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Report of the results from the 64PE503 Expedition
Phase 1 of the North Sea Methane Project

Bubble plumes at abandoned wells and at natural seepage sites in the Dutch North Sea

Royal Netherlands Institute for Sea Research

innovation for life

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Nederlandse samenvatting

Bellenpluimen bij verlaten putten en locaties waar natuurlijk opborrelen plaatsvindt in de Nederlandse Noordzee

Rapport van de resultaten van de 64PE503 Expeditie, fase 1van het Noordzee Methaan Project

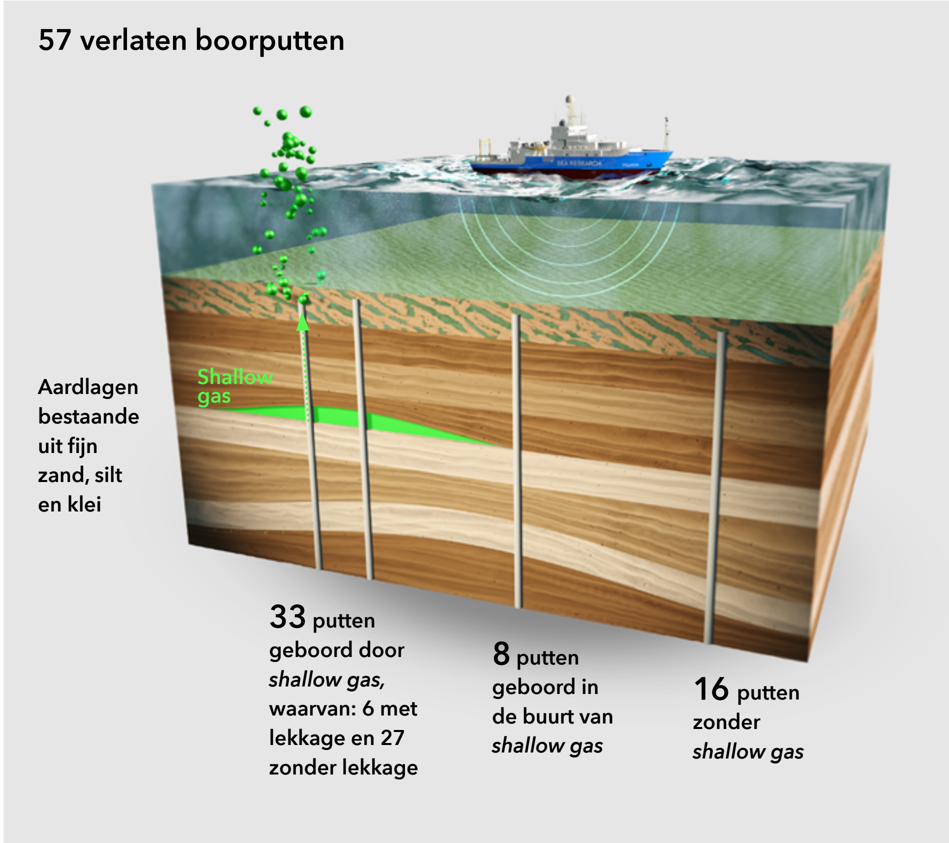
Het Koninklijk Nederlands Instituut voor Onderzoek der Zee (NIOZ) en TNO Geologische Dienst hebben samen met Staatstoezicht op de Mijnen (SodM) onderzoek gedaan naar methaanemissies op de Noordzee. Methaan is het hoofdbestanddeel van aardgas en een krachtig broeikasgas. Methaan komt op natuurlijke wijze vrij uit de zeebodem. Daarnaast zou het vrij kunnen komen als gevolg van de olie- en gaswinning die sinds de jaren 70 plaatsvindt in de Noordzee. Methaanuitstoot is na CO_2 het belangrijkste broeikasgas als we kijken naar de opwarming van de aarde als gevolg van menselijk handelen.

Het onderzoek werd uitgevoerd door het NIOZ en TNO op het onderzoekschip *RV Pelagia*. Tijdens de vaartocht werd data verzameld om te kijken of er methaan lekt uit verlaten olie- en gasputten.

Publicaties leidt tot Kamervragen

Onderzoekers van het Duitse zeeonderzoeksinstituut GEOMAR concludeerden in 2017 dat "alle verlaten putten geboord door *shallow gas* lekken en dat hierdoor eendere van de ruim 11.000 verlaten putten op de Noordzee mogelijk lekken". *Shallow gas* is een term die wordt gebruikt voor aardgas dat zich van nature in de zeebodem bevindt tot een diepte van een kilometer. Ter vergelijking: de meeste gasvelden die geëxploiteerd worden bevinden zich op een diepte van drie tot vier kilometer. Van nature komt *shallow gas* in de hele Noordzee (en veel andere kustzeeën) veel voor. Om de diepere gas- of olievoerende lagen te bereiken moet in sommige gevallen door deze *shallow gas* voorkomens heen geboord worden.

Naar aanleiding van de publicaties van GEONAR werden in de Tweede Kamer vragen gesteld en waren ze voor SodM aanleiding om samen met TNO te inventariseren hoeveel putten in Nederland door *shallow gas* zijn geboord. Het Nederlandse deel van de Noordzee telt 1450 verlaten putten en uit de inventarisatie bleek dat ongeveer 10% door *shallow gas* heen is geboord. *Shallow gas* komt het meest voor in het noordelijkste gedeelte van



Niet op schaal

het Nederlands continentaal plat, zo'n 200 km ten noorden van Texel. Verder onderzoek vanuit GEOMAR suggereerde dat in het Engelse deel van de Noordzee zelfs twee op de drie van de onderzochte putten lekten. Wat hierbij opviel was dat ook putten die in de buurt van *shallow gas* geboord waren (maar niet er doorheen) lekten. Ook naar aanleiding van deze publicatie werden er Kamervragen gesteld en maakten onderzoek naar lekkage in het Nederlands deel van de Noordzee urgent.

Metingen bij verlaten boorputten

In Juni 2022 hebben NIOZ en TNO onderzoek gedaan bij verlaten boorputten in het meest noordelijke deel van de Nederlandse Noordzee. Hier komt *shallow gas* veel voor. Er is een veelvoud aan meting uitgevoerd met de volgende apparatuur.

Een magnetometer werd gebruikt om de locatie van de verlaten putten te bepalen. De putten liggen begraven onder de zeebodem en daarom zijn ze niet zichtbaar. De magnetometer is een soort metaaldetector die de metalen buizen die in de put zitten kunnen lokaliseren. In een gebied rondom de put is vervolgens gekeken of er bellen in de waterkolom aanwezig zijn. Bellenpluimen werden in beeld gebracht met echoapparatuur (multibeam echosounder). Een tweede echoapparaat (de subbottom profiler) werd gebruikt om de bovenste meters sediment in kaart te brengen en de aanwezigheid van veenlagen uit te sluiten. Veenlagen kunnen ook bellenpluimen veroorzaken. Water werd op verschillende manieren geanalyseerd. Water van net boven de zeebodem werd via een slang opgepompt en geanalyseerd in een laserspectrometer. Deze kan simultaan en continue methaan en ethaan meten. Hiermee kan onderscheid gemaakt worden tussen *shallow gas* en gas uit diepere lagen. Daarnaast is een methaansensor gebruikt om methaan in het water te meten op verschillende dieptes. Ook zijn er watermonsters genomen en verschillende parameters gemeten zoals zout gehalte, temperatuur, en akoestische snelheden. Tot slot werd er ook continue gemeten hoeveel methaan er in de lucht aanwezig was met een laserspectrometer.

Zes putten lekken *shallow gas*

NIOZ en TNO onderzochten 57 verlaten putten waarvan 33 door *shallow gas* geboord zijn en acht in de buurt van *shallow gas*. Hierbij werden zes lekkende putten aangetroffen die allen door *shallow gas* geboord waren. Aan de hand van de gas-samenstelling blijkt dat het *shallow gas* is dat lekt en en niet gas uit dieper gelegen gasreservoirs. De lekkages werden vastgesteld door met echoapparatuur naar bellen in de waterkolom te zoeken boven verlaten putten. Hierbij werd ook uitgebreid gekeken of er andere bronnen aanwezig zijn die deze bellenpluimen kunnen veroorzaken. Dat bleek niet het geval.

Het onderzoek wijst dus uit dat niet alle putten die door *shallow gas* heen geboord zijn lekken, maar iets minder dan 20%. Het feit dat de meeste putten niet lekken betekent dat het technisch wel mogelijk is om door *shallow gas* heen te boren zonder dat dit lekkage veroorzaakt. Ook de putten in die in de buurt van *shallow gas* geboord zijn, maar niet er doorheen, lekten niet. De onderzochte putten die niet door *shallow gas* geboord zijn lekten geen van allen.

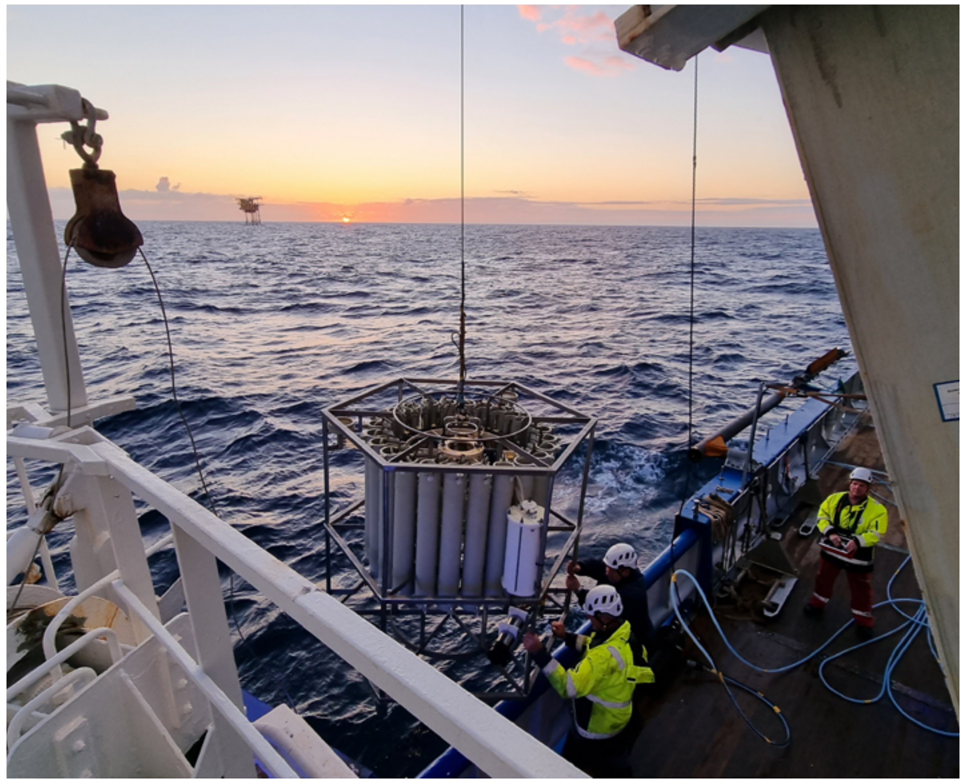
Minder dan 2% van de putten in de Nederlandse Noordzee lekt

Van alle verlaten putten in Nederland is 10% door *shallow gas* geboord, waarvan minder dan 20% lekt. We komen dus tot de slotsom dat waarschijnlijk minder dan 2% van de verlaten putten *shallow gas* lekt.

Het aantal putten dat *shallow gas* lekt in het Nederlandse deel van de Noordzee is fors lager dan eerder gevonden in het Engelse en Noorse deel van de Noordzee. Ook in het Duitse deel van de Noordzee is door een ander Duits onderzoeksinstituut (MARUM) verder onderzoek gedaan naar putten die door *shallow gas* geboord zijn. Daarbij werd geen enkele lekkende put aangetroffen. Deze Duitse studie werd uitgevoerd net ten noorden van het Nederlandse studiegebied, in de ‘Entenschnabel’, waar de geologische omstandigheden vergelijkbaar zijn met die van Nederland.

Methaanemissies lekkende putten zijn klein in vergelijking met natuurlijke bronnen

De grootte van de methaanemissies van de zes lekkende putten wordt nog onderzocht. Wel staat al vast dat het aantal bellenpluimen veroorzaakt door lekkende putten, in dit onderzoek acht in totaal bij zes putten, vele malen kleiner is dan in het gebied waar bellenpluimen van nature voorkomen. Op die lokaties beslaan de bellenpluimen hele velden en op de Doggerbank zijn bijvoorbeeld ongeveer 850 natuurlijke bellenpluimen waargenomen in een gebied van acht km^2. De methaanemissies van lekkende verlaten boorputten valt naar verwachting laag uit vergeleken met de methaanuitstoot die van nature plaatsvindt.



Summary

This report documents the findings of *RV Pelagia* campaign 64PE503 carried out June 5-22, 2022, as part of phase 1 of the NIOZ-TNO North Sea Methane).

The aim of this project is to determine ebullition from abandoned wells related to shallow gas in the Dutch sector of the North Sea and to place it in perspective of possible natural ebullition and seeps in the North Sea. Ebullition is the process in which gas, for example methane, seeps from the seabed to the water column via bubbles. Part of that gas dissolves into the sea water while the bubbles rise through the water column and part reaches the atmosphere. Part of the dissolved methane might subsequently be metabolized. Since methane is a strong greenhouse gas it potentially contributes to climate change. In total 63 locations were surveyed by us, of which 57 were abandoned wells. 33 wells were drilled through shallow gas, 8 were drilled near shallow gas, and 16 are not related to shallow gas.

Well leakage

At 6 wells (A08-01, A14-02, A15-03, B17-03, B17-05, F01-01) a bubble plume was found only at the well head. The only hypothesis for these plumes is that they are caused by well leakage of shallow gas. We conclude this based on the several observations and falsification of all other hypotheses:

- Multibeam echosounder data: At these six wells a plume was found at the wellhead location only and no other plumes are observed in the vicinity. Natu-ral seepage (for example B13) is characterized by many plumes covered over a large area. Natural seepage is therefore unlikely.
- Well data: All six wells are exploration wells (that were never in production) that all encountered shallow gas during drilling. All wells are classified as 'dry' for the deeper intervals (that could contain thermogenic gas). All gas finds and gas shows are related to shallow gas. Leakage from shallow gas is there-fore a valid hypothesis. The gas composition of the shallow gas was measured by the drilling companies at two wells. More than 99% of the gas is methane, while the ethane concentration is negligible.
- Seismic data: All six wells are drilled through a seismic bright spot, related to shallow gas (further confirmation of the shallow gas hypothesis). No tunnel valleys were encountered at the six wells, excluding them as possible source.
- Slurf spectrometer data: Methane peaks were found at 5 of the 6 wells. At these wells only methane (no ethane) was observed in the water near the six wells. This is consistent with the gas composition of shallow gas found in the wells. We expect deep reservoirs to contain ethane too. The absence of ethane makes well leakage from a deep reservoir unlikely and adds to the va-lidity of the 'shallow gas hypothesis'.
- Sub bottom profiler data: No peat layers were not found at the 6 wells, ex-cluding them as a potential source for the bubble plumes.
- Pre-drilling site surveys. For two of the four wells a site survey was available (A08-01 and A14-02). Thes surveys are conducted before drilling and there is no evidence for bubble plumes at the well locations found.
- Literature: Drilling induced fractures causing migration outside the wellbore is not considered as a leakage mechanism because a literature study showed that leakage through drilling induced fractures is highly unlikely in general and drilling induced fractures do not form in shallow, unconsolidated sedi-ments to begin with.

Based on these observations we concluded that *well leakage from shallow gas* is the only hypothesis for these six wells. The well leakage mechanism will be investigated as part of the next round of studies/reporting. We will study well design, drilling practices and abandonment procedures, in order to establish the most probable cause and (if possible) the exact leakage mechanism(s).

All leaking wells are found in the most northern part of the Dutch offshore in an area where shallow gas quantities are the highest (i.e. in an area where the commercial shallow gas fields are found). All six wells are found in the A and B blocks, and the most Northern F block (F01). No leaking wells were found in the southern F Blocks. Three of the six wells were drilled through a shallow gas fields (i.e. A15-A and B17-A) that were not taken in production yet. We conclude from this that significant quantities of shallow gas are present at the leaking wells.

We found non-leaking wells that were drilled through the same shallow gas accumulations as several leaking wells. The A15-03 is leaking, while A15-02 and A15-05 are not leaking and all three well are drilled through the A15-A field. B17-03 and B17-05 are leaking while B17-06 is not leaking and all three well are drilled through the B17-A field. A08-01 (leaking) is drilled through the same shallow gas accumulation as A12-03 (non-leaking). From the fact that we found non-leaking wells drilled through the same shallow gas accumulations as the leaking wells, we concluded that wells can be drilled through shallow gas fields without resulting in leakage.

All the leaking wells were drilled through shallow gas. However, of the 33 wells drilled through shallow gas 82% was not leaking (27 wells). None of the 16 wells that are not associated with shallow gas were leaking. Therefore, we conclude that drilling through shallow gas is associated with a slightly higher risk of leakage compared to wells that are not drilled through shallow gas. At the majority of surveyed locations (54 of 63), no bubble plume was encountered. This is true for all undrilled areas (6), all wells that were not associated with shallow gas (16), and all wells drilled close to shallow gas (6).

Natural seepage

Surrounding 3 wells (B13-01, B17-04, F17-14), natural seepage was concluded based on the following observations. Since all three sites are all different, we describe the findings per site. North of B13-01 numerous plumes were observed. The most likely hypothesis for these plumes is that they are caused by *natural seepage of shallow gas*. We conclude this based on the several observations and falsification of all other hypotheses:

- Multibeam echosounder data: At the well head itself no bubble plume was found. To the north of the well numerous bubble plume were found. The clos-est is 150 m away from the well. We exclude well leakage since it is more like-ly to occur at the wellhead.
- Seismic and wells: The bubble plume clusters are located above a producing shallow gas field. There are several large bright spots related to shallow gas, and shallow gas was encountered during drilling.
- Slurf spectrometer data: Peaks of methane were observed. Only methane (no ethane) was observed in the water, excluding a thermogenic source.
- Sub bottom profiler data: The SBP focused on the well. No peat layers were found at the well and SBP data was not available for the bubble plume loca-tions.
- Literature: The B13 seepage site has been studied intensively and the con-sensus is that the bubble plumes are caused by natural seepage from shallow gas. However, peat layers and tunnel valleys are potentially present too.

