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Methane leakage from abandoned wells in the Dutch North Sea

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ABSTRACT

Methane is a powerful greenhouse gas and the second most important when considering global warming due to anthropogenic added gasses. Global inventories of greenhouse gasses currently do not take into consideration methane emitted from the ocean and seas. The North Sea is an intensely exploited seas for oil and gas and it was recently suggested to be a major source for manmade methane emissions. All wells drilled through shallow gas (methane) were found to be leaking and one-third of all abandoned wells was found to be drilled through shallow gas. Here we present the results from a research expedition to investigate methane leakage at abandoned wells drilled through shallow gas in the Dutch North Sea. We surveyed 57 abandoned wells of which 33 were drilled through shallow gas. Nine locations showed bubble plumes (acoustic flares). We noted a distinct difference between gas leakage of abandoned wells and locations with natural gas seepage. Whereas well leakage consists of one or two bubble plumes at the wellhead itself and no bubble plumes in the surrounding area, natural plume fields are characterized by tens to hundreds of plumes and none at the wellhead. At six wells, we conclude that the plumes are caused by the well leaking shallow gas, whereas three observed plume fields classify as natural seepage. We found that 18% of wells drilled through shallow gas were leaking, with 11% of all abandoned wells being drilled through shallow gas. When we compensated for over-representation of shallow gas wells in our sample (58% of our sample is drilled through shallow gas), we find that less than 2% of all abandoned wells in the Dutch North Sea is likely leaking. Well leakage seems to occur when large quantities of shallow gas are present and the abandoned well apparently suffers from an integrity issue.

1. Introduction

Methane is a powerful greenhouse gas and the second most important for global warming. Different sources contribute to atmospheric methane, both natural and anthropogenic, with the relative contributions of these sources being a subject of intense research (Saunois et al., 2020). Primary anthropogenic contributors to atmospheric methane are the agricultural sector, closely followed by the oil and gas industry. This not only raises scientific interest, but also draws considerable attention from governmental bodies and NGOs. The North Sea is one of the most intensely exploited seas for oil and gas, and it was recently suggested that all wells (100%) drilled through shallow gas accumulations might be leaking (Vielstadte et al., 2015; 2017; Böttner et al., 2020). This would imply that potentially one third of all decommissioned wells are leaking shallow gas, which would result in a potentially appreciable release of methane from the North Sea. This in turn gave rise to concerns in European states bordering the North Sea. In the Dutch House of Representatives, parliamentary questions were asked and the State Supervision of Mines (Staatstoezicht op de Mijnen, SodM) initiated the here presented research, which indicates urgency felt by society.

Gas leakage from abandoned wells may be originating from both deep and shallow gas sources. Shallow gas is defined as the gas that is occurring in the uppermost sediments, up to a maximum depth of 1000 m (Floodgate and Judd, 1992; Schroot and Schüttenhelm, 2003), and which can be of microbial or thermogenic origin (Floodgate and Judd, 1992). In the North Sea, shallow gas is typically of microbial origin (Vielstadte et al., 2015; Verweij et al., 2018; de Bruin et al., 2022) and the occurrence of shallow gas is widespread. As monitoring the release of methane over the sea surface is difficult using satellite observations (MacLean et al., 2023), in-situ observations are needed to determine

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methane release. This also applies to potential methane leakage from abandoned wells, as well as the rate at which these wells leak. Therefore, over the last decade several studies were conducted (Fig. 1) using ship-based observations to investigate methane emissions in the North Sea for natural and anthropogenic (shallow) gas release (Vielstadte et al., 2015; 2017; Böttner et al., 2020, Römer et al., 2021).

Here we present the results from a research cruise with the RV Pelagia (PE503, June 5–22, 2022), jointly organized by the Royal Netherlands Institute for Sea Research (NIOZ), the Geological Survey of the Netherlands (TNO-GDN) and the Dutch State Supervision of Mines (SodM). The aim of this cruise was to investigate methane leakage from abandoned wells in the Dutch North Sea, and how potential leakage relates to the occurrence of shallow gas in the subsurface.

2. Geological setting: Dutch North Sea

For our study, we first made an inventory of all abandoned wells in the Dutch North Sea and selected locations to investigate based on the known geological setting. This setting determines the occurrence of shallow (and deep) gas and defines the structures in subsurface that could be responsible for natural seepage.

In the Southern North Sea shallow gas resides in shallow marine to continental (deltaic) deposits of the Southern North Sea delta or Eridanos Delta (de Bruin et al., 2022; Overeem et al., 2001). This Neogene geological succession is named the Upper North Sea Group (TNO-GDN, 2024a) and is characterized by a westward prograding sedimentary succession comprising mostly of very fine sand, silts and clays of Middle Miocene to Pleistocene age. These sediments are unconsolidated and consist of erosional products from Scandinavia, mainly derived from southern Sweden (Verweij et al., 2018). The Cenozoic sediments in the Dutch sector host an abundance of seismic-amplitude anomalies related to shallow gas occurrences including bright spots, velocity pull-downs, flat spots, seismic blanking, and phase reversals (de Bruin et al., 2022).

In the North Sea shallow gas is widespread, and in the Dutch sector numerous and often large accumulations are found in the Dutch Central Graben (DCG) and Step Graben (Doornenbal et al., 2019). At least 8 accumulations have large enough quantities of gas that they can be profitably produced or will be produced in the near future (https://www.nlog.nl/media/3052). Shallow gas production started in 2008, and in 2022, the production of shallow gas was 968 million Nm^3, which was 13% of the total offshore gas production of the Netherlands (TNO-GDN, 2024b). Deep Carboniferous sourced (thermogenic) gas fields are not found in the DCG, with the exception of the southernmost part. This is because the Carboniferous source rocks are buried too deep in the DCG and are therefore overmature. Thermogenic (deep) gas fields are predominately found south of the DCG (e.g. south of our study area). With the production of thermogenic gas declining, the relative contribution of shallow gas produced increases. In the DCG (study area), oil fields are found, which are sourced by Jurassic Posidonia source rocks (Doornenbal et al., 2019). Most of the wells drilled in the northern sector of the Dutch North Sea are exploration wells that did not find deep (thermogenic) gas (in commercial quantities), while in some instances oil was encountered. Because these deep wells were drilled through the overlaying succession, they should have passed through shallow gas when present.

