Figure from Vielstädte et al. 2015 shows no bright spot at well 16/4-2, but the measured leakage at that well was used to compute the high-end leakage scenario for leakage from wells that penetrate bright spots.

6 Discussion and conclusions

6.1 Quantifying natural and anthropogenic flow rates

Naturally methane leakage is poorly studied in the Dutch North Sea. We know that the Eridanos delta (Upper North Sea Group) petroleum system is a naturally leaking system emitting significant amounts. However, the current data is insufficient to quantify the natural leakage for the Dutch Offshore. Another source of natural (thermogenic) methane leakage could be methane fluxes of (active) petroleum systems in the subsurface. Distinguishing between natural and anthropogenically induced methane leakage, in prolific petroleum systems, is non-trivial as a high number of wells are drilled in areas were methane leakage occurs naturally. The fact that different studies show a large spread in methane fluxes (Table 2-1) indicates that the subject is poorly understood. TNO-AGE did not find references to case studies on pre-drilling methane emission measurements. Without these measurements the effect of drilling activities is unclear. Pre-drill methane leakage measurements are essential to better distinguish natural from anthropogenic emission and the effect on methane leakage from drilling activities. Only post-drill measurements do not suffice.

TNO-AGE concludes that just studying wells that go through shallow gas accumulations for anthropogenic methane leakage without pre-drill measurements cannot be justified. In general, more research is needed about methane leakage due to well integrity problems.

6.2 Analysis of wells penetrating seismic bright spots

One of the assignments was to compose a list of wells penetrating shallow gas accumulations, specifically accumulations with a high gas saturation and not the accumulations with a low gas saturation. A total of 216 out of a total of 2027 Dutch offshore wells (including side-tracks) penetrates bright spots. It is technically impossible to differentiate between seismic bright spots with a high and a low gas saturation since both very low and high gas concentrations result in an anomalous seismic response (bright spot). Dedicated well logging tools can confirm gas saturations and are normally only run at the exploration target interval. Most wells have deeper targets and therefore no dedicated logging data for shallow gas is available. An exception is most of the wells that penetrate the shallow gas production fields (Table 4-1). Therefore, the categorization of the amount/concentration of the gas for the other wells (appendix A1) only gives an initial indication of gas.

6.3 Vielstädte et al. (2015, 2017).

Vielstädte et al. (2015, 2017) calculates methane leakage using the total number of wells (11,122) with the likelihood that a bright spot is drilled (33%± 6%), with the change of leakage (100%) and a low end (1 t/yr) to high end (4 t/yr) methane leakages case. This results in a total methane leakage to the water column of 3,000

to 17,000 t/yr. Besides the small data set of only three wells, most numbers in the publications are likely overestimates or cannot be shown to be the result of wells drilled in shallow gas accumulations the values for total methane leakage are not representative and overestimated.
Moreover, it is important to use methane leakage measurements, before and after drilling to (eventually) distinguish anthropogenic from natural methane leakage. It should be realized that oil and gas wells are (normally) drilled in areas where already natural methane leakage occurs.

6.4 Parliamentary question

TNO-AGE concludes, in response to the parliamentary question, that shallow gas accumulations are also present on the Dutch Continental Shelf. However, the basis for this question, the methane leakage as described in Vielstädte et al. (2015, 2017), is insufficiently substantiated to be the result of human activity and is overestimated. In general, "the distinction between" and "size of" natural and anthropogenic methane leakage requires further investigation before defining targeted measures.

6.5 Recommendations

Studying only wells with shallow gas is not justifiable. A thorough study of a representative set of wells is needed to determine which factors contribute the most to leakage. Well integrity issues are not exclusive for wells that penetrate shallow gas accumulations and consequently studying only the wells on our list is not justifiable. At this stage the data available is insufficient to determine which factors (i.e. age of the well, well design, type of casing, cement, pressures, geological formation, fluid conditions, presence of shallow gas, etc.) indicates the largest risk of leakage. We recommend a follow-up study to determine which factors contribute the most to leakage in wells.

Moreover, it is recommended to use methane leakage data, before and after drilling to (eventually) distinguish anthropogenic from natural methane leakage since oil and gas wells are (normally) drilled in areas where already natural methane leakage occurs. Also, more study is needed to investigate natural leakage like the numerous pockmarks as indicated on Figure 2-7. This will give better insight for the comparison of natural with anthropogenic methane leakage.

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Appendix A: List of wells within the ‘shallow’ gas areas

Table A-1
General list with wells that penetrate the bright spot polygons compared with EBN HC show database or the quick scan by TNO.