Based on these observations we concluded that *natural seepage of shallow gas* is the most likely hypothesis for this location.
Around B17-04 numerous plumes were observed. The most likely hypothesis for these plumes is that they are caused by *natural seepage of shallow gas*. We conclude this based on the several observations and falsification of all other hypotheses:

- Multibeam echosounder data: At the well head itself no bubble plume was found. Surrounding the well numerous bubble plume were found. The closest is 74 m away from the well. We exclude well leakage since it is more likely to occur at the wellhead.
- Seismic and wells: The bubble plume clusters are located above a seismic chimney (vertical disturbed zone, indicating vertical gas migration). Natural seepage from shallow gas is therefore a valid hypothesis. No tunnel valleys were encountered and therefore they are not considered the source for the bubble plumes.
- Slurf spectrometer data: Peaks of methane were observed. Only methane (no ethane) was observed in the water, excluding a thermogenic source.
- Sub bottom profiler data: No peat layers were encountered, excluding peat as a source.
- Literature: The B17 seepage has not been studied to our knowledge.

Based on these observations we concluded that *natural seepage of shallow gas* is the most likely hypothesis for this location.

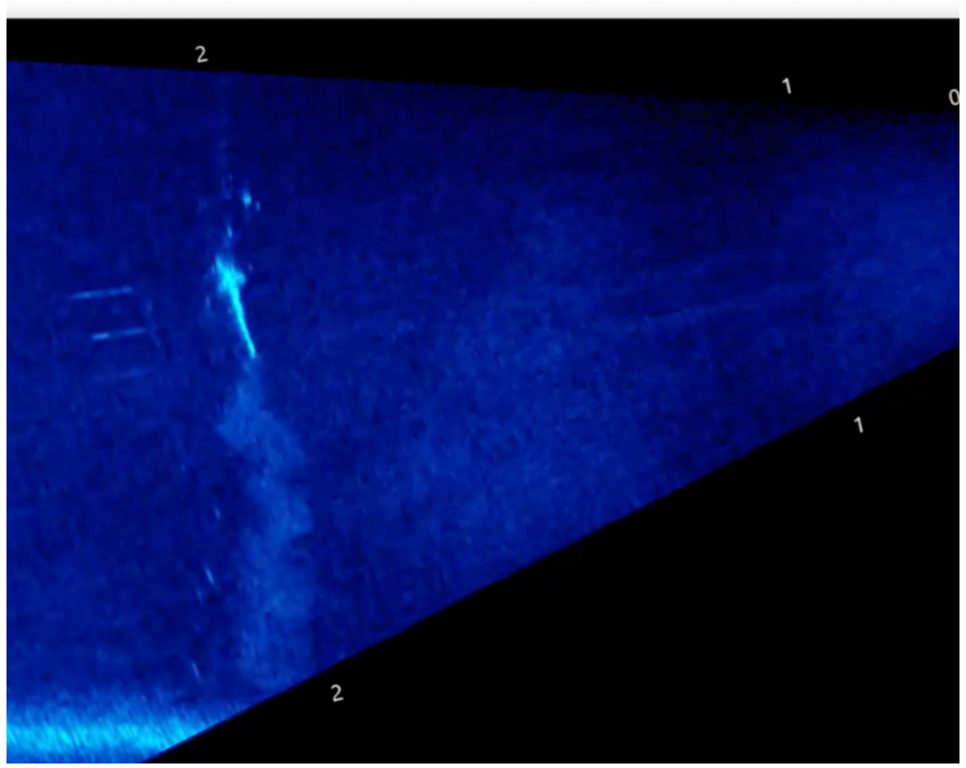
In the vicinity of F17-14 several plumes were observed. The most likely hypothesis for these plumes is that they are caused by *natural seepage of peat layers*. We conclude this based on the several observations and falsification of all other hypotheses:

- Multibeam echosounder data: At the well head itself no bubble plume was found. Several bubble plume were found in the vicinity. The closest is 240 m away from the well. Well leakage is more likely to occur at the well and is therefore unlikely. The number a nd the size of the bubble plumes is small in comparison to the B13 and B17 seepage site.
- Seismic: The bubble plume clusters are not located above a bright spot, and shallow gas is therefore not a likely source.
- Well data: the well data was confidential at the time of writing.
- Slurf spectrometer data: No peaks of methane were observed, which is ex-pected when dealing with small bubble plumes.
- Literature: TNO study identified Basisveen Beds in the area.

Based on these observations we concluded that natural seepage of peat layers is the best fitting hypothesis. However, this is concluded on limited amounts of data. We recommend obtaining additional data to proof this hypothesis.

Natural seepage vs well leakage
We observe a large difference in the number of bubble plumes between the leaking wells and the natural seepage locations. Natural seepage sites are characterized by numerous plumes covered over an area, while the leaking wells have one or two plumes originating from the well.

The amount of methane (both natural and from well leakage) that is released into the water column is part of a future research and will be studied in the upcoming expedition.



Contents

1 Introduction

This report documents the findings of RV Pelagia campaign 64PE503 carried out June 5-22, 2022, as part of the NIOZ/TNO North Sea Methane Project, a joint scientific research project of NIOZ, TNO and the State Supervision of Mines (Staatstoezicht op de Mijnen, SodM). This report is a part of a series of reports on this project and only covers the results of this cruise. Previous report is the cruise report, which covers the methodology during the this expedition.

The aim of this project is to determine ebullition from abandoned wells in the Dutch sector of the North Sea and to place it in perspective of possible natural ebullition and seeps in the North Sea. Ebullition is the process in which gas, for example methane, seeps from the seabed to the water column via bubbles. Part of that gas dissolves into the sea water while the bubbles rise through the water column and part reaches the atmosphere. Part of the dissolved methane might subsequently be metabolized. Since methane is a strong greenhouse gas it potentially contributes to climate change.

In order to gain more insight into possible methane ebullition associated with past exploitation of oil and gas from the North Sea (from the precautionary principle and to map the contribution to climate change), SodM has asked TNO and NIOZ to carry out measurements at sea. A first campaign of 18 days with RV Pelagia was carried out June 5-22, 2022, and subsequent campaigns are planned for 2023 and 2024.

The goal of this first campaign was to assess the extent of gas ebullition in the Dutch North Sea, by determining the presence of ebullition at a representative selection of wells and background sites. The focus was on wells drilled through 'bright spots', as observed on seismic data, which are an indication for the presence of so-called shallow gas. Shallow gas is natural gas (mostly biogenic methane, Verweij et al., 2021) that is present in the upper unconsolidated sediments to a maximum depth of 1000 m. Böttner et al. (2020) previously stated that all wells (=100%) closer than 300 m from, or penetrating through, a shallow gas pocket are associated with methane ebullition and hence leakage. However, Römer et al. (2021) showed that shallow gas may not in all cases cause leakage and research by TNO showed that other methane sources could cause the observed ebullition (Wilpshaar et al, 2021). Other possible sources of biogenic methane gas in the North Sea are shallow peat layers and so-called tunnel valleys (see Figure 1-1). To distinguish potential sources the first campaign therefore also targeted abandoned wells not penetrating shallow gas.

Two campaigns are planned for 2023 and 2024 in which we will focus on the quantities of leakage and the extent to which ebullition varies over time (potential tidal impact) and its determining factors, the composition and origin of the gas, the extent to which the gas dissolves in the water column and how much is metabolized by microbes or released into the atmosphere.

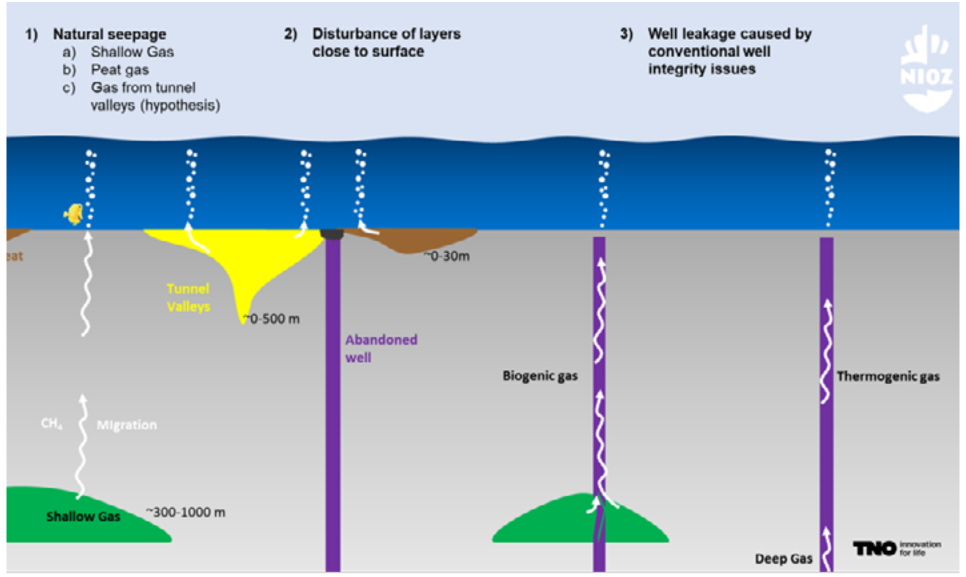


Figure 1-1: *Sources of biogenic methane and leakage mechanisms for biogenic and deep (thermogenic) gas. Potential leakage pathways for existing wells are (a) between cement and casing, (b) between the casing and the cement plug, (c) through the cement, (d) through the casing, (e) through fractures in the cement, and (f) between cement and formation (Celia et al., 2004).*

2 Methodology

2.1 Methodology
An in-depth description of the used methodology can be found in the cruise report (de Stigter et al., 2022). In short, bubble plumes were imaged with the multibeam echosounder, the sub bottom profiler was used to image the presence of peat layers, the magnetometer was used to confirm the location of the abandoned wells, the 'slurf' (water situated just above the seafloor was pumped up via a hose and analysed in a laser spectrometer) was used to measure methane and ethane, a methane sensor was used to measure methane in the water, and discrete samples were taken with the CTD.

2.2 Positioning of the abandoned wells
In order to establish to what extent observed bubble plumes are originating from abandoned wells, it is important to first establish the accuracy of the given (known) well location in relation to observed position of potential bubble plumes. Data accuracy is in this context an important issue since some of the wells in the Dutch North Sea were drilled in the 1970s when satellite navigation with sub-meter accuracy was not yet available. To get insight into potential errors and/or inaccuracies in existing well positions, we looked at magnetic anomalies mapped at 88 wells by the Hydrographic Service of the Royal Netherlands Navy. Based on these measurements we calculated differences between given well coordinates and the observed magnetic anomaly. This difference was on average 13.7 m, with a maximum observed offset of 88.4 m. These differences can be caused by errors in the well-positioning as well as inaccuracies in the positioning of the magnetometer. In accuracy in well positioning can be caused by a positioning error or calculation errors when converting between different coordinate systems. Errors in magnetometer are expected. The Hydrographic Service towed a Seaspy magnetometer about 200 m behind the vessel. The position of the magnetometer was calculated based on the ships heading and the cable length. The Hydrographic Service estimates an accuracy of their magnetic anomalies of about 15 m (personal communication), offsets depending on the current oblique to the ships heading. For 30% of the wells that were measured by the hydrographic service an offset of more than 15 m was observed (see Figure 2-1). Based on this we concluded that a significant number of wells could potentially have an error in the reported position and a recalibration would be needed during the measurement campaign.

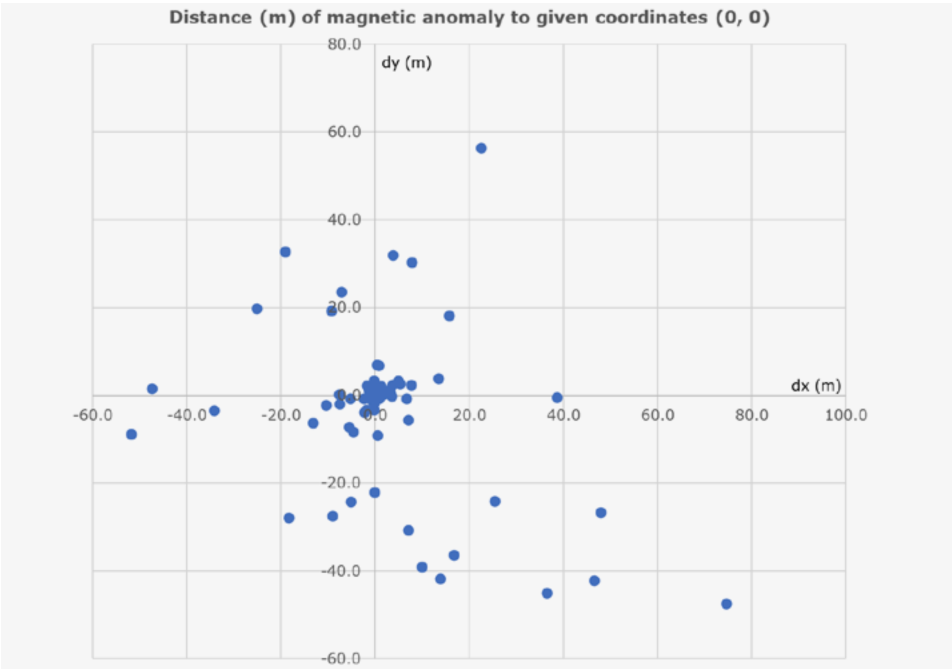


Figure 2-1: *Deviation in meters N-S and E-W direction of magnetic anomalies measured at 88 abandoned wells relative to the given coordinates of those wells. The blue dots represent the distance of the recorded magnetic anomalies relative to the given well coordinate (0, 0).*

2.2.1 Offsets in well position
The 64PE503 campaign also comprised a survey at well F05-06, where drilling had been completed 2 months earlier (well completion date 15-04-2022, survey date 16-06-2022). Based on the impressions in the seabed made by the spud cans of the jack-up rig (Figure 2-2), and the geometry of the used jack-up (Borr Prospector 1), we inferred the exact position of the well from an observed depression in the seafloor. This depression was 7 m away from the given coordinates of the well. Although this is anecdotal evidence and does not provide statical underpinning of the above, it illustrates that also with accurate satellite positioning systems available, offsets still occur. Accordingly, a geomagnetic survey was conducted at all well head positions.

2.2.2 MBES.
We aim to determine the exact location of bubble plumes with the Multibeam Echosounder. However, when we sailed over a single bubble plume in different directions, we found an offset between the locations of that single plume on the different tracks. The plume at well A08-01 is a good example. Here we passed over the well 3 times (see Figure 2-3). The distance between the three determined positions is 4, 11 and 14 m. We observe that the distance between two points where the MBES was closest to (but not directly over) the bubble plume is 4 m (16:45 and 14:24). While the third point (14:05), where the MBES was not directly above the bubble plume is located 11 and 14 meters from the other two points. We conclude that accuracy is generally higher when the MBES is over the plume

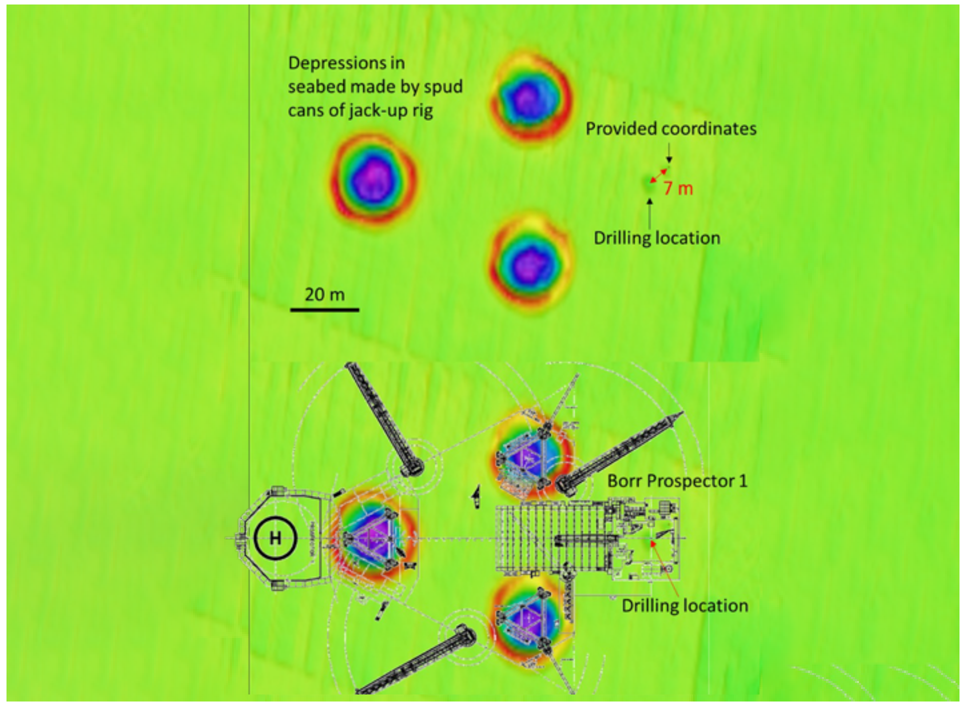


Figure 2-2: *(Top) At well F05-06 the impressions of the legs of the jack-up rig are still visible as depressions in the seabed. (Bottom) When the plan view of the jack-up rig used for drilling this well is projected over the depressions, we find that a depression in the seabed lines up with the location of the drillstring. This drilling location is 7 m from the well coordinates provided by the operator.*

and decreases outward. Generally, accuracy of the position of bubble plumes is a few meters when the MBES is directly over the plume.