3. Methods

In addition to abandoned wells drilled through shallow gas, we also included wells drilled close to shallow gas accumulations (<1 km) as

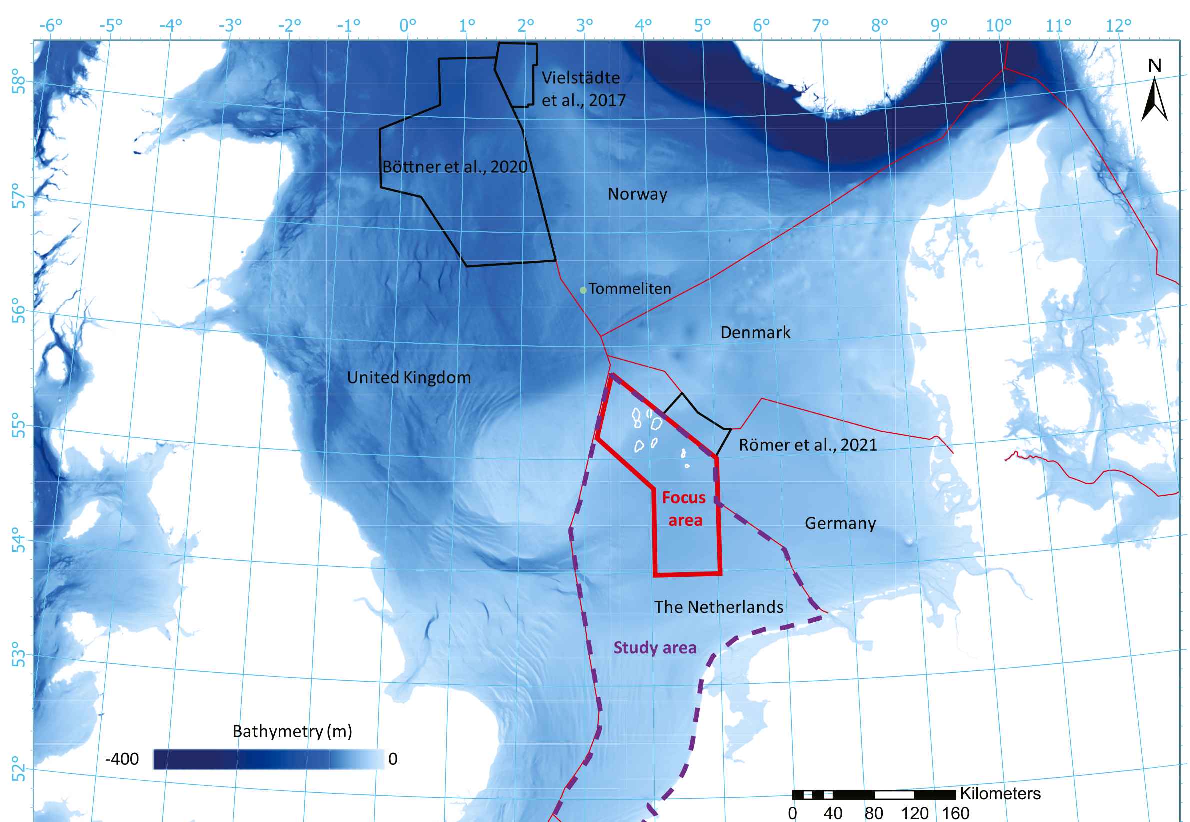

Fig. 1. Bathymetric map of the North Sea with limits of exclusive economic zones of bordering states, and areas from which gas leakage or natural seepage has been reported in previous studies. For the present study seismic and well data of the entire Dutch sector was analyzed, but the focus is on the northern part where most of the shallow gas is found (marked in white). In the focus area (red) we conducted the PE503 expedition.

these might be prone to leakage too (Böttner et al., 2020). We also investigated other sources for methane emissions such as natural seepage, leakage from deep reservoirs and seepage from methane sources close to the seabed. Wilpshaar et al. (2021) argued that these could all potentially interfere when trying to link abandoned wells and ebullition.

To distinguish gas from shallow sources from gas derived from deeper reservoirs, we looked at differences in gas composition. Deep thermogenic gas is characterized by a relatively high ethane concentration (typically 3–6%), while ethane is only present in trace amounts (0.02%) in shallow gas (Verweij et al., 2018). To exclude natural seepage, we first looked at the reports of the surveys that were conducted before drilling. Such pre-drilling surveys are specifically conducted to assess drilling risks related to potential shallow gas occurrences close to the seabed. When shallow gas is found, it is common practice to change a planned location. Chances for a well being drilled exactly at a location where natural seepage occurs are therefore very small. Still, there are some examples where wells were drilled close to natural seepage sites (e.g. well 15/25b-1A described by Böttner et al., 2019), but never directly in a bubble plume. Accordingly, we argue that a single bubble plume or a few plumes directly at the wellhead location, with no plumes in the vicinity, is very unlikely natural seepage and hence indicates well leakage. In contrast, natural seepage in the Dutch part of the North Sea (Römer et al., 2017) is generally characterized by large numbers (up to several hundreds) of bubble plumes over large areas (several square kilometers).

Finally, we distinguished locations with and without methane sources close to the seabed. The reason for this is that ebullition has been reported at places without a direct indication for shallow gas. For example, one of the wells in the study of Vielstadte et al. (2015) showed ebullition (well 16/4–2) but was not drilled through a bright spot (the closest bright spot being about a kilometer away from the drill site). Therefore, we also need to include sources for biogenic gas close to the seabed in our analyses, which are inherently less visible on conventional seismic data. Holocene and Pleistocene sediments may contain considerable amounts of gas of (shallow) biogenic origins (Brekke et al., 1997; Borges et al., 2016; Missiaen et al., 2002; Lippmann et al., 2020). This gas may even accumulate in so-called 'tunnel valleys' (U-shaped channels that formed under the ice of the last ice age and were rapidly filled with sediment during and after the deglaciation) or in and beneath organically rich sediments such as peat layers (known as "Basisveen", TNO-GDN, 2024c), which in the North Sea represent the last phase of sea level rise during the deglaciation (Oele, 1969).

3.1. Site selection

There is a total of 1450 abandoned wells in the Dutch North Sea sector, which made a pre-selection of sites necessary. Here we first explain the rationale for our site selection and how this needs to be accounted for in the later statistical data treatment.