TNO seismic study Wells that penetrate bright spot polygon	EBN HC show database: Gas shows in NU (left) and N (right) (blank= not in database)		TNO gas show Quick scan
A08-01	Fair		
A12-01		Fair	Shallow gas field
A12-02		Fair	Shallow gas field
A12-03	Fair		Shallow gas field
A12-A-01 t/m A-09	Good		Shallow gas field
A14-02	Poor		
A15-02	NO DATA		Shallow gas field
A15-03			Shallow gas field
A15-04		Poor	
A15-05			Shallow gas field
A18-01	Poor		
A18-02	Fair		Shallow gas field
A18-A-01 t/m A03			Shallow gas field
B10-03	Good		Shallow gas field
B10-04			Shallow gas field
B13-01		Poor	Shallow gas field
B13-03	Fair		Shallow gas field
B13-A-01 t/m A-04			Shallow gas field
B14-01		Fair	
B14-03		Fair	
B16-01	Good		Shallow gas field
B17-03		Fair	Shallow gas field
B17-05	Good		Shallow gas field
B17-06	Good		Shallow gas field
B18-02		Good	
E17-03			NO DATA
E18-07	Poor		
F01-01		Good	
F02-03			Gas show
F02-04			NO DATA
F02-05			Gas show
F02-06			Shallow gas field
F02-A-02 t/m A-06	Good		Shallow gas field

TNO seismic study Wells that penetrate bright spot polygon	EBN HC show database: Gas shows in NU (left) and N (right) (blank= not in database)		TNO gas show Quick scan
F02-B-01			Shallow gas field
F03-02		Good	
F04-01			NO DATA
F05-02	Poor		
F07-01			NO DATA
F12-05			NO DATA
F14-03			NO DATA
F16-02		Fair	
F17-13			NO DATA
G13-02	Fair		
G16-01		Fair	
G16-03		Fair	
G16-A-01 t/m A-03		NO DATA	
K05-11			Gas show
K05-F-02			Gas show
K05-F-03			NO DATA
K06-07			NO DATA
K06-C-01 t/m C-02			NO DATA
K06-D-01 t/m D-02			NO DATA
K06-DN-01 t/m			Gas show
DN-05			
K08-14			NO DATA
L02-08	Good		
L04-10		NO DATA	
L05-12		NO DATA	
L05-FA-103	Good		
L08-04	No show		In sediment wave [KEEP]
L08-05	Fair		
L08-06		NO DATA	
L08-10	Poor		
L08-G-01 t/m G-04		No show	L08-05 in same bright spot [KEEP]
L08-P-01 t/m P-05	NO DATA		
L09-08			NO DATA
L09-09			NO DATA
L09-10			NO DATA
L09-11			NO DATA
L09-12			NO DATA
L09-13			NO DATA
L09-FF-101 t/m			Gas show

TNO seismic study Wells that penetrate bright spot polygon	EBN HC show database: Gas shows in NU (left) and N (right) (blank= not in database)		TNO gas show Quick scan
FF-108			
P02-02			NO DATA
P06-01			Gas show
P06-03			NO DATA
P06-04			NO DATA
P06-05			NO DATA
P06-10			NO DATA
P06-A-01 t/m A-07			Gas show
P06-B-01 t/m 04			Gas show
P06-C-01 t/m C02			NO DATA
P06-S-01			Gas show
P15-E-01			NO DATA
Q01-03			Gas show
Q01-05			Gas show
Q01-21			Gas show
Q01-28			Gas show
Q01-D-02			NO DATA
Q01-HAVEN-A-01 t/m A-09		NO DATA	
Q04-02			NO DATA
Q04-04			NO DATA
Q04-05			NO DATA
Q04-07			Gas show
Q07-01		Fair	
Q08-05			Gas show
Q10-02	NO DATA		
Q10-06			NO DATA

Table A-2
Wells with "good" gas shows in N or NU according to EBN HC show database but located outside bright spot polygons of this study.

Wells located outside bright spot	Seismic observations
B17-04	No bright spot (Fizz gas?)
E18-01	No bright spot (Fizz gas?)
F02-01-S1	No bright spot (Fizz gas?)
F03-01	No bright spot (Fizz gas?)
F03-05-S1	No bright spot (Fizz gas?)
F16-03	No bright spot (Fizz gas?)
L01-03	No bright spot, Bright at MMU
L02-FA-101	No bright spot, Bright at MMU
L02-FA-102	No bright spot, Bright at MMU
L02-FA-103	No bright spot, Bright at MMU
L04-PN-01	No bright spot, near fault
L04-PN-04-S1	No bright spot, near fault
L05-FA-101	No bright spot, Bright at MMU
M07-06	No bright spot (Fizz gas?)

Table A-3
Wells that penetrate a bright-spot polygon but are classified as “no show” in EBN HC show database. These wells were studied and the bright spot was discarded unless there was a good indication that the well information was insufficient or wrong. The following wells were kept:

Wells within bright spot	TNO quick scan, because classified as “no show” in EBN HC database
L08-04	Near sediment wave
L08-G-04	L08-05 in same bright spot