2.2.3 Magnetometer

For the wells where magnetometer measurements from the Hydrographic Service were not available yet to verify their position, a magnetometer survey was conducted. Our approach differed from that used by the Hydrographic Service was used in that we used a different type of magnetometer and ultra-short baseline (USBL by GAPS) to exactly determine the position of the magnetometer in the water. Whereas the Hydrographic Service sailed multiple parallel tracks to cover a larger area, we combined two crossing lines over the given well coordinates. The positioning of the magnetometer is not the issue. However, the accuracy is dependent on the offset between the actual well position and the given well coordinates. Highest accuracy is achieved when the survey line passes directly over the well with the magnetometer recording a single distinct maximum intensity.

Accuracy decreases when the well is located offset from the reported position, and the survey line hence passes at some distance from the well. The maximum observed in that case becomes increasingly flatter and broader. Unfortunately, we have no test data where a metal object was placed in a known location and our ability to locate it was tested. Calibrating the remaining inaccuracy of our positioning therefore cannot be fully resolved. Nevertheless, all but one well was detected with the magnetometer (i.e. a magnetic peak was observed on two passes over the given well coordinates), which provides evidence that the well was located within the area covered by the MBES. In those cases, we have proof that the well is located within the area covered by MBES.

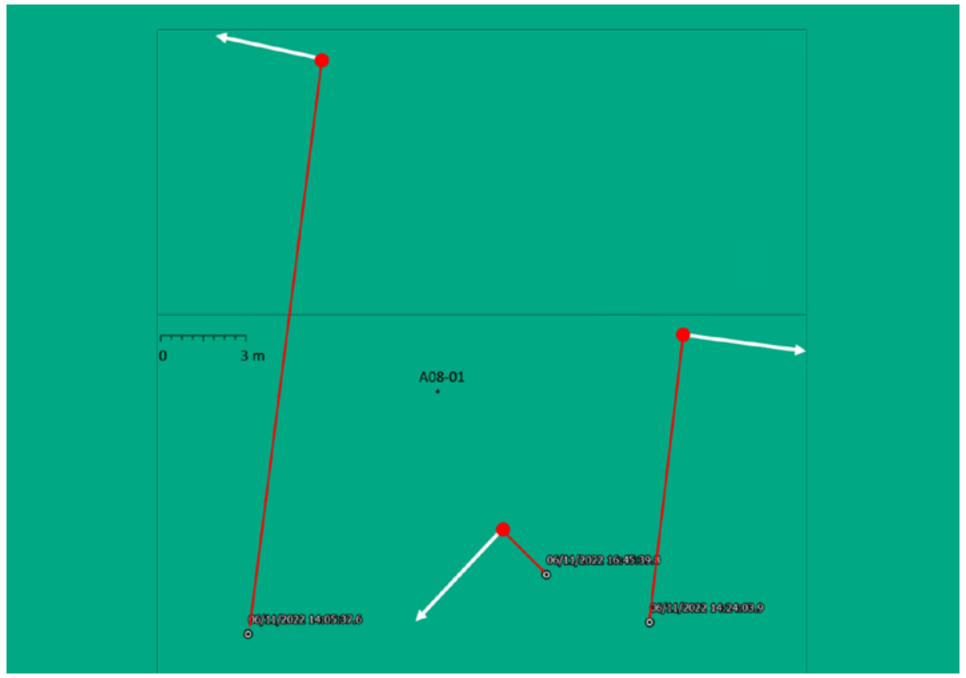


Figure 2-3: *At well A08-01 a single bubble plume was detected during 3 different passes over the well. The red dot is the position of the MBES, while the white arrow indicates in which direction (track) the vessel was traveling. The red arrow points to the position of the bubble plume source that was identified at that MBES position.*

3 Bubble plume detection with the Multibeam Echosounder

3.1 Wells drilled through shallow gas with bubble plume(s) at wellhead

At the location of 6 abandoned wells a bubble plume was observed directly at the wellhead, while no plumes(s) were detected in the vicinity. All these wells were drilled through shallow gas. All these wells are individually described below.

3.1.1 Well A08-01

At this well location a clear bubble plume was observed at approximately 8 m from the given wellhead coordinates (Figure 3-1). In the vicinity of the well no other bubble plumes were observed.

3.1.2 Well A14-02

At this well a clear bubble plume was observed at approximately 3 m from the given wellhead coordinates (Figure 3-2). In the vicinity of the well no other bubble plumes were observed.

3.1.3 Well A15-03

At the wellhead of well A15-03 two distinct bubble plumes were observed 2 meters from the wellhead (Figure 3-3). In the surroundings no other bubble plumes were found.

3.1.4 Well B17-03

At well B17-03 a small bubble plume was observed. The source of this bubble plume coincided with the side lobe of the seabed reflection and it is therefore hard to distinguish in the MBES data (Figure 3-4).

3.1.5 Well B17-05

At well B17-05 a very large bubble plume was observed. It is the largest of the plumes observed during this expedition (Figure 3-5).

3.1.6 Well F01-01

At well F01-01 a faint bubble plume was observed (Figure 3-6). The bubble plume was difficult to identify during acquisition of the MBES data, and therefore several additional passes were sailed over the reported well location.

3.2 Wells with bubble plumes away from the wellhead

At 3 wells bubble plumes were observed at an appreciable distance from the well head, while no plume was observed at the wellhead itself.

3.2.1 Well B13-01

Well B13-01 was drilled close to a natural seepage area characterized by numerous bubble plumes (Figure 3-7). This seepage area on the Doggerbank has been studied by Brussaard (2013), Römer et al. (2017 & 2021) and Menoud et al. (in review). Directly at the wellhead itself no bubble plume was observed. The nearest bubble plume was located 150 m away from the well (Figure 3-8).

Figure 3-1: *A single bubble plume was found at the well-head of well A08-01.*

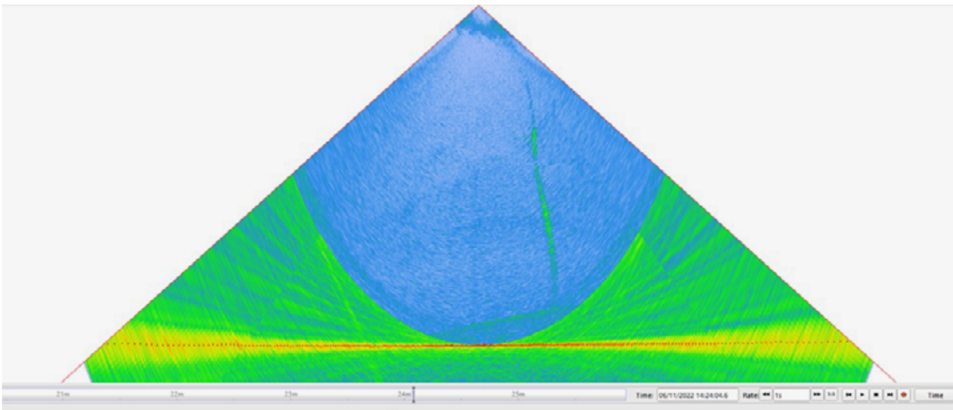


Figure 3-2: *At the wellhead of A14-02 a bubble plume was found.*

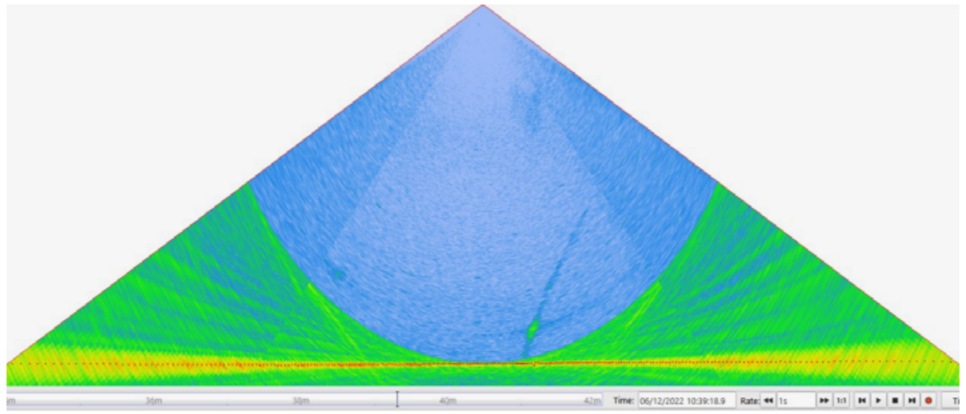
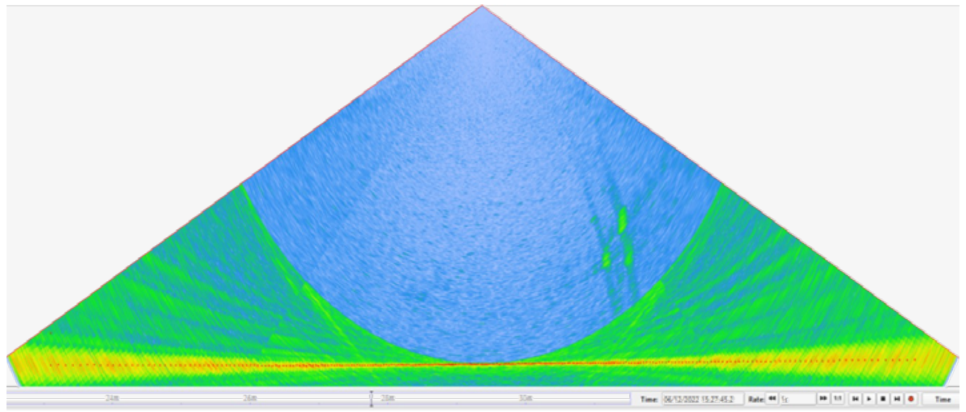


Figure 3-3: *At the wellhead location of well A15-03 two bubble plumes were observed.*



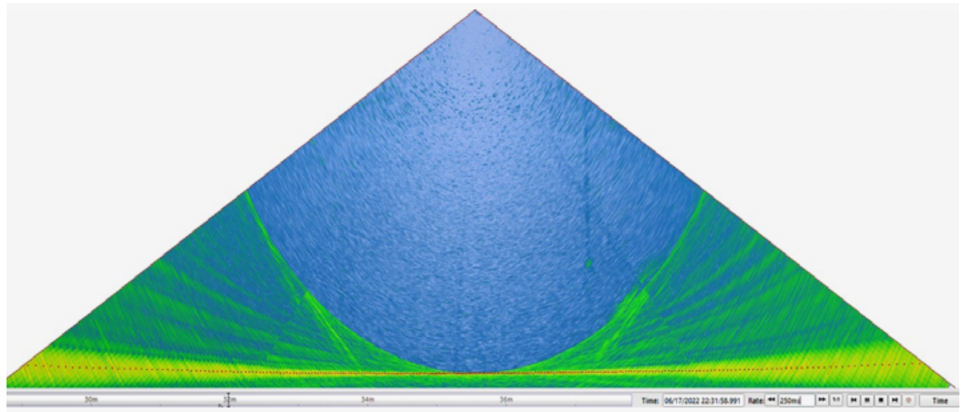


Figure 3-4: *The bubble plume source at B17-03 is very hard to see, since it coin-cides with the side lobe of the first seabed reflection.*

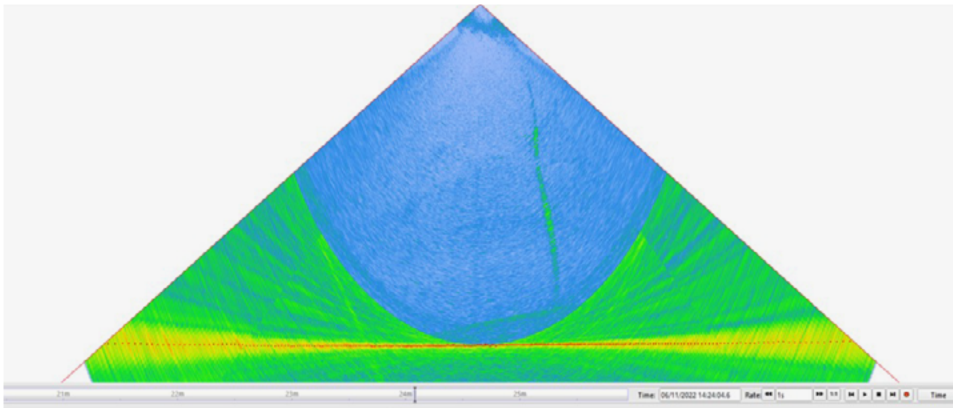


Figure 3-5: *At well B17-05 a very large bubble plume was observed.*

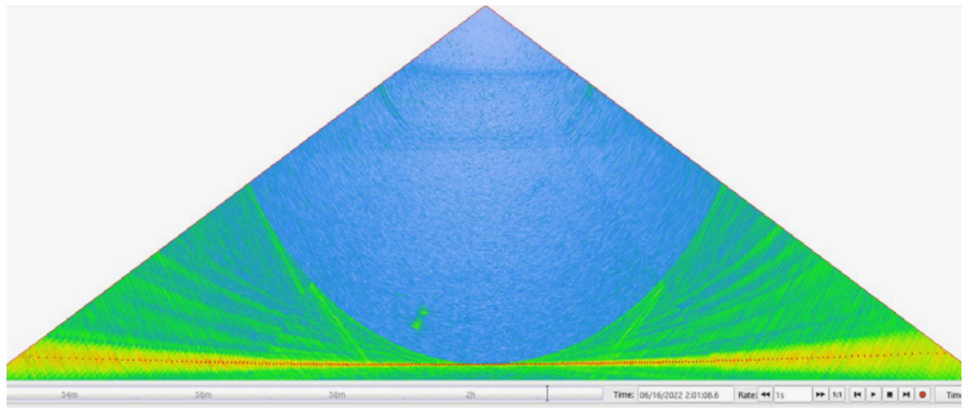


Figure 3-6: *At well F01-01 a faint bubble plume was observed.*

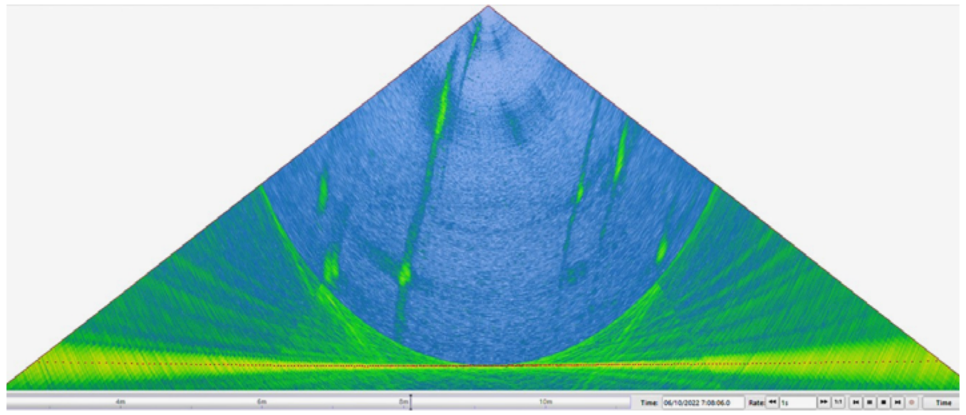


Figure 3-7: *Numerous bubble plumes were observed at a distance of 150 m or more from well B13-01. This is a natural seepage site.*

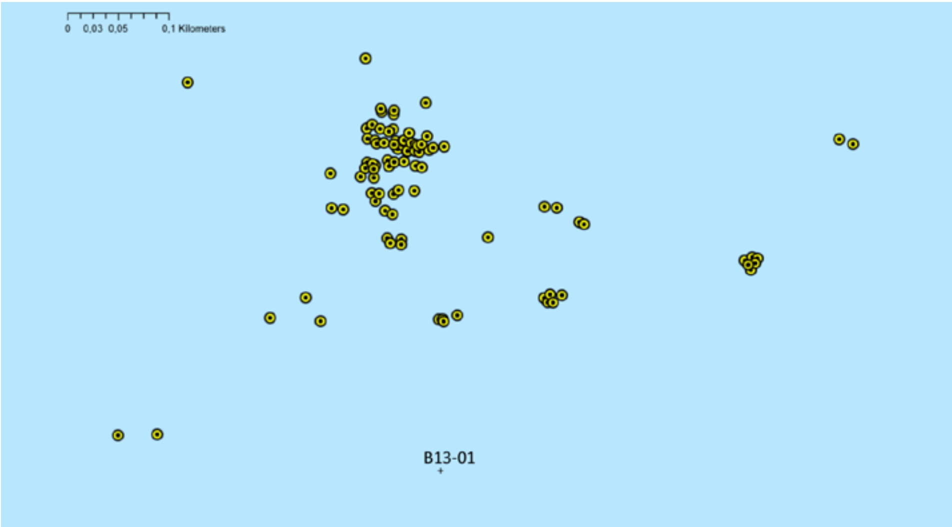


Figure 3-8: *Map of the bubble plumes (yellow) and well B13-01 (cross).*

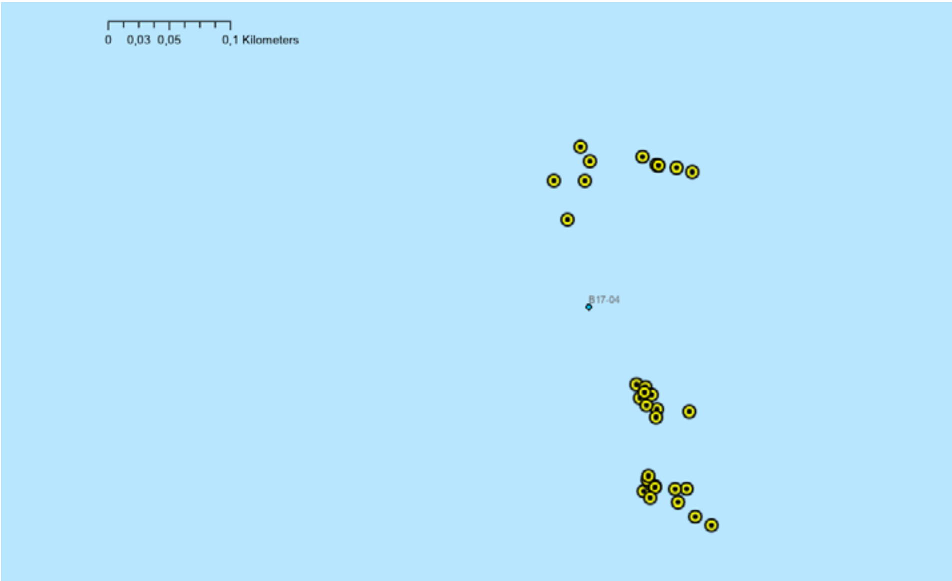


Figure 3-9: *Numerous bubble plumes were found surrounding well B17-04. The distance from the well-head to the closest plume is 74 m. There is no bubble plume at the well head.*

3.2.2 Well B17-04

Surrounding well B17-04 numerous bubble plumes are observed. No plumes were found at the well head. The closed bubble plume is 74 m from the well head (Figure 3-9 and Figure 3-10).