Firstly, we established which wells were drilled through shallow gas and which not, based on available seismic and well data. All seismic bright spots (and related seismic anomalies) related to shallow gas in the entire Dutch Offshore were manually mapped using seismic data which is available at TNO-GDN (www.nlog.nl). Based on these maps, we established which wells were drilled through seismic anomalies indicative of shallow gas occurrences and which not. Using a database of gas shows (provided by Energie Beheer Nederland, EBN), we also established whether gas was encountered during drilling at the depth of the observed bright spots. This way, bright spots could be directly linked to shallow gas occurrences. We found that, out of the 1450 wells drilled in the Dutch sector, 153 wells were drilled through a bright spot (Fig. 2) and for 91 of these wells, actual gas was recorded during drilling at the depth of the bright spot. For the remaining 62 wells, the bright spot could not be linked to gas based on well data. Still, in many cases no well data was available because either the data was not recorded during

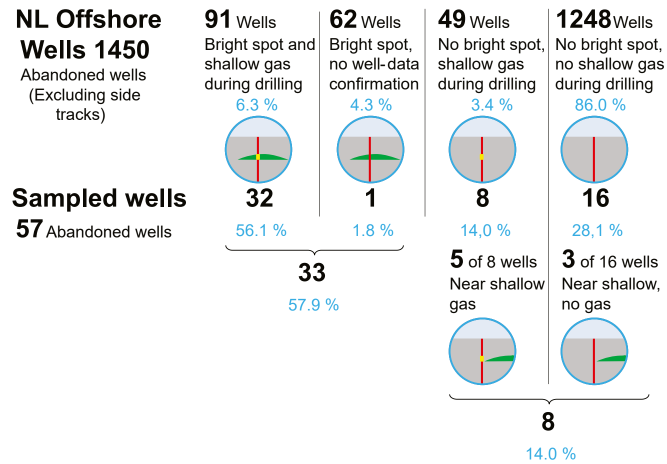

Fig. 2. Overview of all abandoned wells including sidetracks (1450) in the Dutch North Sea, and the relation to shallow gas. We selected 57 wells of which 33 were drilled through shallow gas, 8 drilled near a bright spot and 16 were not associated with shallow gas.

drilling, or the drilling circumstances prevented gas from entering the well. Although gas could be absent at sites with bright spots, we considered this to be unlikely and find it more likely that a lack of direct gas observations is due to operational limitations. Conversely, 49 wells had gas shows (all in the shallow domain) while no bright spot was distinguished in the available seismic data (Fig. 2). Most of these wells were, however, drilled close to a bright spot. Because shallow gas accumulations are typically very flat (only 10–20 m gas column and a couple of kilometers wide), they tend to thin out towards the edges. Hence, at a distance, the gas column gets so thin that tuning occurs and the bright spot is no longer observed.

We selected a total of 57 abandoned wells (App. A). All wells were drilled as exploration or appraisal wells (no production wells). Most wells targeted an underlying thermogenic interval, albeit that most wells were unsuccessful. Of all the selected wells, only 16 wells encountered thermogenic hydrocarbons, mostly in the form of shows (noncommercial quantities). Seven wells were drilled through an oil field and 41 did encounter shallow gas. 33 wells were drilled trough a shallow gas related bright spot and eight wells showed gas shows, although the seismic data did not show a bright spot. However, five of these wells were drilled close to of a bright spot (less than 1 km) and therefore likely penetrated a thinned-out gas layer no longer visible locally as a bright spot. There are also three wells that encountered shallow gas while drilling, whereas no bright spot was observed, also not in the vicinity of the well (Fig. 2 and appendix B.).

3.2. Sensors used during the survey and observations made

The survey comprised of both real-time observations with sensors and discrete sampling (de Stigter et al., 2022). Before observations were made at the abandoned well sites, the given positions of abandoned well heads buried below the seabed were verified. For this purpose, we conducted surveys with a magnetometer (Geometrics G882), that detects the metal component of the buried well. In addition, profiles of the shallow subsurface geology were acquired with a Sub Bottom Profiler (Innomar Medium 100).

Presence of active ebullition was assessed on the basis of water column acoustic backscatter profiles acquired with a high resolution multibeam echosounder (Kongsberg EM2040). Gas bubbles give a strong acoustic signal and are therefore clearly visible. Since the bubbles are rising from the seafloor, bubble plumes form long, vertical reflectors rising from a distinct source. At each location, at least 5 parallel lines were recorded using a swath overlap of approximately 50%. In order to achieve this overlap, a distance of 40–50 m was maintained between subsequent lines, depending on water depth (30–50 m). At each well location, an area of approximately 250 by 400 m was covered this way. The orientation of the lines was largely decided on the basis of maneuverability of the ship depending on weather and sea state conditions.

A methane sensor (Franatech Laser Methane Sensor) was used for measuring the CH_4 partial pressure in-situ in the water column at several depths. In addition, analysis of gas content in near-bottom water was performed with a laser spectrometer (Tunable Infrared Laser Direct Absorption Spectroscopy; TILDAS; Aerodyne Research Inc., Billerica, USA). Water from a few meters above the seabed was pumped up via a weighted hose (named "Slurf"), degassed using a Weiss equilibrator or a membrane filter and the gasses were continuesly analyzed with a laser spectrometer (de Stigter et a., 2020). The spectrometer measured simultaneously methane and ethane, which is essential for distinguishing shallow gas from deep thermogenic gas.

3.3. Surveys conducted

Due to time constraints, not all selected locations were fully surveyed. In total 48 wells (App. A) were fully surveyed (i.e. at least 5 parallel multibeam echosounder (MBES) tracks, Sub Bottom Profile, Magnetometer, LMS Methane Sensor, 'Slurf' continuous near-bottom water analysis) while 9 wells were partially surveyed (i.e. one pass with MBES, and 'Slurf'), which is listed in appendix A.

4. Results

4.1. Multibeam detection of bubble plumes

At nine abandoned wells, bubble plumes (acoustic flares) were observed (Fig. 3). From the observed bubble plumes in relation to the wellhead locations (confirmed by the magnetometer), we conclude that there are two distinct types. 1) *Wellhead plumes*: one or two bubble plumes at the wellhead (within 23 m) and no bubble plumes in the surrounding area. 2) *Plume fields*: Numerous plumes (tens to hundreds) at a considerable distance from the well (74 m or more) and none at the wellhead itself.