3.2.3 Well F17-14

Well F17-14 was passed once only, collecting both MBES and Slurf data. At the well location no bubble plume was found. Since it is a recent well, depressions in the seafloor made by the jack-up were still visible. Several small bubble plumes were found (Figure 3-11) at more than 240 m from the well.

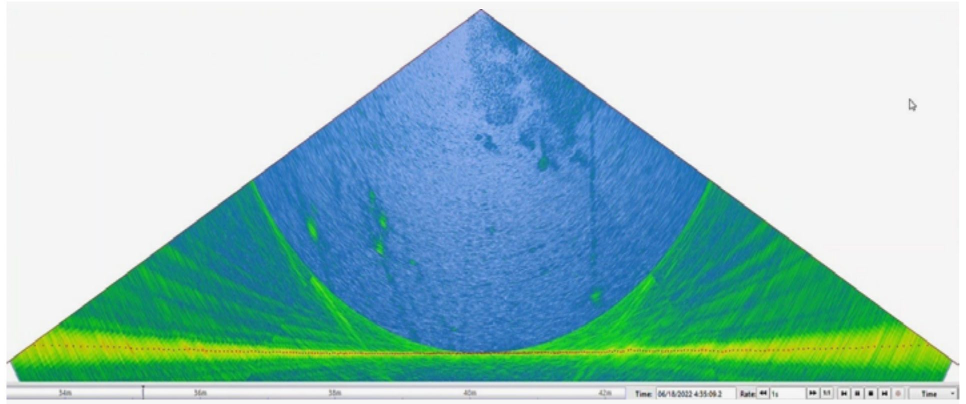


Figure 3-10: *Bubble plumes at in the vicinity of well B17-04. At the well itself no bubble plume was found. Note that the SLURF, a hose with depressor weight used for pumping up water from near the seabed, is visible on the right.*

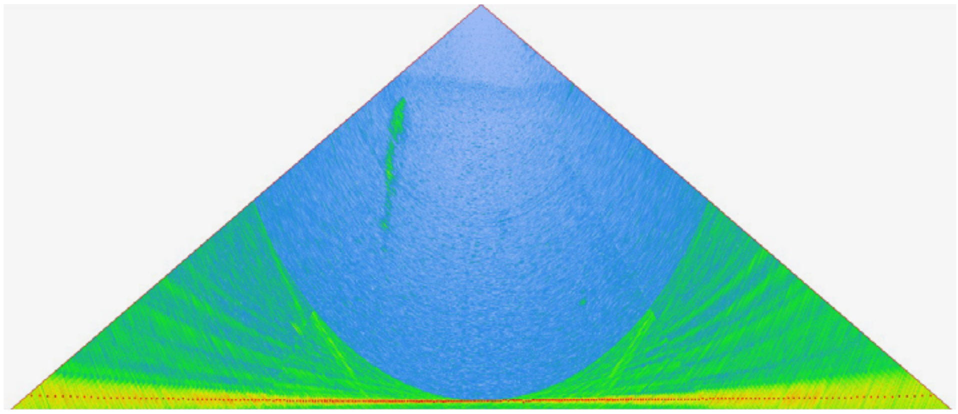


Figure 3-11: *Bubble plume found in the F17 block.*

3.3 Overview of results

An overview of the findings are found in Table 3-1, Table 3-2 and Figure 1-1.

Table 3-1

Wells with only a bubble plume at wellhead location		
Well name	Minimal distance bubble plume(s) to wellhead	Station numbers
A08-01	8 m	19, 29
A14-02	3 m	21, 30
A15-03	2 m	22
B17-03	23 m	53, 59
B17-05	2 m	53, 59
F01-01	5 m	38, 41

Table 3-2

Wells with a plume in the vicinity but not at the well location		
Well name	Minimal distance bubble plumes to wellhead	Station numbers
B13-01	150 m	13
B17-04	74 m	51, 54
F17-14	240 m	67

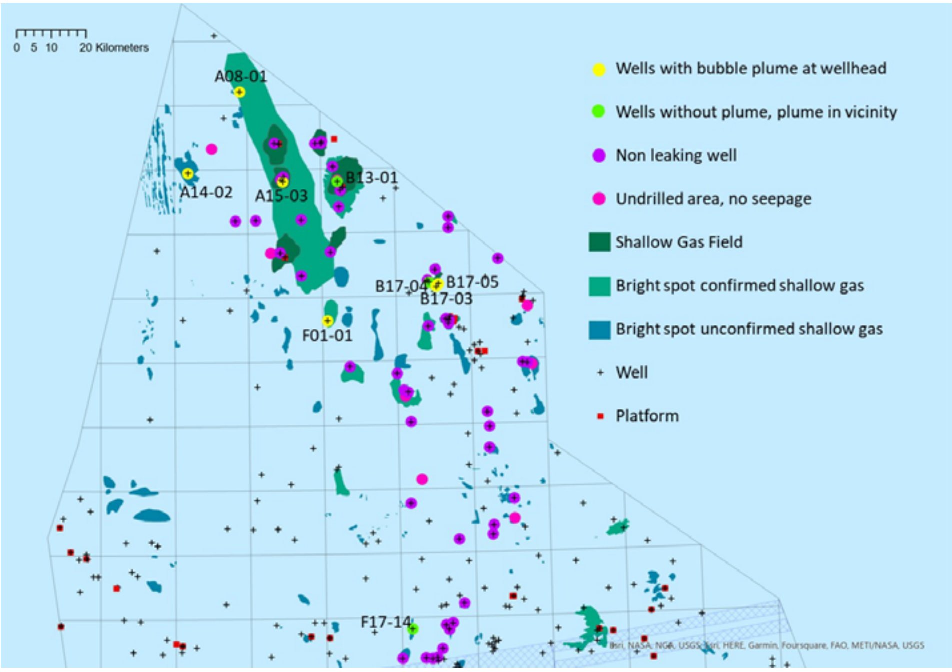


Figure 3-12: *Overview map of surveyed locations. Scale bar in the upper left corner. At the location of 6 abandoned wells a bubble plume was observed at the wellhead location (yellow), at 3 well locations no bubble plume observed at the well head, but bubble plumes were observed in the vicinity of these wells (green).*

3.4 Results statistics

In total 54 locations were selected for a MBES survey, with the aim to identify bubble plumes in the water column. At each location at least 5 parallel passes with MBES were made over the location of interest, giving a clear image of the presence (or absence) of bubble plumes at or in the surroundings of that location. Furthermore, at these locations all other analyses (Sub Bottom Profile, Magnetometer, CTD water samples, LMS Methane Sensor, Slurf water analysis, Air sampling) were performed as well. Of these 54 locations 48 locations contained an abandoned well (Figure 3-13), and 6 locations were undrilled (Figure 3-14). Of the 48 fully surveyed wells, 32 were drilled through shallow gas, 6 were located near shallow gas, and 10 were drilled more than 1 km away from shallow gas.

In addition, 9 wells were surveyed partially in that these wells were only passed once and only MBES and Laser-Spectrometer data were recorded. A full overview of the results is shown in Figure 3-15. Of these 9 wells, one was drilled through shallow gas.

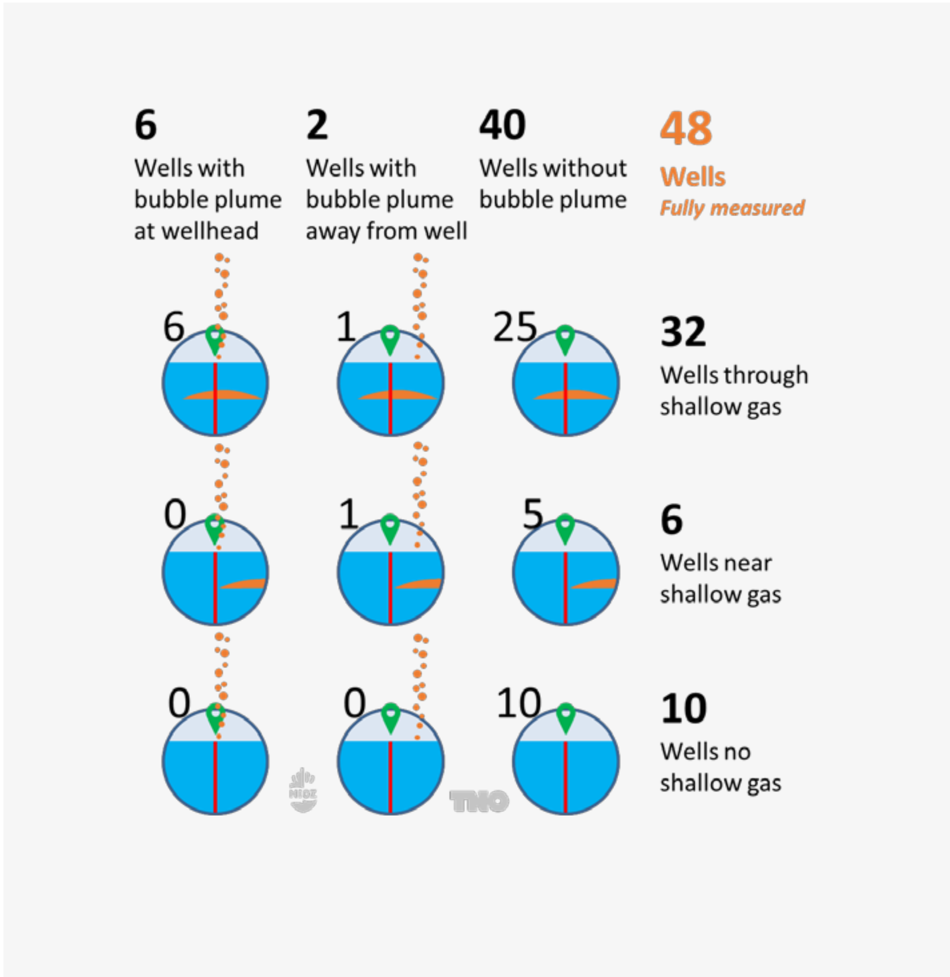


Figure 3-13: *48 wells were fully surveyed (i.e. with at least 5 parallel MBES passes). Most wells (40) did not show a bubble plume. At 6 wells that were drilled through shallow gas a bubble plume was found at the wellhead (see table 1). These wells will be further studied to determine the cause of the bubble plume (i.e. well leakage or natural seepage). For well B13-01 numerous bubble plumes were found a considerable distance away from the wellhead. These bubble plumes are part of a natural seepage site. At well B17-04 numerous bubble plumes were at a distance of at least 74 m from the wellhead. This well was drilled in a chimney (seismic disturbance caused by vertical gas migration), close to remnants of a shallow gas accumulation, indicating natural seepage. Also this well will be studied further.*

Figure 3-14: *No bubble plumes were found at the surveyed undrilled locations.*

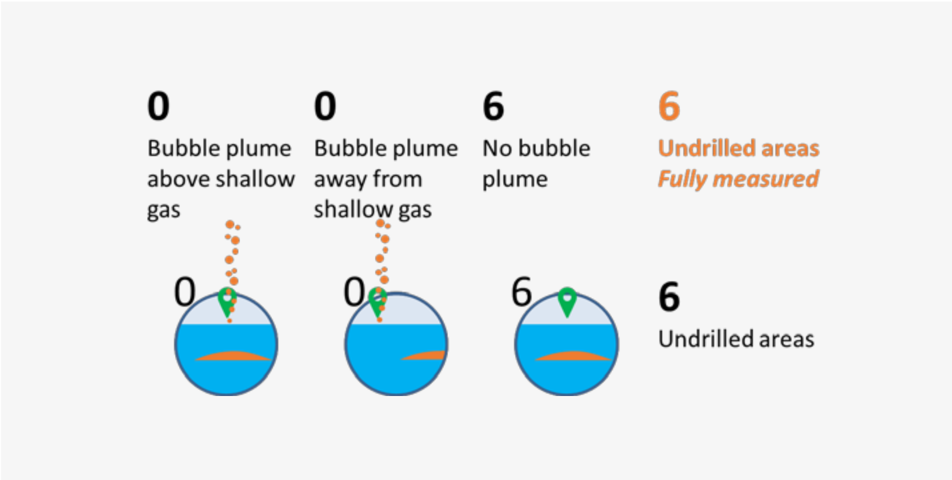
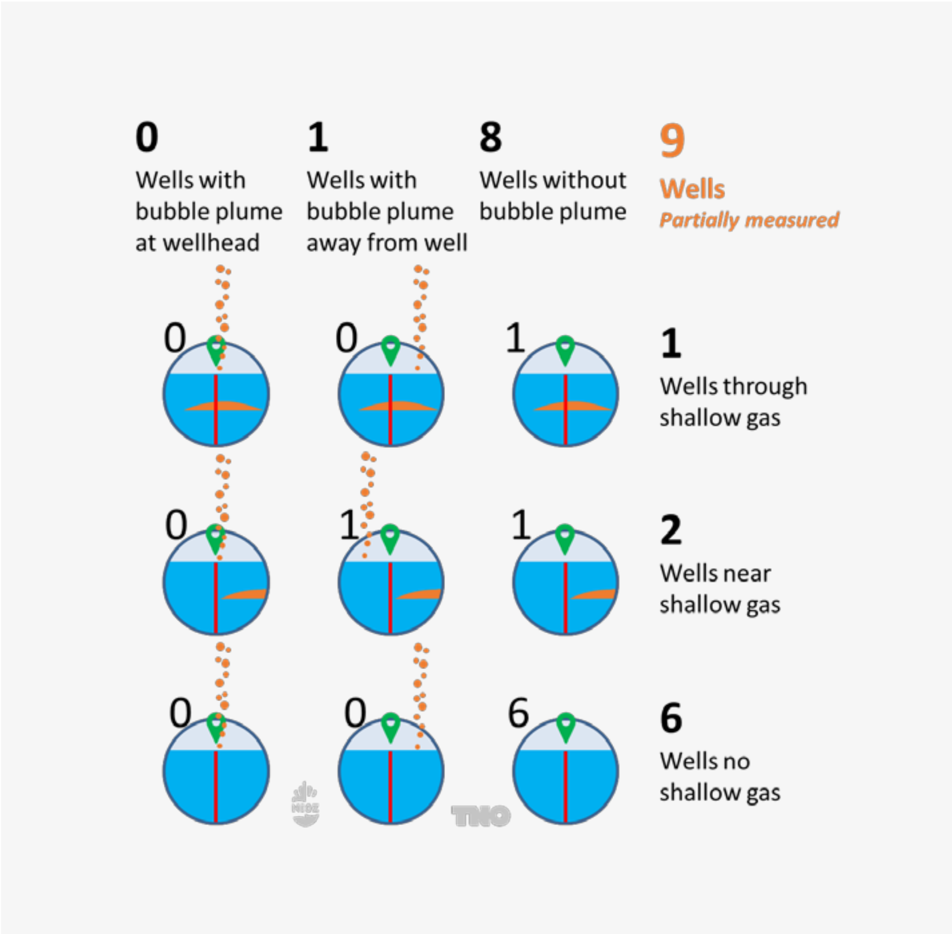


Figure 3-15: *9 wells were passed once with the MBES (i.e. partially surveyed). Bubble plumes were observed in the vicinity of only one of these locations, but seem unrelated to wells or shallow gas. The bubble plumes were observed 240 m south of well F17-14, in an area where Basisveen Bed (peat) is present. Shallow gas is not known to be present underneath the bubble plume location and F17-14, but only more than 330 m further to the north and 130 m further to the south of these locations. 8 wells showed no bubble plumes at their wellhead.*



4 Geological background of the wells associated with bubble plumes

Here we describe the background of the wells that are associated with one or more bubble plume. It is a summary of the main drilling history and the relevant geological findings.

4.1 Well A08-01

Well A08-01 was drilled as an exploration well for oil and shallow gas in 1996 by the NAM. In the drilling report a list of objectives is mentioned (Figure 4-1).

OBJECTIVES	ACHIEVED
Find oil-bearing Upper Jurassic Fulmar Sandstones in a large stratigraphic trap	No (Trap not present)
Prove the presence of Fulmar sandstones in the Dutch Northern Offshore Sector	No (Sandstones not found)
Prove the presence of oil charge in the Northern A and B blocks	No (Oil not present)
Obtain quality log and core data within the objective interval	Yes (Coreable sands not encountered)
Evaluate one of the two regionally extensive Pliocene levels which may contain biogenic gas	Yes (Shallow gas encountered)

Figure 4-1: *Objectives and achievements of well A18-01 (source: NAM).*

The main objective was to find oil-bearing Jurassic Fulmar sandstones (which were not encountered) and to "evaluate one of the two regionally extensive Pliocene levels which may contain biogenic gas". Although no further detail is given about the specifics of the "two regionally extensive Pliocene levels", we believe that NAM is referring to two very large bright spots (Figure 4-2 and Figure 4-3) that were mapped also by TNO (Ten Veen et al., 2013). However, these sand layers, interbedded between relatively thick clays, are of early Gelasian age. So, NAM dates them slightly younger than TNO, but since age dating by biostratigraphy was not commonly used in industry, errors in age dating are common. The well is indeed drilled trough the lowest of the two large bright spots, at a time-depth of 968 ms. This bright spot runs from the A5 block to the A18 block and is 70 by 13 km.

The two regionally extensive sands have been eroded by contour currents and are characterized by a wavy pattern (Ten Veen et al., 2013). The sands were deposited during glacial and interglacial periods and correspond to the S5 or S6 as defined by Overeem (2002) and ten Veen et al. (2013). Interestingly, the sands were deposited during the interglacials, when sea level was high, and the shales during the glacial periods. Consequently, the sands contain more organic matter than the shales, and biogenic gas could have been generated within the sands (Ten Veen et al., 2013).

The drilling report states that “shallow gas (was) encountered”. Since the bright spot is so large, the presence of shallow gas has also been confirmed by other wells. However, no commercial quantities of gas were encountered. Shallow gas was encountered at 419 m in A08-01 but in the seismic data no bright spots are observed at that depth. Some brightening is visible, but not as clear as would be expected for a bright spot. This is most likely due to the poor quality of the seismic data in the upper 300-400 m.

The drilling report states that Jurassic strata were the deepest target, but the well was drilled into the Zechstein salts. Although not mentioned in the drilling report, it seems that the Zechstein Carbonates were targeted. The well has a total depth of 3348 m. A08-01 must therefore be considered a deep well that reached the thermogenic gas domain, and leakage from deeper gas sources (i.e., not shallow gas) could hence also contribute to the observed bubble plume.

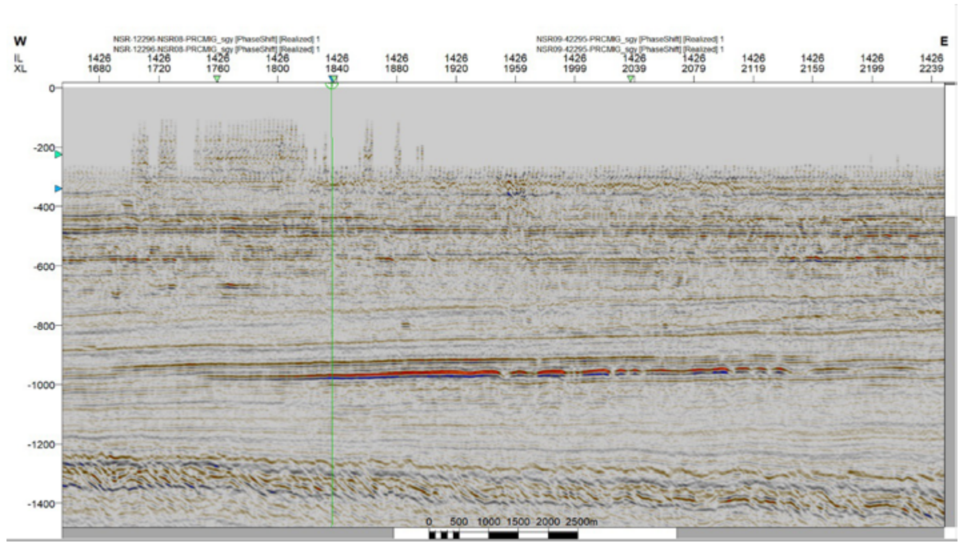


Figure 4-2: *Seismic profile through well A08-01 (Green Line). Note large shallow Gas bright spot at approximately 900 ms.*

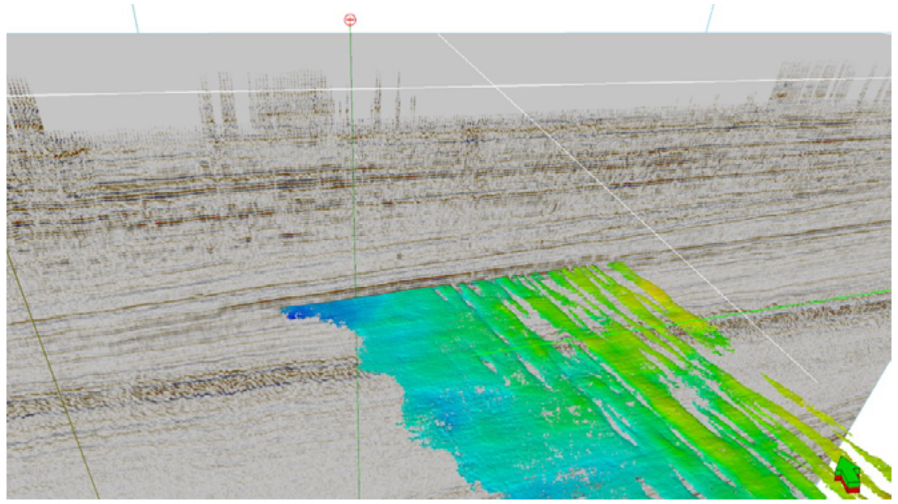


Figure 4-3: *3D perspective view of the large shallow gas related bright spot (blue is deepest, yellow is the shallowest) drilled through in well A08-01 (green line). The sand containing shallow gas that produces the bright spot seem to be eroded by contour currents.*

4.2 Well A14-02

Well A14-02 was drilled in 2002 by the NAM. The aim of the well was to explore for oil in the Jurassic Fulmar Sandstones and the Zechstein Carbonates. However, both potential reservoirs were absent. The well was drilled following the ‘shallow gas procedure’ and shallow gas was encountered while drilling. The quality of the seismic data obtained is not great (Figure 4-4). The data collected is probably not zero phase, resulting in asymmetric reflector pairs for the bright spots (i.e. the top reflectors are much brighter than the bottom reflectors). Furthermore, the resolution of the upper 200 m appears to be rather low. Consequently, the encountered shallow gas cannot be linked precisely to a bright spot. The drilling report states that the (shallow) gas readings during the drilling of the pilot hole were not high. Gas was recorded at 268 m, with the highest peak seen at 466 m, and gas also encountered at 649 m. The well reached a total depth of 2636 m TVD (true vertical depth) and ends in the Zechstein halites. This means that A14-02 is a deep well that reached the thermogenic gas domain, and leakage from deeper gas sources (i.e., not shallow gas) needs to be considered as potential cause for the observed bubble plume.

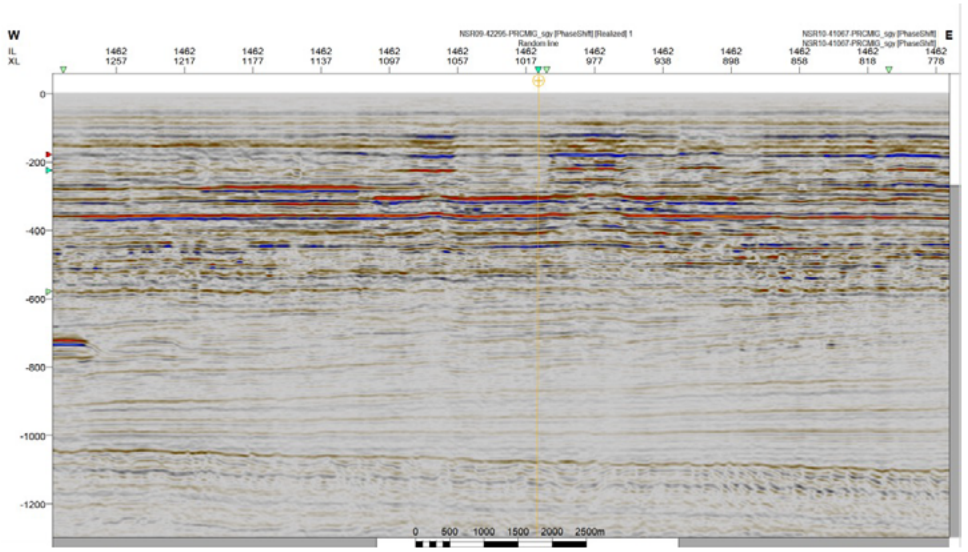


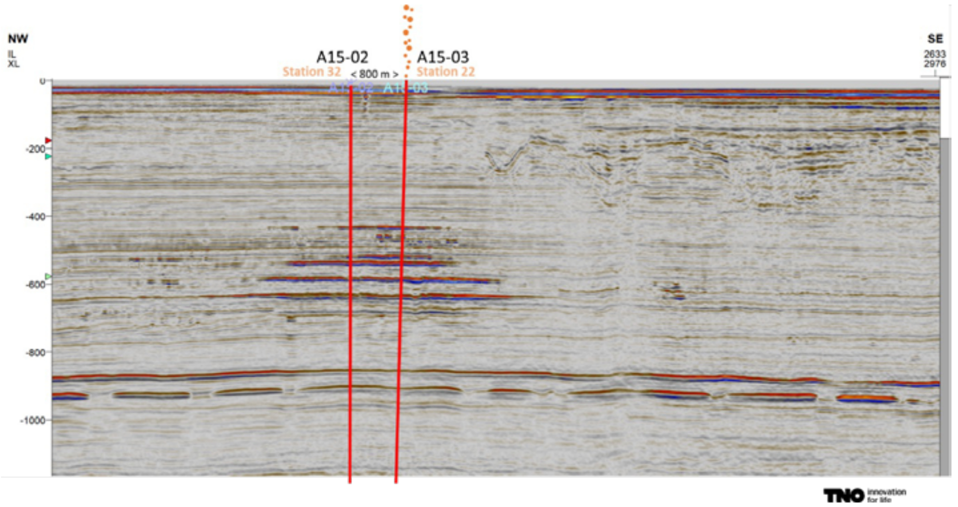
Figure 4-4: *Seismic profile through well A14-02 (Amber).*

4.3 Well A15-03

Well A15-03 is an exploration well for shallow gas and was drilled through 7 bright spots related to shallow gas (Figure 4-5). The well was drilled by Wintershall in 1999. Wintershall had identified that 2 of these layers could contain commercial quantities of gas.

Since A15-03 specifically targeted shallow gas, there is a substantial amount of data available, including logs, cores, pressure data, gas composition, gas-related stable isotopes, etc. Consequently, many publications have appeared about A15-03 and the A15 block in general (e.g. Overeem, 2002; Ten Veen et al., 2011, 2013; Donders et al., 2018; Foschi et al., 2018; Verweij et al., 2018; de Bruin et al., 2022). Since the well targeted only shallow gas it ends in the Middle North Sea Group (NM) (i.e. no deep reservoir or source rocks were drilled). Commercial quantities of shallow gas were encountered, and the A15-A shallow gas field has been bought by Petrogas. This field will be put in production in the coming years.

Figure 4-5: *Seismic section through wells A15-02 and A15-03. While both wells were drilled through the same shallow gas field and shallow gas related bright spots, a bubble plume was detected only at well A15-03. Note the tunnel valleys south-east of well A15-03.*



Interestingly, well A15-03 is only 800 m away from well A15-02, where no bubble plume was observed. Both wells were drilled through the same bright spots and shallow gas field. A15-02 is drilled earlier (1992) as an exploration well targeting the Chalk (Cretaceous). Similarly no bubble plume was observed at well A15-05, located 1400 meters from A15-03. This well was drilled in 2019 by Petrogas to evaluate the A15-A gas field (shallow gas).

4.4 Geological story of the B17 salt dome

B17-01, B17-03, B17-04, B17-05 and B17-06 were all drilled in the strata overlying the same salt dome (Figure 4-6). The deformation of this salt resulted in an overall N-S elongated dome structure in the Upper North Sea strata. This created a 4-way dip closure. This deformation also resulted in faulting, of which several N-S faults with visible displacement are observed on seismic data. For unknown reasons the faults that run through the eastern flank of this dome structure are sealing, and therefore a distinct shallow gas field (bright spot) is present on the eastern flank. A flat spot (gas water contact) is clearly visible on seismic data.

The strata above the bright spot are clearly visible (i.e. the geology is not prohibiting a proper seismic definition of layers). On the western flank no bright spot is visible at the level where one would expect one based on the geometry of the bright spot and flat spot. Only a faint remnant of the flat spot is observed here. The layers above the interval where the bright spot should be present are very disturbed and have low amplitudes. This pattern is interpreted as a seismic chimney, caused by vertical gas migration. Especially at the seabed reflector, around well B17-04 this seismic chimney is clearly visible. Based on these observations we infer that the faults on the western flank are leaking, and that the accumulated gas migrated to the surface via the chimney.

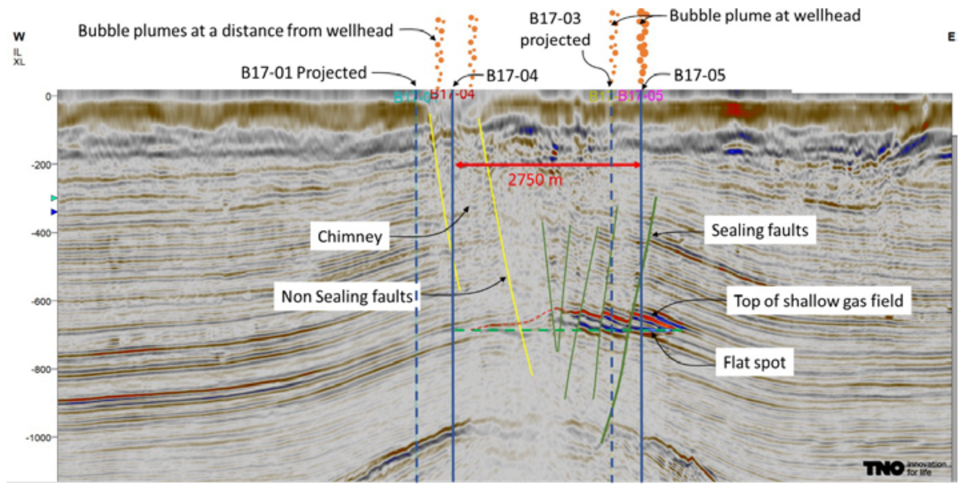


Figure 4-6: *East-West profile over the B17 salt dome. Wells B17-01 (projected), B17-04 were drilled on the eastern flank, where a chimney is observed. B17-03 (projected) and B17-05 were drilled on the eastern flank through the B17-A field (shallow gas). At wells B17-03 and B17-05 bubble plumes were found at the wellhead locations, but not in the surroundings. At wells B17-01 and B17-04 no plumes were found at the wellhead locations, but numerous plumes were found in the surroundings of B17-04. We conclude that the faults of the western flank are naturally leaking, creating a chimney. The wells on the eastern flank are sealing, resulting in an accumulation of shallow gas.*

4.5 Well B17-03

B17-03 was drilled on the eastern flank of the B17 salt dome (see section 4.4) through the B17-A field (shallow gas). The well was drilled in 1977 by BP Netherlands, targeting the Upper Cretaceous Chalk structure above the salt dome. Shallow gas was encountered during drilling. At a depth of 600 m there was a rapid increase of measured methane. The peak in methane concentrations was located at 650 m, where up to 80,500 ppm was measured. Only trace amounts of ethane where encounterd.

4.6 Well B17-05

Well B17-05 well was drilled by the NAM in 1991 as an exploration well targeting a shallow gas bright spot, with a flat spot. Shallow gas was encountered at 664 m to 677 m, which corresponds to the depth at which gas was observed in the B17-A field. The well was drilled therefore comparable to well B17-03 (see 4.5) and was also drilled on the eastern flank of the B17 salt structure (see 4.4). The well ends in the Middle North Sea Group (NM) and therefore, no deep thermogenic source rocks or reservoirs were drilled here.

Since the well targeted shallow gas, NAM wanted to core the interval of interest, but recovery of the cores was hampered by the unconsolidated nature of the strata. Recovery varied between 33% and 100%, and was for the B17-A field interval 88% on average. Maximum gas concentration observed during coring was 80690 ppm, similar to the concentration observed at B17-03. Production tests were also ran, suggesting that a maximum of 287.000 m^3 per day could be reached. The gas contained 98.8% Methane 0.4% CO_2, 0.034% ethane and no H_2S. The reservoir pressure was 62.2 bar.

4.7 Well F01-01

Well F01-01 is an exploration well drilled in 1990 by Arco. The well targeted a Chalk (Cretaceous) prospect and had shallow gas as a secondary objective. The well ends in the Zechstein at a depth of 1993 m. The seismic data clearly shows a deep salt dome and shallow gas (Figure 4-7). Push-down is visible below the shallow gas, which is an indication of levels with high gas saturation. Push-down is a result of the significantly lower seismic velocity of the gas-filled sands relative to the water filled-sands. Therefore, the time it takes for a seismic pulse to travel through the gas-filled sand is longer than through the water-filled sands, resulting in an apparent push down of the layers below the gas-filled sand.

Shallow gas was encountered at several depth intervals. The molar composition of the gas is provided showing that the gas consists mainly of methane (Table 4-1). Such a composition is in line with a biogenic origin of the gas.