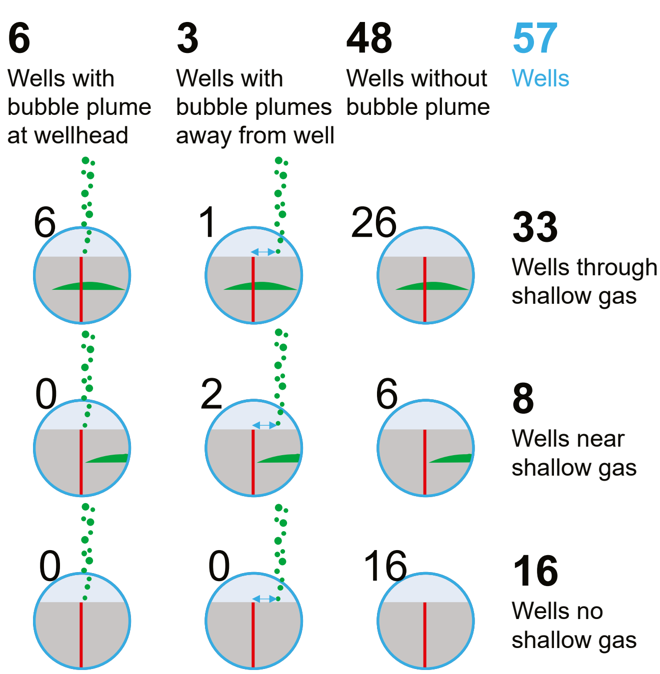

Fig. 3. Occurrence of bubble plumes detected in multibeam water column data (MBES) in relation to the wellhead and the occurrence of shallow gas. At six wells a plume was observed at the wellhead. All six wells were drilled through shallow gas. At 3 locations, multiple plumes were found at a significant distance from the wellhead.

4.1.1. Wellhead plumes

At six abandoned wells (A08–01, A14–02, A15–03, B17–03, B17–05, F01-01, appendix A) one or two bubble plumes were observed directly at the wellhead (Fig. 5), while no plumes were detected in the vicinity (i.e. there are only one or two plumes at the wellhead location itself). An example of such a bubble plume observed by multibeam is shown in Fig. 4 for location B17-05. All six wells that showed bubble plumes at the wellhead are drilled trough known shallow gas accumulations.

4.1.2. Plume fields

At 3 locations (near wells B13–01, B17–04, F17-14), plumes were observed at tens to hundreds of meters distance from the wells (i.e., no bubble plume was observed at the wellhead itself). In blocks B13 and B17, fields of plumes were found (i.e., tens of plumes spread over a larger area), which could be linked to the presence of shallow gas. The plumes in the vicinity of well F17-14 are not related to any known shallow gas occurrence.

4.2. Methane and ethane in near-bottom water

With the 'Slurf' based measurements, we found elevated methane concentrations at locations where bubble plumes were seen with the MBES. Peaks in methane were seen at five of the six wells where bubble plumes were observed, at A08–01, A14–02, A15–03, B17–03 and B17-05. The 'Slurf' only detected enhanced methane concentration and did not detect any enhanced ethane concentrations at the bubble plume locations. To test the sensitivity of the 'Slurf', measurements were done around a pipeline used for transport of natural gas, which did show simultaneous peaks of methane and ethane.

5. Discussion

Fig. 6 shows an overview of all the results, such as the number of observed bubble plumes, distance to the well, all sources of methane that the well penetrates, the methane measurements, and whether plumes were present before drilling. No peat was present at any of the wells that featured a bubble plume at the wellhead based on inspection of the SBP data. The SBP data were only recorded at the wells and not at the three bubble plume locations away from wells, which therefore still might correspond to the occurrence of peat.

5.1. Leakage at six wells

During our survey, we observed both isolated wellhead plumes and plume fields at some distance from the well (Fig. 6). For the plumes categorized as 'wellhead plumes', we observed that these bubble plumes are isolated and located at the wellhead. Hence, we conclude that they are caused by leakage of the well, rather than natural seepage. To further rule-out interference of natural seepage, we used data from pre-drill site

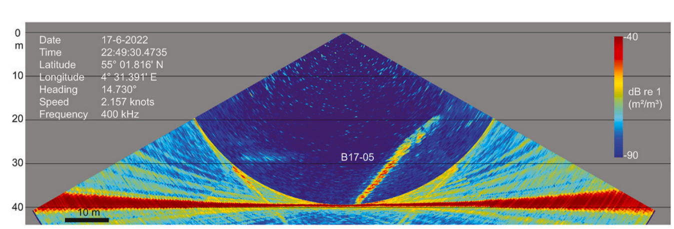

Fig. 4. At well B17-05, a bubble plume was observed at the wellhead. Example of data used for identifying and pin-pointing bubble plumes.

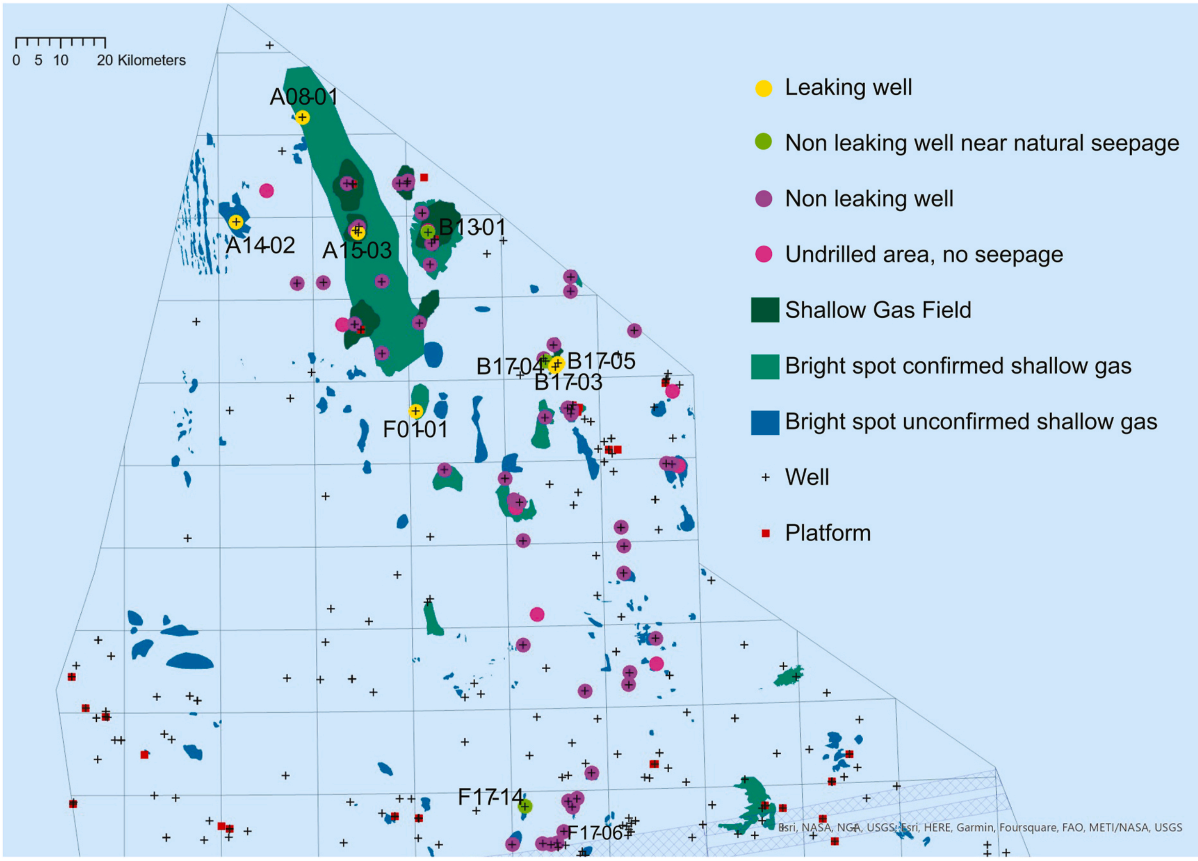

Fig. 5. Overview map of the northern part of the Dutch North Sea and the surveyed locations. Scale bar in the upper left corner. At the location of 6 abandoned wells, a bubble plume was observed at the wellhead (yellow). At 3 well locations, bubble plumes were observed in the vicinity of these wells but not at the wellhead (green).