Table 4-1: *Molar composition of gas encountered at well F01-01 during drilling in 1990.*

Compound	Molar **composition** M%
Methane	99.22
Nitrogen	0.52
Heptane plus	0.14
Hexane	0.09
Ethane	0.02
Carbon dioxide	0.01
Hydrogen sulphide	0.00

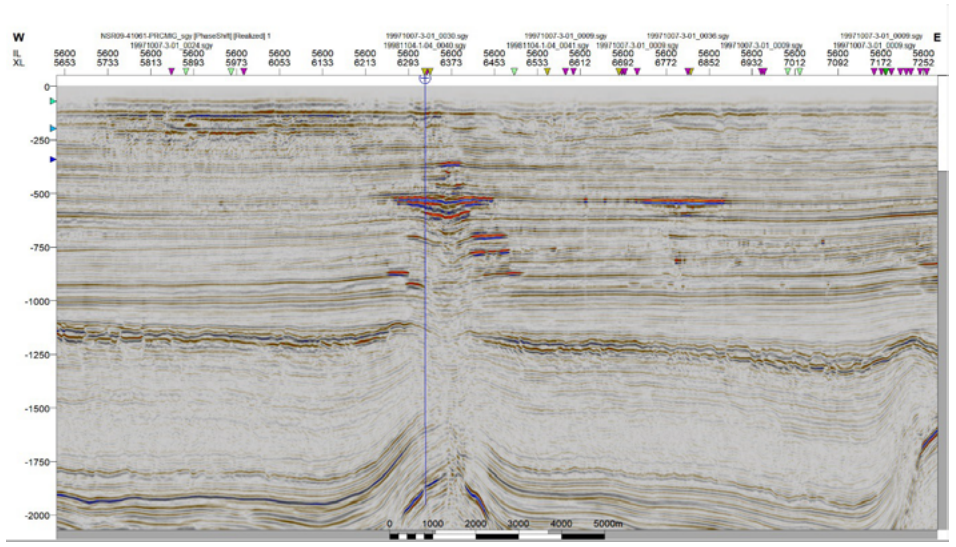


Figure 4-7: *Seismic profile through F01-01 shows that the well is drilled through shallow gas. Note the push down below the gas, which is an indication of higher gas saturation. Also note the salt some at the base of the profile.*

4.8 Well B13-01

Well B13-01 is an exploration well drilled by BP Netherlands in 1973. The well targeted the Zechstein and has a total depth of 2867 m. The well was drilled through shallow gas, later designated as the B13-FA field, that is producing at the moment. Gas peaks were measured while drilling, reaching concentration up to 25.000 ppm at several depths.

4.9 Well B17-04

Well B17-04 was drilled in 1990 by Arco. It is an exploration well that targeted a deep Lower Carboniferous prospect, while the Buntsandstein (Triassic) was the secondary target. The well was drilled on the west flank of the B17 salt dome (see section 4.4). The well was drilled into a chimney, close to what appears to be the remnant of a flat spot. This made the well difficult to classify. Wells that are drilled through a bright spot, and where gas was encountered during drilling, are classified as "Confirmed Shallow Gas". Following this logic, this well did not fall into the "Confirmed Shallow Gas" class, since it was not drilled through a bright spot. There is a bright spot at 400 m distance, and therefore we classified this well as "Near Shallow Gas".

However, an argument can be made to classify this well as "Confirmed Shallow Gas" because a chimney is a clear indication for the occurrence of shallow gas, and a chimney could mask a bright spot located underneath. Shallow gas was also encountered at several intervals during drilling. Notable peaks in methane occurred at 475 m (13.021 ppm CH_4), 590 m (1.93% total gas), 762 m (12.190 ppm CH_4), 823 m (12.720 ppm CH_4).

4.10 Well F17-14

Well F 17-14 is an exploration well drilled in 2018 by Wintershall. The well is still confidential at the time of writing and therefore only fundamental data is available. The well encountered gas and oil shows, but in which interval is not specified but from the fact that oil was found we can derive that the well probably targeted the Chalk (Cretaceous).

5 Analysis of pre-drill site surveys

When a bubble plume is observed near or at an abandoned well it is important to rule-out natural seepage, before labeling it well leakage. Data from the pre-drilling conditions can be used to distinguish well leakage from natural seepage. Here we use pre-drill site surveys obtained by the different operators/drilling companies.

Before a well is drilled a survey of the drilling site is made to determine whether the site is suitable and safe. The focus is on shallow gas near the seabed. It is common practice to change the planned location of the well when shallow gas is observed below the seabed or in the water column. Consequently, the chance that a well is drilled at the location of a natural seepage location is very small. However, there are examples where wells are drilled close to natural seepage sites (e.g. well 15/25b-1A described by Böttner et al., 2019).

For the six wells (A08-01, A14-02, A15-03, B17-03, B17-05, F01-01) with a bubble plume at the wellhead location we want to investigate if there is any evidence of a natural bubble plume from pre-drilling reports.

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 NAM. NAM is also owner of B17-05, but they indicated that they no longer had the site survey. B17-03 was drilled by BP Netherlands and F01-01 was drilled by Arco. Both companies are no longer active in the Netherlands and we could not obtain the site surveys. Finally, A15-03 was drilled by Wintershall and the well is currently located within the license of Petrogas. The site survey was not yet found by either company at the time of writing.

5.1 A08-01 Site survey

Before well A08-01 was drilled a site survey was conducted. An area of approximately 1250 by 1250 m was surveyed with multibeam echo sounder, side scan sonar, sub bottom profiler and boomer. The center point of the survey was the planned well location A18-A which is only a couple of meters away from the location were the well A08-01 was drilled. During the survey two shallow boreholes (10 and 22 m below the seabed) were made and analyzed.

The site survey revealed that in some areas of the study areas shallow gas was trapped in the upper sediments. About 445m Northeast of well A08-01 shallow gas breaks through these sediment layers and reaches the seafloor. At that location a pockmark was found. There is no mention of the pockmark showing a bubble plume. This pockmark is just outside the area that was surveyed by us.

There is no evidence that there was a bubble plume present at the location of well A08-01 before it was drilled.

5.2 A14-02 site survey

Before well A14-02 was drilled a site survey was conducted. The surveyed area is approximately 1500 by 1500 m, with two center lines that are 3 km. The center of the survey was centered around the original proposed location (which is not the same as the location where the well was eventually drilled). The survey consisted of single- and multi-beam echosounders, side scan sonar and boomer generated data.

At nine different depth intervals (up to 444 m depth) potential shallow gas accumulations were identified at or near the proposed location (A14-B). Due to the presence of shallow gas the well was drilled approximately 145 m to the WSW of the original proposed location. At the seabed only sand ripples are observed, and no indications of seepage (i.e. pockmarks, bubble plumes, etc.) were reported.

There is no evidence that there was a bubble plume present at the location of well A14-02 before it was drilled.

5.3 Plumes at well location

The pre-drilling-survey reports show no evidence for bubble plumes (related to natural seepage) before drilling at the two well locations. Secondly, we can derive for the other wells where no site survey was available that it is highly unlikely that a well is drilled within a few meters of a bubble plume (related to natural seepage). When shallow gas is detected at the proposed well-location, the procedure is to change the drilling location in order to avoid drilling through shallow gas. Our observations show only a bubble plume at the well location and no other bubble plumes in the vicinity, so avoiding the bubble plume would have been very easy and therefore likely acted upon by the drillers. Consequently, it is highly unlikely that the bubble plumes at the six wells are caused by natural seepage.

6 Detecting peat at bubble plume locations using the Sub Bottom Profiler

Another potential source for bubble plumes could be very shallow (e.g. first meters below the seabed) peat layers of early to middle Holocene age. Such peat layers can still actively produce methane biogenically. In the North Sea this would be the Basisveen Bed (NUNIBA[1]), which has been mapped by TNO and patches of the Basisveen Bed can be found in the entire Dutch North Sea. This Basisveen has been deposited in a freshwater environment during the final stages of the last glacial period and microbial investigation showed that it still produces limited amounts of methane (Lippmann et al., 2020). During the 64PE503 expedition, Sub Bottom Profiler data was acquired to map the first meters below the seabed in order to potentially relate the occurrence of Basisveen to methane ebullition. Here we only discuss the locations where a bubble plume was observed and identify whether peat layers are present at these bubble plume locations.

1 *https://www.dinoloket.nl/stratigrafische-nomenclator/basisveen-laag*

6.1 No peat layers are present at the 6 wells with a plume

No peat was found at the 6 wells where a bubble plume was observed at the wellhead (A08-01, A14-02, A15-03, B17-03, B17-05, F01-01). Nevertheless, the Sub Bottom Profiler (SBP) data shows very interesting geological features such as clinoforms, channels, glacial moraine deposits (see Figure 6-1). Furthermore, in some cases the bubble plume itself is visible.

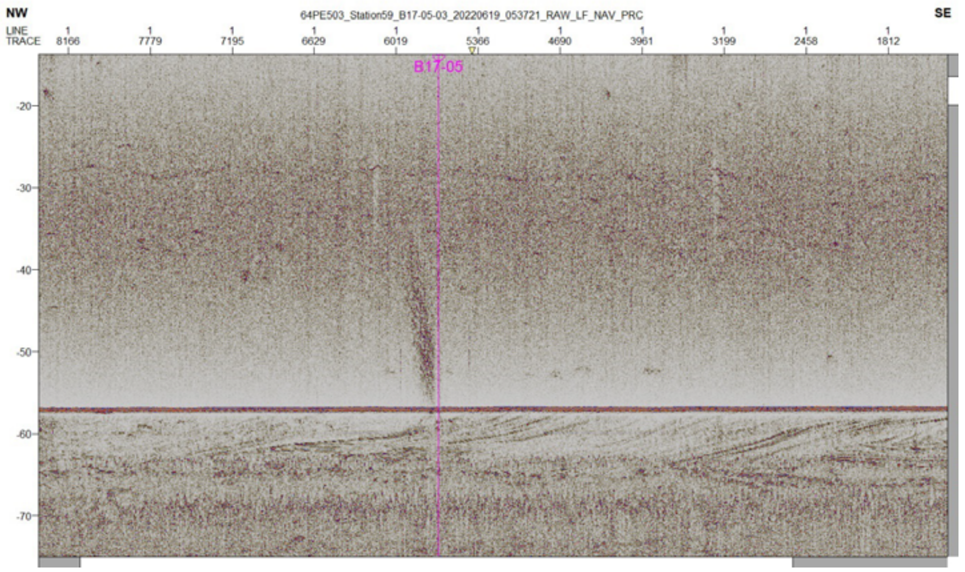


Figure 6-1: *Sub bottom profile acquired during this measuring campaign, 64PE503, over well B17-05 showing the bubble plume at the wellhead, and clinoforms. No peat layer is observed here.*

6.2 No peat layers are found at B17-04 and B13-01

At wells B17-04 (see Figure 6-2) and B13-01 many bubble plumes were found at some distance away from the wellhead. No bubble plumes were found directly at the wellhead itself. B13-01 was drilled close to a natural seepage site. At both well locations no peat layers are identified. We can thus conclude that peat is not the source of the observed bubble plumes. However, in the wider B13 area the Basisveen Bed has been identified.

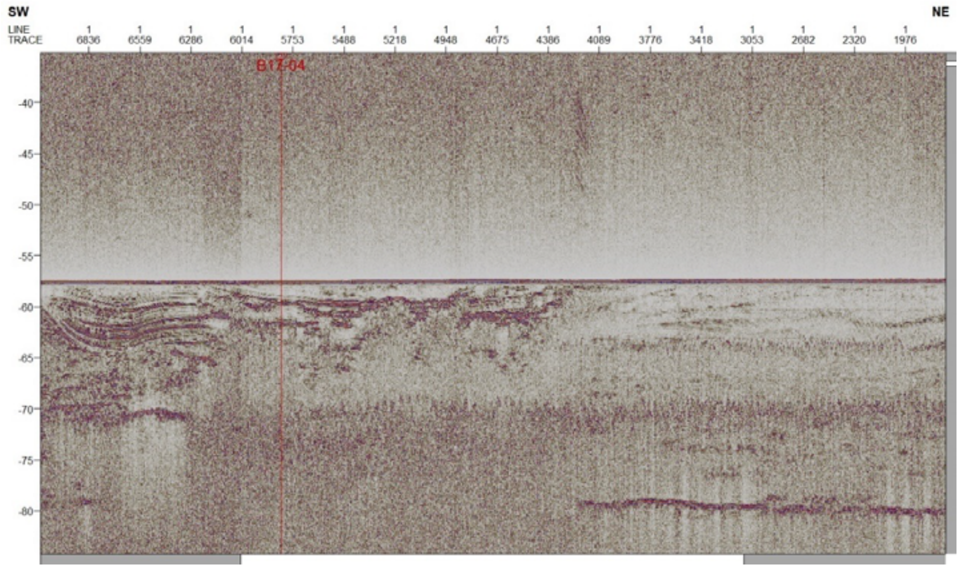


Figure 6-2: *SBP data at well B17-04. No bubble plume is present at the wellhead, but one can be seen North-East of the well between traces 4386 and 4089. Around the well, a channel complex is present. Peat is not identified in this profile.*

6.3 Peat is present at the bubble plumes near F17-14

Several bubble plumes were found at more than 240 m away from well F17-14. Unfortunately, no SBP data was collected here. However, the Basisveen bed was here previously identified by TNO (Figure 6-3). Since no shallow gas, or tunnel valleys are present at the plume locations, the most obvious source of methane would be the Basisveen Bed.

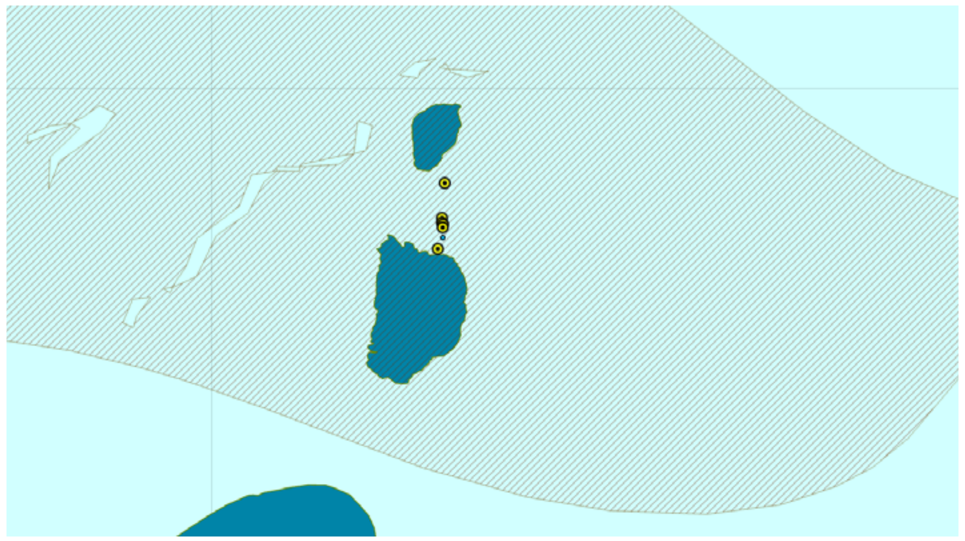


Figure 6-3: *Bubble plumes (yellow with black dots), well F17-14 (blue dot), shallow gas (dark blue fill with green outline, and Basisveen Bed (brown dashed).*

7 Tunnel Valleys at wells with a bubble plume

Tunnel valleys have been suggested as a potential source for methane because of the storage of organic matter rich sediment at the base of the infill. A mechanistic linkage to ebullition was formulated because a tunnel valley was encountered underneath the A11 pockmark described by Schroot et al. (2015). However, none of the wells with a bubble plume at the wellhead were drilled through a tunnel valley. Well A15-03 (see Figure 7-1 and Figure 7-2) was drilled close to it, but A15-05 (non-leaking well) was drilled right on the edge of a tunnel valley. For the wells investigated here tunnel valleys can thus be excluded as a source for the observed bubble plumes.

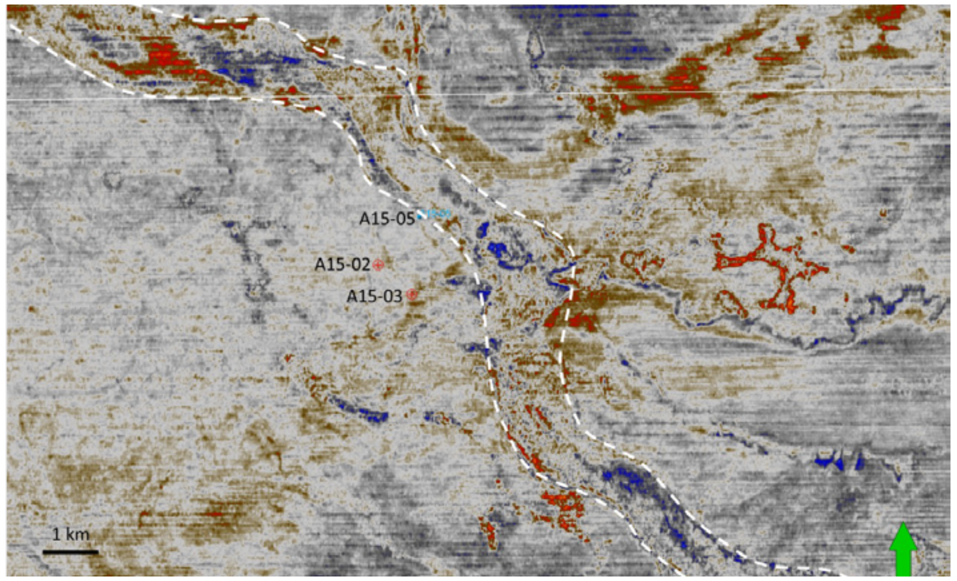


Figure 7-1: *Time slice through 3D seismic volume showing tunnel valleys in the A15 area. Note that A15-05 was drilled on the edge of a tunnel valley. No plume was detected at that well. At A15-03 a bubble plume was observed, but the well is located further away from the tunnel valley.*

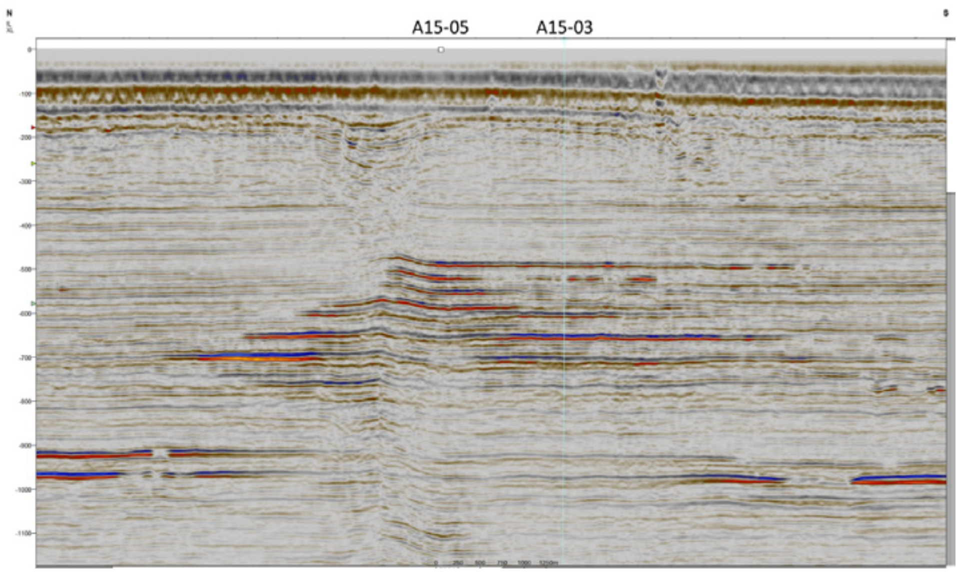


Figure 7-2: *Seismic section through wells A15-05 and A15-03. Since A15-05 is a recent well, no well trajectory information is present. The well is located at the edge of a tunnel valley.*

8 Methane and ethane in the seawater

The goal of the first campaign with RV Pelagia was to gain insight in the extent of methane escape into the water column in the vicinity of abandoned wells and to estimate the potential for microbial methane oxidation. For this, we selected 54 locations of interest, including a subset of abandoned wells, covering a range of geological conditions to account for the diversity of geological background conditions in the North Sea (de Stigter et al., 2002).

8.1 Analysis of dissolved gasses in the water column.

We aimed to apply three different and independent approaches to measure methane in the water column:

(i) Methane concentrations were measured directly and in situ with a Franatech La-ser Methane Sensor (LMS). This instrument comprises a measurement cavity sealed to the ambient water column with a membrane. Ambient methane diffus-es across the membrane into the cavity and is quantified as a function of laser light absorption. The detection limit of the LMS is 10 ppm methane in the meas-urement cavity. The concentration in the water column is then calculated from the methane mixing ratio in the cavity and corrected for the diffusion time lag in accordance with statistical inverse theory (Dølven et al., 2022).

(ii) To measure CH_4, C_2H_6, N_2O, CO_2 and CO, a laser spectrometer (Tunable Infrared Laser Direct Absorption Spectroscopy; TILDAS; Aerodyne Research Inc., Billerica, USA) was used. This instrument contains a quantum cascade laser (QCL) and an interband cascade laser (ICL) and can simultaneously measure CH_4, C_2H_6, N_2O, CO_2 and CO.

(iii) We also took discrete water samples with a CTD-Rosette system and measured methane with a head space technique (e.g. Green, 2005). For this, a sea water sample is filled headspace-free into a glass measuring vial, capped with a rubber septum, after which a nitrogen headspace is added, and the sample is poisoned with a concentrated NaOH solution. Methane in the headspace is then measured by gas chromatography with flame ionisation detection.

Both in situ Franatech LMS measurements and sampling of discrete water samples were carried out at hydrocast stations with a CTD device equipped with a Rosette sampler. The LMS was mounted in the CTD frame measuring continuously during the hydrocast and individual water sampling bottles (PRISTINE ultraclean sampler bottles developed by NIOZ, Rijkenberg et al., 2015) were closed remotely. Typically, we took 4 water samples per hydrocast, ~equally distributed over depth (surface, above the pycnocline, below the pycnocline, and close to the sea floor: ~5, ~15, ~30, ~40 m).

Immediately upon recovery, water aliquots were filled in triplicates into glass vials, both for methane concentrations and methane oxidation measurements. For measurements with the cascading laser spectrometer water was pumped from deep water that was pumped up via a weighted hose (called the "SLURF") from a few meters above the bottom or from surface water of 4 m depth which was taken in at the bow of RV Pelagia via the Aquaflow system of the ship (de Stigter et al., 2022).

8.2 LMS Methane sensor results

Methane concentrations measured in situ with the LMS were variable ranging from below detection limit to 370 nM dissolved in the water column (Figure 8-1). The measurement results of the LMS are in agreement with previous findings from seepage locations at the southern flank of the Doggerbank (Römer et al., 2021) where methane ebullition from the sea floor was found to cause water column methane anomalies of several hundred nM (Menoud et al., in review). We will employ LMS type measurements again in the following campaigns where we intend to install this device also on a lander frame and operate it from an ROV.

Well / location		F12-01	B13-01	B10-02	A08-01	A14-02	A15-03	B13-04	B13-03	B16-01	A18-02	A18-EBU	A14-01	A15-02	A15-04
Station		8	13	14	19	21	22	24	25	26	27	28	31	32	34
LMS nM	~5 m	3	33	8	10	0	4	18	28	12	12	28	6	6	29
	~15 m	14	52	14	14	0	7	35	0	28	28	57	11	11	86
	~30 m	19	238	25	26	0	11	126	0	131	130	95	SFL	SFL	337
	~40 m	0	162	0	147	SFL	SFL	0	0	363	352	243	SFL	SFL	371

Well / location		A15-01	A18-01	F01-01	F05-06	F05-Ch	F04-02	B17-06	B17-05	B17-04	F02-05	B17-03	B14-03	B14-01	F08
Station		35	37	41	46	47	50	52	53	54	56	59	60	61	65
LMS nM	~5 m	11	10	0	3	0	6	6	9	6	4	9	10	6	6
	~15 m	17	14	0	7	6	10	14	12	10	57	15	21	11	0
	~30 m	25	26	0	13	6	19	26	18	0	13	25	26	70	0
	~40 m	15	35	0	0	0	19	9	17	0	4	17	0	0	0

Figure 8-1: *Methane concentrations in the water column measured with a Franatech laser spectrometer. At the wells marked in yellow a bubble plume was observed at the well head. At the wells marked in green bubble plumes are observed away from the wellhead (and not at the well head itself). At locations with a shallow water depth, "SFL" indicates that samples could not be taken because the intended measuring depth lies below the seafloor. The following wells were measured but the methane concentrations were under the detection limit: F12-03, F12-05, F12-BS, F09-01, F09-03, F06-04, F06-02, F06-05, B13-BS, B10-03, B10-04, A12-02, A12-03, A11-PM, A14-02, A15-05, F04-01, F05-02, F05-05, F02-04, F02-03, F02-06, B18-02, F03-EBU, F11-03, F14-03, F11-01*

8.3 Methane and ethane from cascading laser spectrometer

With the SLURF based measurements it was possible to show enhanced methane concentrations when sampling water from close to the seafloor, at locations where bubble plumes were seen with the MBES. Peaks on top of the atmospheric background concentrations indicating methane coming from the water phase. Methane peaks were seen at five of the six wells where bubble plumes were seen, at A08-01, A14-02, A15-03, B17-03 and B17-05 (Figure 8-2 to Figure 8-14).

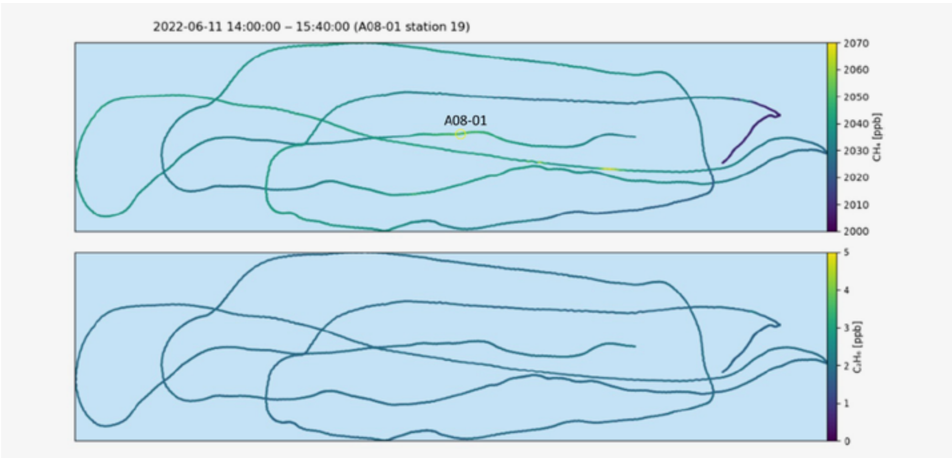


Figure 8-2: *Concentration CH_4 and C_2H_6 measured by the SLURF using the membrane, around A08-01 shows methane peaks east of the well*

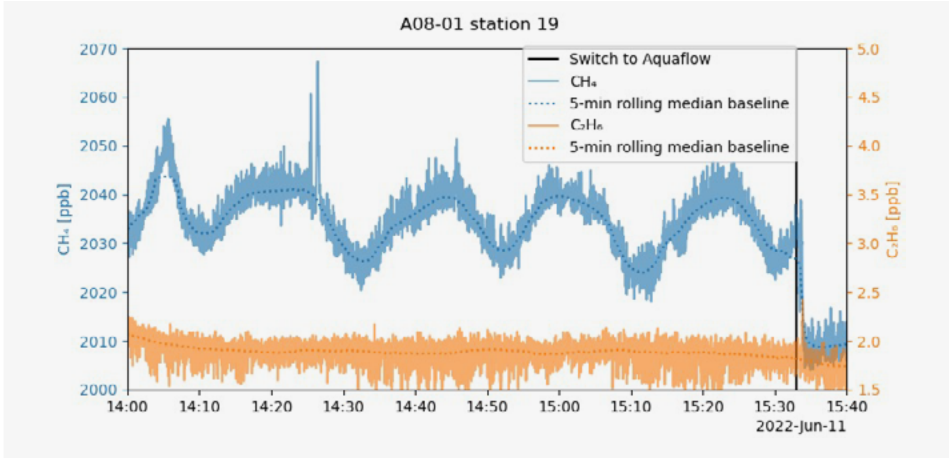


Figure 8-3: *Concentration CH_4 and C_2H_6 around A08-01, with the peaks between 14:25 and 14:27 showing CH_4 enhancements. Ethane stays constant, indicating that the bubbles contain no thermogenic gas.*

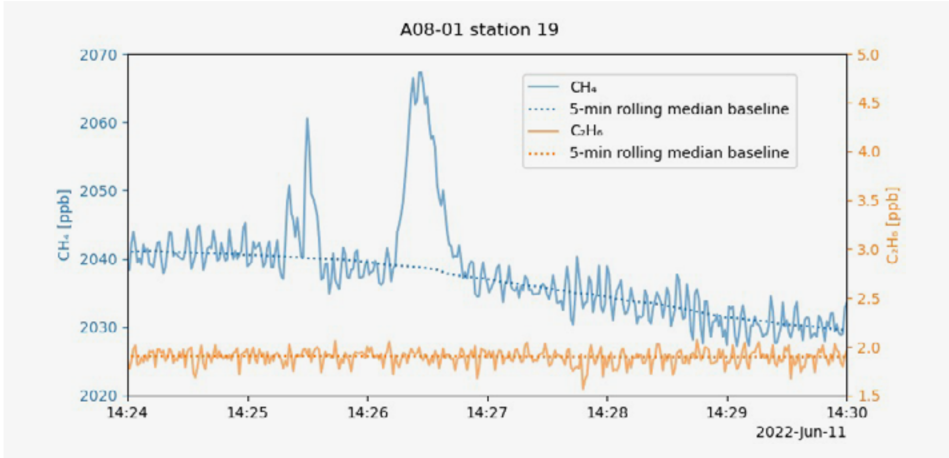


Figure 8-4: *Zoom in on the plumes of CH_4 on top of the atmospheric background at A08-01.*

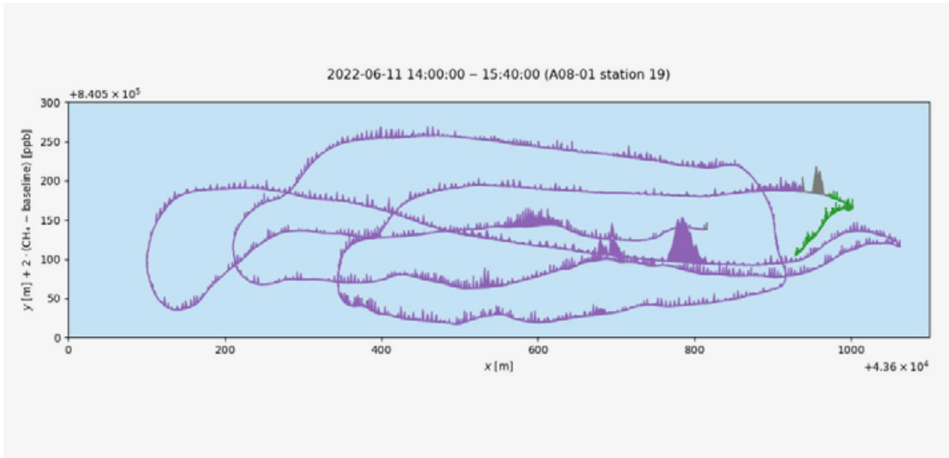


Figure 8-5: *Concentration CH_4 plotted at the track. Every ppb at the baseline is projected as 2m.*

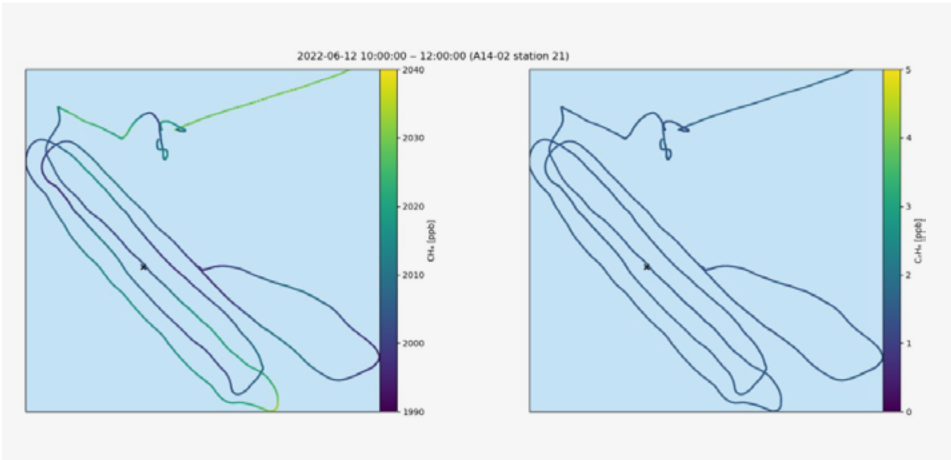


Figure 8-6: *Concentration CH_4 and C_2H_6 measured by using the SLURF and the membrane, around A14-02 (pointed with x).*

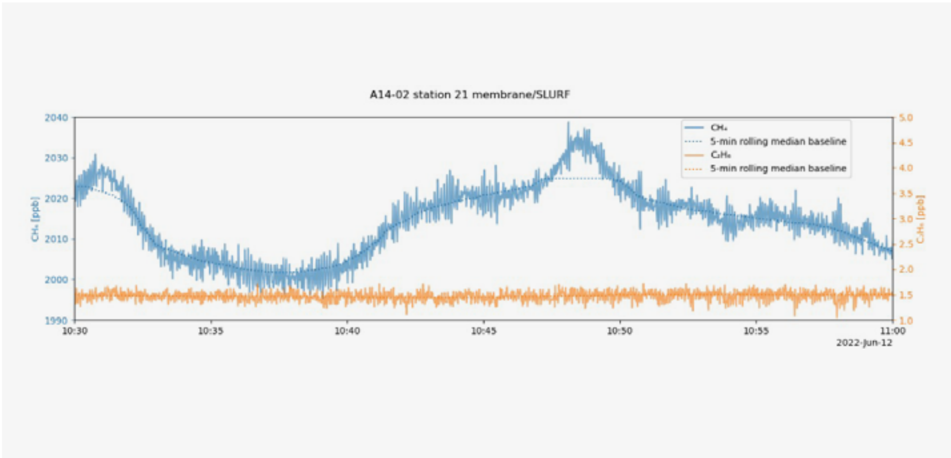


Figure 8-7: *Concentration CH_4 and C_2H_6 around A14-02, with the peaks between 10:47 and 10:50 showing CH_4 enhancements.*

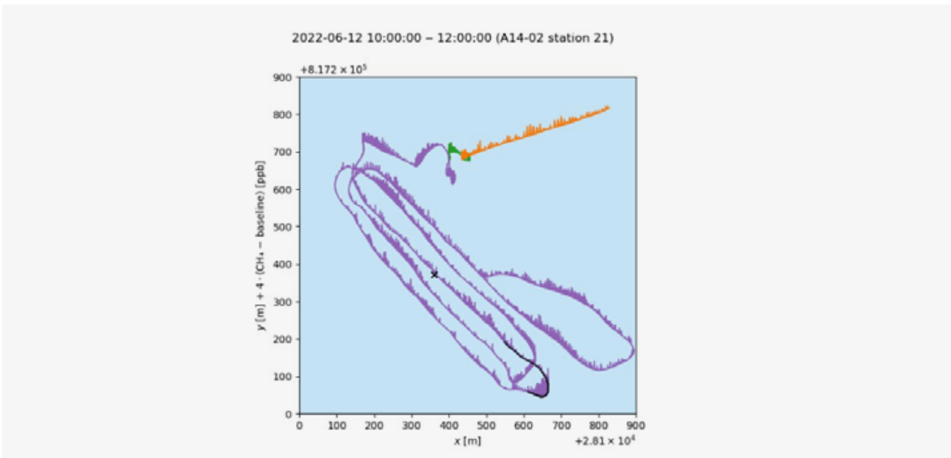


Figure 8-8: *Concentration CH_4 plotted at the track. Every ppb at the baseline is projected as 4m. A14-02 is pointed with x, purple is membrane/SLURF, green is membrane/Aquaflow, orange is Weiss/Aquaflow.*