Well	Number of plumes	Min plume to well distance	Potential CH_4 sources	LSM CH_4 max	Slurf CH_4 peaks	Plume before drilling
A08-01	1	8 m				No
A14-02	1	3				No
A15-03	2	2				No data
B17-03	1	23				No data
B17-05	2	2				No data
F01-01	1	5				No data
B13-01	90+	150				No data
B17-04	30+	74				No data
F17-14*	6	240		No data		No data

Fig. 6. Overview of wells where plumes were observed, the number of plumes, the minimal distance between the wellhead and the bubble plume(s). The potential sources encountered in the well are peat layers close to the surface (yellow), tunnel valleys (orange), shallow gas (green) and deep thermogenic gas (blue). LMS is the Franatech Methane sensor that was attached to the CTD rosette. 'Slurf' (laser spectrometer) measured only methane at the wells, no ethane was encountered at these locations. Plume before drilling refers to the results of the surveys conducted before the wells were drilled. Only data for two wells was available.

surveys obtained by the different operators/drilling companies. Site surveys are not publicly available, and the survey reports have to be supplied by the owners of the well. We received reports of the site surveys at A08–01 and A14-02 from the Nederlandse Aardolie Maatschappij (NAM). The pre-drilling-survey reports show no evidence for bubble plumes (related to natural seepage) before drilling. Our observations show only bubble plumes at the six well locations and no other bubble plumes in the vicinity, so avoiding the bubble plume would have been easy for the drillers. Consequently, it is highly unlikely that natural seepage was present at these six sites prior to drilling.

All putatively leaking wells discussed here were drilled through shallow gas, with no other sources encountered. This is in line with the 'Slurf' not detecting enhanced ethane concentrations. The absence of enhanced amounts of ethane near the leaking wellheads makes it likely that the gas is of microbial, biogenic, origin (i.e. shallow gas). Since all six wells were drilled through shallow gas, the observed well leakage is most likely from this shallow gas. The actual mechanism responsible for the observed leakage remains to be proven and is discussed below.

5.2. Natural seepage of shallow gas

The plumes categorized as 'plume fields' are most likely caused by natural seepage. The plumes in the B13 block have been studied before (Schroot et al., 2005; Römer et al., 2017; de Groot et al., 2024), and the consensus is that these plumes are part of a larger natural seepage area above a producing shallow gas field. There are four abandoned wells (B10–02, B13–01, B13–03 and B13-04) drilled through this gas field. The absence of a bubble plume at the four well heads, in contrast to the presence of numerous plumes at considerable distance (B13-01 being the closest at 150 m), suggests that natural seepage is most likely the main mechanism for these plumes.

We found a similar setting in the vicinity of well B17-04, where no bubble plume was observed at the wellhead itself, but numerous plumes were found at some distance. B17-04 was drilled through a so-called seismic chimney (vertically disturbed zone, indicative for vertical gas migration), most likely related to faults above a salt dome. A shallow gas field (B17-A) is present on the eastern flank of this salt dome. There is no gas field found on the western flank, since the reservoir appears to have leaked through faults, causing the chimney. The bubble plume clusters are located directly above this seismic chimney, which implies natural gas is still escaping here. Hence natural seepage of shallow gas, migrating from the reservoir via the faults, is most likely the source for the observed ebullition.

In the vicinity of F17-14 several plumes were observed at a distance of 240 m away from the well, although fewer than at B13 and B17. Again, the distance makes leakage from the well itself highly unlikely. Shallow gas has not been observed locally and therefore we cannot link the seepage to a distinct source. No new sub bottom profiler data was collected during the survey at this location, but shallow drilling in the area identified a clear Basisveen Bed to be present. Hence, natural seepage of gas from this peat layer is probably best explaining the locally dispersed occurrence of bubble plumes. Still, new data at the actual location would be needed to match the locally found ebullition with a potential source.

5.3. Statistical analysis of well leakage

Extrapolating our observations to a larger area to infer the chances of well leakage to occur requires to first consider the possibility that we might have missed leaking wells (false negative) during the survey and/or misidentified wells as leaking that are actually not leaking (false positive). This could potentially introduce a systematic bias, which cannot be accounted for by statistics. For instance, a false positive could be caused by a school of fish or another unknown acoustic artefact being misinterpreted as a bubble plume at a wellhead. Chances on such a false positive are, however, extremely small since ebullition was always consistently identified at the leaking sites in a series of subsequent passes (at least 3 times) over the wellhead. Also, the chance of a false negative, missing an actually leaking well, is small because of the repetitive and multi sensor observations. Temporal changes could still interfere with our observations, when a leaking well is not constantly leaking resulting in an intermittent flux, with long intervals of no leakage. For instance, de Groot et al. (2024) found that the natural seeps in the B13 area have a clear tidal control. Comparing our observations with the tidal cycle however shows that we observed leaking wells during all phases of the tidal cycle (i.e. mid, low and high tide), indicating that although tides may modulate flow, this likely not cause an intermittent flux. Overlapping MBES-swaths also guarantees at least some temporal coverage, albeit that the overall MBES survey at one location was mostly completed within 2 h. Each well was covered at least by three swaths of the MBES survey and the MBES was also continually recording during CTD deployment at the well locations. Hence, only intermittency with a very long down time would result in a false negative. We are therefore confident that chances of a false positive are very small and chances for a false negative are small but cannot be fully ruled out and that we can treat the data and statistics without considering a systematic bias.

Our results show that 18% (6 out of 33) of the investigated wells drilled through shallow gas are leaking. Using the Wilson score interval (Wilson, 1927), compensated for a finite population (i.e. there is a finite number of wells drilled in the Dutch North Sea sector), we calculated the binomial proportion confidence interval for the probability of leakage (Table 1, App. C.). At 90% confidence level, the estimated probability range for true leakage is between 9 and 32%.

Although the wells not drilled through shallow gas inherently have a much lower chance of leakage (as they showed no leakage in our survey), we also investigated much fewer of these well. Hence, based on this study, some leakage occurring in these wells cannot be fully excluded here, albeit that it would be much more limited compared to the wells drilled through shallow gas.

Table 1
Observed leakage percentages and computed confidence intervals of the wells drilled through shallow gas, and calculated for the entire population of surveyed abandoned wells, also those not drilled through shallow gas. We compensated the latter for the over-representation of shallow gas wells in our sample (i.e., 58% of our sample is drilled through shallow gas, while 11% of all abandoned wells in the Dutch North Sea are drilled through shallow gas).

	Leakage percentage	Confidence interval (90%)
6 leaking wells of 33 wells drilled through shallow gas	18%	9–32 %
67 sampled wells compensated for oversampling shallow gas	1.8 %	1.4–2.3 %

In the vicinity of 4 of the 6 leaking wells (A18–01, A15–03, B17–03, B17-05), we found other, non-leaking wells (A12–03, A15–02, A15–05, B17-06), drilled through the same shallow gas accumulations. In three cases, those were proven shallow gas fields (i.e. large quantities of shallow gas were proven). This implies that even large quantities of shallow gas do not necessarily result in well leakage. The occurrence of well leakage is clearly avoidable and further investigation is needed to identify the correct measures to avoid it.

From the surveyed wells, 58% were drilled through shallow gas, whereas for the entire Dutch North Sea, the percentage of wells drilled through shallow gas is only 11%. Since we found that about 18% of all surveyed wells drilled through shallow gas are leaking, we predict that 28 of the total of 153 wells drilled through shallow gas in the Dutch North Sea are leaking, which is less than 2% of all wells (1450) in the Dutch North Sea (see Table 2).

5.4. Comparison with previous studies

Previous studies such as performed by Böttner et al. (2020) concluded leakage at 28 out of the 43 wells that were investigated in the UK sector of the North Sea, of which eight were drilled through shallow gas (Table 2), whereas Vielstädte et al. (2017) measured the flux of three leaking wells, leaking biogenic gas. In contrast, Römer et al. (2021) found no leaking wells at the 10 wells they investigated, of which six were drilled through shallow gas.

When looking specifically at wells drilled through shallow gas, we find that there is a striking difference between our findings and Römer on the one side and Böttner et al. (2020) and Vielstädte et al. (2017) on the other. Statistically our findings are comparable to Römer et al. (2021) but differ from those by Vielstädte et al. (2017) and Böttner et al. (2020). As the studies by Vielstädte et al. (2017) and Böttner et al. (2020) concentrated on a different sector in the North Sea, this might be due to differences in geology or the way how wells are designed, completed and ultimately abandoned.

Table 2
Summary of observations on well leakage from wells drilled through shallow gas in the Norwegian, UK, German, and Dutch North Sea, as well as leakage of deep thermogenic gas onshore the Netherlands.

North Sea wells drilled through shallow gas	Wells	Leaking	Leakage percentage
This study	33	6	18%
Norwegian Offshore, Vielstädte et al., 2017	3	3	100%
UK Offshore, Böttner et al., 2020	8	8	100%
German offshore, Römer et al. (2021)	6	0	0%
NL Wells drilled through thermogenic HC	Wells	Leaking	Leakage percentage
This study, thermogenic HC only	16	0	0%
Dutch Onshore, Schout et al., 2019	29	1	3%

Schout et al. (2019) investigated well leakage onshore the Netherlands. All wells had a deep thermogenic target (and no shallow gas was observed while drilling). They observed that 1 of the 29 investigated wells was leaking (3%). We surveyed 16 wells reaching deep thermogenic hydrocarbons, and no leakage was found. Because leakage at these wells is rare, the limited number of sampled wells do not allow for a meaningful statistical comparison other than that we have no evidence for differences in leakage between land-based and offshore abandoned wells.

5.5. Leakage mechanism

The mechanism responsible for the observed leakage is still under debate (see Wilpshaar et al., 2021 for discussion). Vielstädte et al. (2017) and Böttner et al. (2020) proposed that leakage is likely focused along drilling-induced fractures around the borehole. The authors proposed such a leakage mechanism for the Nordland Group (Middle Miocene to recent) sediments present in the North Sea in Norway. However, the Nordland Group consists of unconsolidated to weakly consolidated silt and clay layers, which show an almost elastic-perfectly plastic behavior during tri-axial tests (Pillitteri et al., 2003). Therefore, it is highly unlikely that fractures form. Even when rocks are sufficiently consolidated to display brittle deformation, fractures only occur when the drilling fluid used (mud weight) is too heavy during drilling. Such drilling conditions are typically not found at the shallow intervals where shallow gas occurs (TNO R10056). To our knowledge, gas migration through drilling-induced fractures in consolidated rock has not been observed and/or demonstrated in any other study.

Excluding drilling induced fracturing as a source for leakage, we consider only well integrity issues as a potential viable leakage mechanism. Leakage pathways concern mostly the casing, the cement, the interfaces between casing and cement, and the interface between cement and formation. Further research is needed to establish what the most common leakage mechanism is.

5.6. Comparison natural seepage and well leakage

We surveyed 57 wells and found six leaking wells with in total eight bubble plumes. B17-05 had the largest plumes and F01-01 had a very small plume. At the natural seepage site of B17, we found 31 bubble plumes in a surveyed area of only 0.05 km^2 (the total area where seeps occur is probably larger). Römer et al. (2017) found between 490 and 854 bubble plumes in an 8 km^2 area at the B13 natural seepage site. The number of observed natural plumes is hence far greater than the man-induced plumes. Exact amounts of methane leakage are still under investigation, but based on comparison between natural and anthropogenic seepage, it is clear that natural seepage exceeds well leakage. However, many uncertainties about the methane emissions remain. Leakage could decline over time due to diminishing methane volumes, but leakage could also increase due to deterioration of well-integrity issues (rust, etc.). Also, the influence of the production of shallow gas on both well leakage and natural seepage is unknown at this moment. The B13 natural seepage site is located above the B13-FA field that is currently in production. Whether the natural seepage will locally decrease because of the production of shallow gas is unknown. The leaking well A15-03 is drilled through the A15-A field that will be taken in production soon. Also here, production of this shallow gas may decrease methane leakage from the abandoned A15-03 well. When gas is produced pressure in the field will decline and thereby the gas escaping from the abandoned well. Still, there are several gas-bearing intervals present, and it is unclear which interval is the source of the leakage and whether that interval is actually being produced.

6. Conclusions

Six wells of 57 investigated abandoned wells are leaking shallow gas in the Dutch North Sea. Of the investigated wells drilled through shallow gas, 18% showed ebullition. No ethane was detected, which implies that the leakage was sourced from shallow gas. Since leakage is consistently associated with shallow gas in the subsurface, we conclude that drilling through shallow gas has a somewhat higher risk of leakage compared to wells that are not drilled through shallow gas. All leaking wells are found in the northern part of the Dutch North Sea in an area where shallow gas quantities are the highest, which is the area with most commercial shallow gas fields. Because most wells drilled through shallow gas are not leaking, we also conclude that wells can be drilled through shallow gas accumulations without resulting in leakage, even when the wells are drilled through shallow gas fields with high concentrations of shallow gas present. There appears to be large regional variation in percentage of wells leaking when considering the entire North Sea. This is evident from the comparison of our results with those from studies performed in the Norwegian, German, and British sectors of the North Sea. The underlying cause of this offset is not yet clear and could be due to the way wells are constructed (in accordance with different national mining regulations in the different sectors), the local geology, or both. Further research into the leakage mechanism(s) is essential. However, it is clear that the findings from one specific area are not necessarily applicable to the entire North Sea.

CRediT authorship contribution statement

G. de Bruin: Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **H. de Stigter:** Writing – review & editing, Supervision, Investigation, Formal analysis, Data curation. **M. Diaz:** Writing – review & editing, Investigation, Data curation. **A. Delre:** Writing – review & editing, Investigation. **I. Velzeboer:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **N. Versteijlen:** Writing – review & editing, Resources, Investigation, Formal analysis, Data curation. **H. Niemann:** Writing – review & editing, Supervision. **M. Wilpshaar:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **G.J. Reichart:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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Data availability

Data will be made available on request.

References

Borges, A.V., Champenois, W., Gypens, N., Delille, B., Harlay, J., 2016. Massive marine methane emissions from near-shore shallow coastal areas. Sci. Rep. 6, 27908.

Böttner, C., Haeckel, M., Schmidt, M., Berndt, C., Vielstädte, L., Kutsch, J.A., Karstens, J., Weiß, T., 2020. Greenhouse gas emissions from marine decommissioned hydrocarbon wells: leakage detection, monitoring and mitigation strategies. Int. J. Greenh. Gas Control 100, 103119.

Böttner, C., Berndt, C., Reinardy, B.T.I., Geersen, J., Karstens, J., Bull, J.M., et al., 2019. Pockmarks in the witch ground basin, central North Sea. G-cubed 20, 1698–1719. https://doi.org/10.1029/2018GC008068.

Brekke, T., Lønne, Ø., Ohm, S.E., 1997. Light hydrocarbon gases in shallow sediments in the northern North Sea. Mar. Geol. 137 (1–2), 81–108.

de Bruin, G., ten Veen, J., Wilpshaar, M., Versteijlen, N., Geel, K., Verweij, H., Carpentier, S., 2022. Origin of shallow gas in the Dutch North Sea — seismic versus geochemical evidence. Interpretation 10 (1), SB63–SB76. https://doi.org/10.1190/INT-2021-0081.1, 2022.

de Groot, T.R., Menoud, M., van Bleijswijk, J., van Leeuwen, S.M., van der Molen, J., Hernando-Morales, V., Czerski, H., Maazallahi, H., Walter, S., Rush, D., Röckmann, T., Niemann, H., 2024. Tidal and seasonal controls on water column methane dynamics and the activity of methanotrophs at cold seeps. Communications Earth and Environment. https://doi.org/10.1038/s43247-024-01483-8.

de Stigter, H., de Bruin, G., Velzeboer, I., Ourradi, Y., 2022. Unpublished results, Cruise report RV Pelagia campaign 64PE503. North Sea Methane, Texel-Texel, pp. 6–22.

Doornenbal, J.C., Kombrink, H., Bouroullec, R., Dalman, R.A.F., De Bruin, G., Geel, C.R., Houben, A.J.P., Jaarsma, B., Juez-Larré, J., Kortekaas, M., Mijnlieff, H.F., Nelskamp, S., Pharaoh, T.C., Ten Veen, J.H., Ter Borgh, M., Van Ojik, K., Verreussel, R.M.C.H., Verweij, J.M., Vis, G.-J., 2019. New insights on subsurface energy resources in the Southern North Sea Basin area. In: Patruno, S., Archer, S.G., Chiarella, D. (Eds.), Cross-border Themes in Petroleum Geology. 1, the North Sea, Geological Society of London, vol. 494. Geological Society Special Publication, London, UK, pp. 233–268, 494.

Floodgate, G.D., Judd, A.G., 1992. The origins of shallow gas. Continent. Shelf Res. 12 (10), 1145–1156. https://doi.org/10.1016/0278-4343(92)90075-U, 1992.

Lippmann, T.J.R., in 't Zandt, M.H., Van der Putten, N.N.L., Busschers, F.S., Hijma, M.P., van der Velden, P., de Groot, T., van Aalderen, Z., Meisel, O.H., Slomp, C.P., Niemann, H., Jetten, M.S.M., Dolman, H.A.J., Welte, C.U., 2020. Microbial activity, methane production, and carbon storage in Early Holocene North Sea peats. Biogeosciences 18, 5491–5511. https://doi.org/10.5194/bg-18-5491-2021, 2021.

MacLean, J.-P.W., Girard, M., Jervis, D., Marshall, D., McKeever, J., Strupler, M., Ramier, A., Tarrant, E., Young, D., 2023. Offshore Methane Detection and Quantification from Space Using Sun Glint Measurements with the GHGSat Constellation. EGUsphere. https://doi.org/10.5194/egusphere-2023-1772, 2023.

Missiaen, T., Murphy, S., Loncke, L., Henriet, J.P., 2002. Very high-resolution seismic mapping of shallow gas in the Belgian coastal zone. Continent. Shelf Res. 22 (16), 2291–2301.

Oele, E., 1969. The quaternary geology of the Dutch part of the North Sea, north of the Frisian isles. Geol. Mijnbouw 48, 467–480. https://drive.google.com/file/d/0B7j8bPm9Cse0R0UtXzJ2QzF1RlU/view?resourcekey=0-HQkygGTqdPJG7lExoLHmjA.

Overeem, I., Weltje, G.J., Bishop-Kay, C., Kroonenberg, S.B., 2001. The Late Cenozoic Eridanos delta system in the southern North Sea Basin: a climate signal in sediment supply? Basin Res. 13, 293–312. https://doi.org/10.1046/j.1365-2117.2001.00151.x.

Römer, M., Wenau, S., Mau, S., Veloso, M., Greinert, J., Schlüter, M., Bohrmann, G., 2017. Assessing Marine Gas Emission Activity and Contribution to the Atmospheric Methane Inventory: a Multidisciplinary Approach from the Dutch Dogger Bank Seep Area (North Sea) G-Cubed, p. 18. https://doi.org/10.1002/2017GC006995, 2017.

Pillitteri, A., Cerasi, P., Stavrum, J., Zweigel, P., Bøe, R., 2003. Rock mechanical tests of shale samples from the cap rock of the Utsira Sand in well 15/9-A11. SINTEF Petroleum Research. In: https://www.sintef.no/globalassets/project/ik23430000-sacs/technical-reports/pillitteri_etal_2003_caprock_shale_rockmechtests_report.pdf.

Römer, M., Blumenberg, M., Heeschen, K., Schloemer, S., Müller, H., Müller, S., Hilgenfeldt, C., Barckhausen, U., Schwalenberg, K., 2021. Seafloor methane seepage related to salt diapirism in the northwestern part of the German North Sea. Front. Earth Sci. 9, 556329. https://doi.org/10.3389/feart.2021.556329.

Saunois, M., Stavert, A.R., Poulter, B., Bousquet, P., Canadell, J.G., Jackson, R.B., Raymond, P.A., Dlugokencky, E.J., Houweling, S., Patra, P.K., Ciais, P., Arora, V.K., Bastviken, D., Bergamaschi, P., Blake, D.R., Brailsford, G., Bruhwiler, L., Carlson, K. M., Carrol, M., Castaldi, S., Chandra, N., Crevoisier, C., Crill, P.M., Covey, K., Curry, C.L., Etiope, G., Frankenberg, C., Gedney, N., Hegglin, M.I., Höglund-Isakson, L., Hugelius, G., Ishizawa, M., Ito, A., Janssens, Maenhout, G., Jensen, K.M., Joos, F., Kleinen, T., Krummel, P.B., Langenfelds, R.L., Laruelle, G.G., Liu, L., Machida, T., Maksyutov, S., McDonald, K.C., McNorton, J., Miller, P.A., Melton, J.R., Morino, I., Müller, J., Murgia-Flores, F., Naik, V., Niwa, Y., Noce, S., O′Doherty, S., Parker, R.J., Peng, C., Peng, S., Peters, G.P., Prigent, C., Prinn, R., Ramonet, M., Regnier, P., Riley, W.J., Rosentreter, J.A., Segers, A., Simpson, I.J., Shi, H., Smith, S. J., Steele, P.L., Thornton, B.F., Tian, H., Tohjima, Y., Tubiello, F.N., Tsuruta, A., Viovy, N., Voulgarakis, A., Weber, T.S., van Weele, M., van der Werf, G.R., Weiss, R. F., Worthy, D., Wunch, D., Yin, Y., Yoshida, Y., Zhang, W., Zhang, Z., Zhao, Y., Zheng, B., Zhu, Q., Zhu, Q., Zhuang, Q., 2020. The global methane budget 2000–2017. Earth Syst. Sci. Data 12, 1561–1623. https://doi.org/10.5194/essd-2019-128.

Schout, G., Griffioen, J., Hassanizadeh, S.M., Cardon de Lichtbuer, G., Hartog, N., 2019. Occurrence and fate of methane leakage from cut and buried abandoned gas wells in The Netherlands. Sci. Total Environ. 659, 773–782. https://doi.org/10.1016/j.scitotenv.2018.12.339.

Schroot, B.M., Schüttenhelm, R.T.E., 2003. Expressions of shallow gas in The Netherlands North Sea. Neth. J. Geosci./Geol. Mijnbouw 82 (1), 91–105.

Schroot, B.M., Klaver, G., Schüttenhelm, R.T.E., 2005. Surface and subsurface expressions of gas seepage to the seabed – examples from the Southern North Sea. Mar. Petrol. Geol. (22), 499–515.

TNO R10056, unpublished results, Integrated pressure information system for the onshore and offshore Netherlands. https://www.nlog.nl/pressure-southern-north-sea-psns-database.

TNO-GDN, 2024a. Upper North Sea Group. In: Stratigraphic Nomenclature of the Netherlands. TNO – Geological Survey of, the Netherlands. https://www.dinoloket.nl/en/stratigraphic-nomenclature/upper-north-sea-group. (Accessed 1 February 2024).

TNO-GDN, 2024b. NLOG, Dutch oil and gas portal, 2024. https://www.nlog.nl/datacenter/field-overview.

TNO-GDN, 2024c. Basisveen bed. In: Stratigraphic Nomenclature of the Netherlands. TNO – Geological Survey of, the Netherlands. https://www.dinoloket.nl/en/stratigraphic-nomenclature/basisveen-bed. (Accessed 7 December 2023).

Verweij, J.M., Nelskamp, S.N., ten Veen, J.H., de Bruin, G., Geel, C.R., Donders, T.H., 2018. Generation, migration, entrapment and leakage of microbial gas in the Dutch part of the Southern North Sea Delta. Mar. Petrol. Geol. 97, 493–516. https://doi.org/10.1016/j.marpetgeo.2018.07.034.MPEGD80264-8172.

Vielstadte, L., Karstens, J., Haeckel, M., Schmidt, M., Linke, P., Reimann, S., Liebetrau, V., McGinnis, D.F., Wallmann, K., 2015. Quantification of methane emissions at abandoned gas wells in the Central North Sea. Mar. Petrol. Geol. (68), 848–860.

Vielstädte, L., Haeckel, M., Karstens, J., Linke, P., Schmidt, M., Steinle, L., Wallmann, K., 2017. Shallow gas migration along hydrocarbon wells – an unconsidered, anthropogenic source of biogenic methane in the North Sea. Env. Sci. Tech. (51), 10262–10268.

Wilpshaar, M., De Bruin, G., Versteijlen, N., Van der Valk, K., Griffioen, J., 2021. Comment on "Greenhouse gas emissions from marine decommissioned hydrocarbon wells: leakage detection, monitoring and mitigation strategies". In: Böttner, Christoph, Haeckel, Matthias, Schmidt, Mark, Berndt, Christian, Vielstädte, Lisa, Kutsch, Jakob A. (Eds.), Jens Karstens & Tim Weiß.

Wilson, E.B., 1927. Probable inference, the law of succession, and statistical inference. J. Am. Stat. Assoc. 22 (158), 209–212. https://doi.org/10.1080/01621459.1927.10502953. JSTOR 2276774.