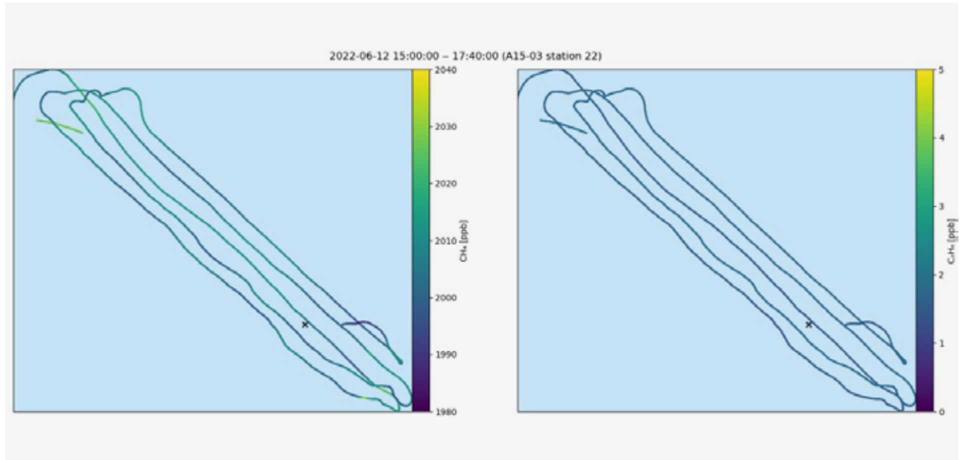


Figure 8-9: *Concentration CH_4 and C_2H_6 measured by using the SLURF and the membrane, around A15-03 (pointed with x).*

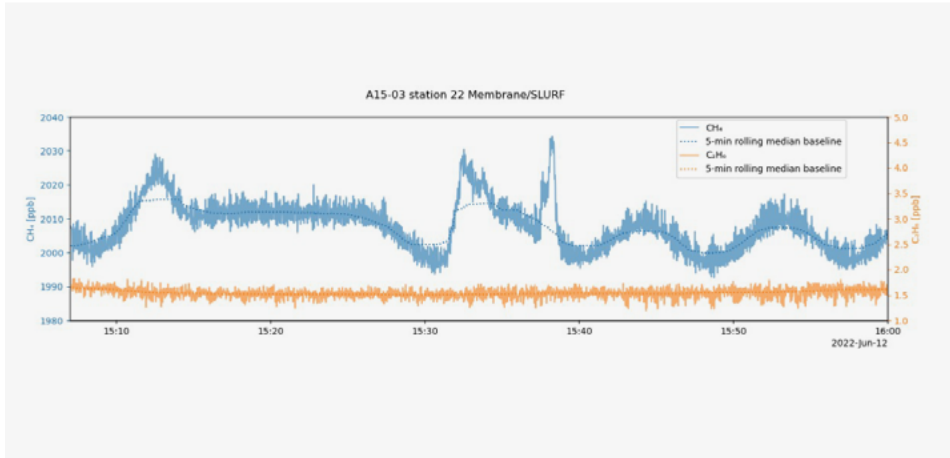


Figure 8-10: *Concentration CH_4 and C_2H_6 around A15-03, with the peaks on top of the background atmospheric concentration showing CH_4 enhancements.*

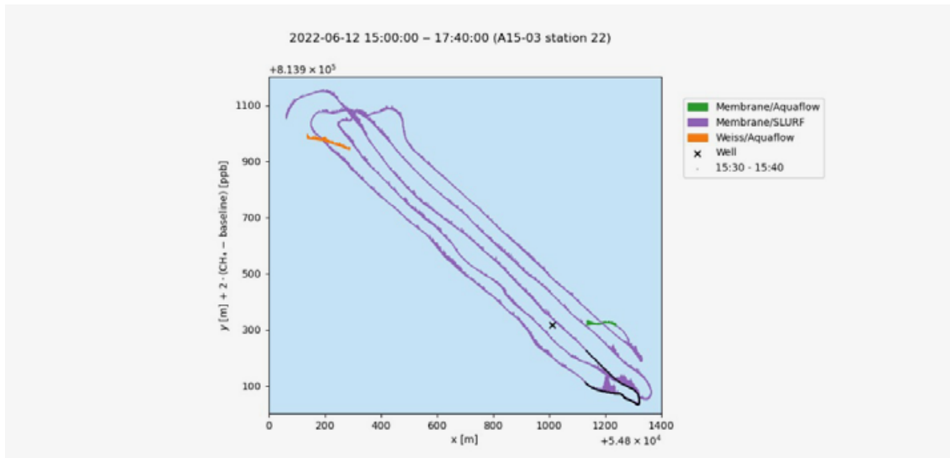


Figure 8-11: *Concentration CH_4 plotted at the track around A15-03. Every ppb at the baseline is projected as 2m.*

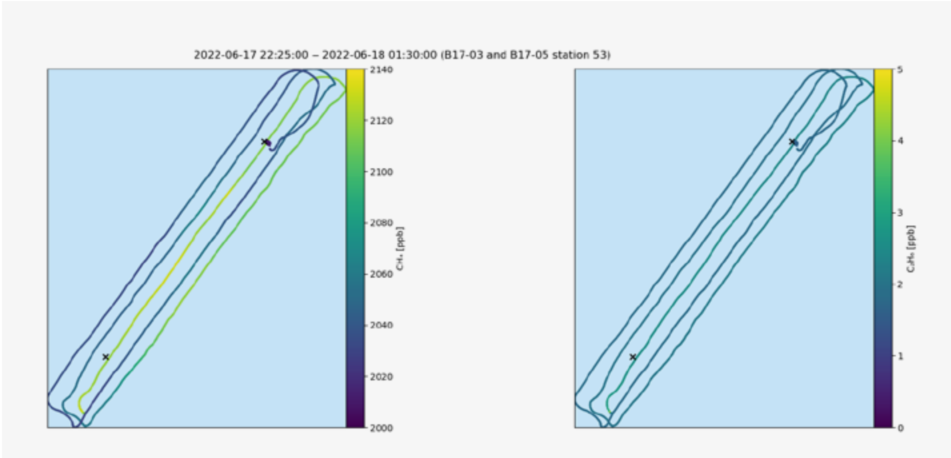


Figure 8-12: *Concentration CH_4 and C_2H_6 measured by using the SLURF and the membrane, around B17-3 and B17-05 (pointed with x).*

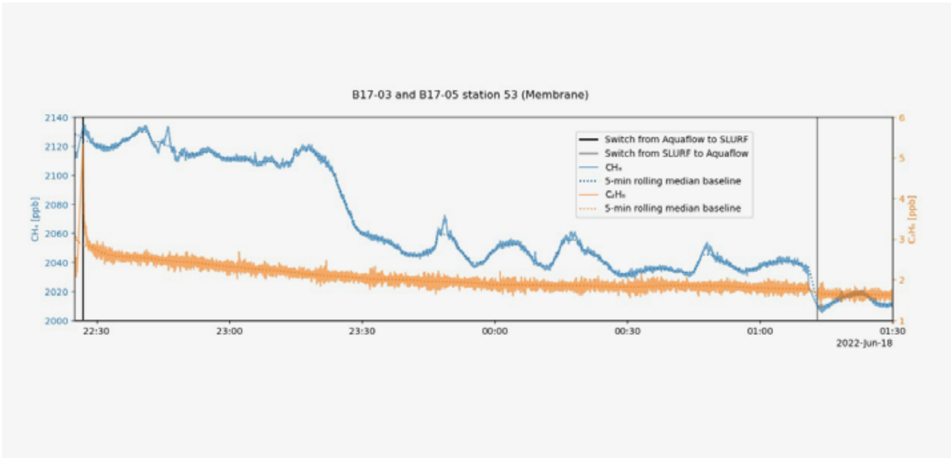


Figure 8-13: *Concentration CH_4 and C_2H_6 around B17-03 and B17-05, with the peaks on top of the background atmospheric concentration showing CH_4 enhancements.*

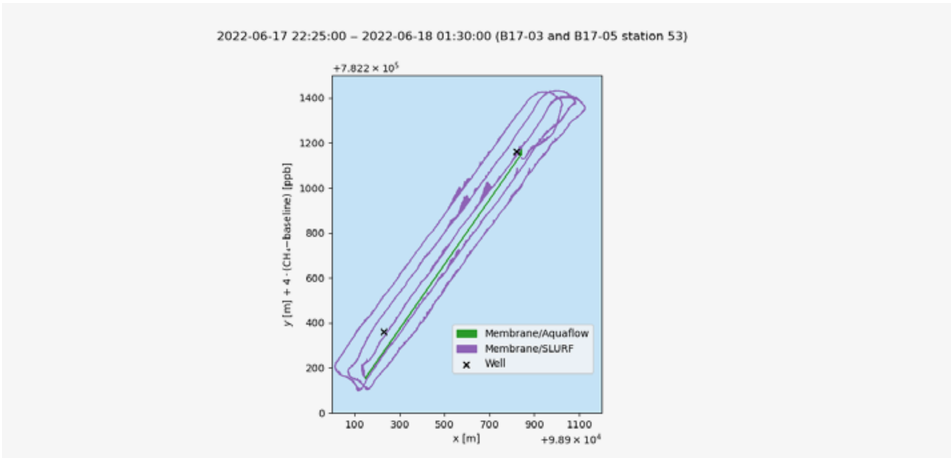


Figure 8-14: *Concentration CH_4 plotted at the track around B17-03 and B17-05. Every ppb at the baseline is projected as 4m.*

At F01-01 no methane enhancements were seen with the SLURF based measurements (Figure 8-15 to Figure 8-17). This is also the well that had a very small bubble plume and several on the MBES-data. Furthermore, at B13-01 and B17-04 methane peaks were shown (Figure 8-18 to Figure 8-23), at F17-14 no methane enhancements were seen with the SLURF based measurements (Figure 8-24 and Figure 8-25).

No ethane was detected at all the bubble-plume locations, indicating that the bubble plumes did not contain thermogenic gas. When sailing in the vicinity of a pipeline, methane and ethane were shown simultaneously, showing that it is possible to measure thermogenic gas coming from the sea floor, with the applied method. Below the resulting methane peaks from the six wells with bubble plumes and the three locations with bubble plumes in the vicinity of the wells are shown.

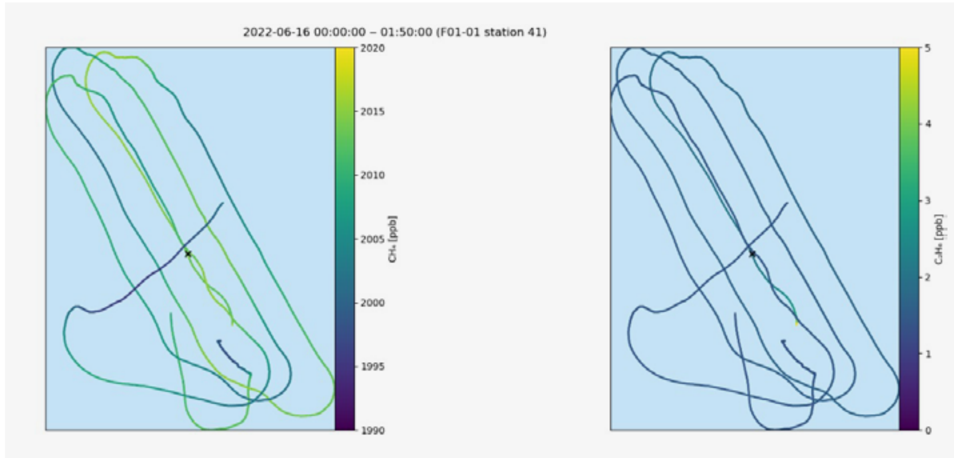


Figure 8-15: *Concentration CH_4 and C_2H_6 measured by using the SLURF and the membrane, around F01-01 (pointed with x).*

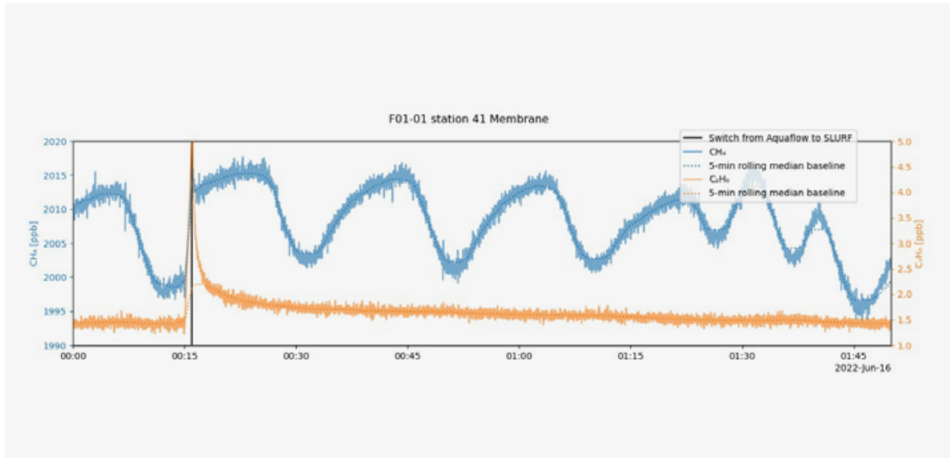


Figure 8-16: *Concentration CH_4 and C_2H_6 around F01-01, without peaks on top of the background atmospheric concentration indicating no CH_4 enhancements.*

Figure 8-17: *Concentration CH_4 plotted at the track around F01-01. Every ppb at the baseline is projected as 16 m.*

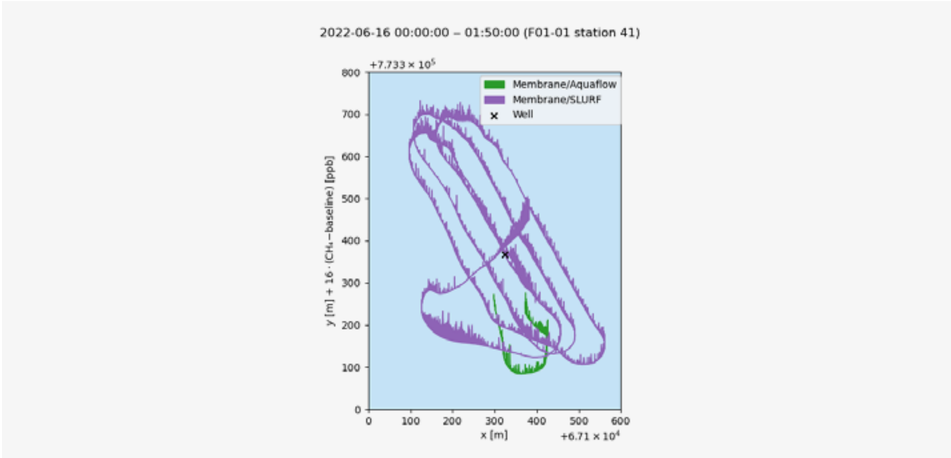


Figure 8-18: *Concentration CH_4 and C_2H_6 measured by using the SLURF and the membrane, around B13-01 (pointed with x).*

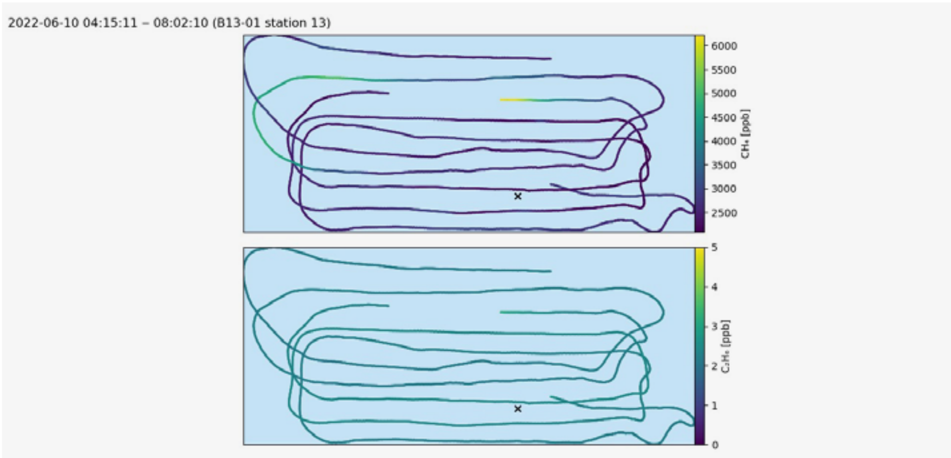


Figure 8-19: *Concentration CH_4 and C_2H_6 around B13-01, with the peaks on top of the background atmospheric concentration showing CH_4 enhancements.*

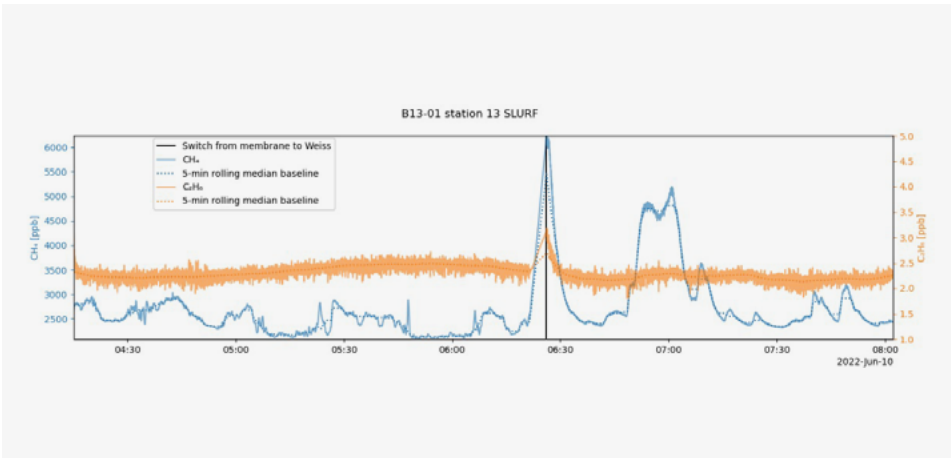


Figure 8-20: *Concentration CH_4 plotted at the track around B13-01. Every ppb at the baseline is projected as 0.05m.*

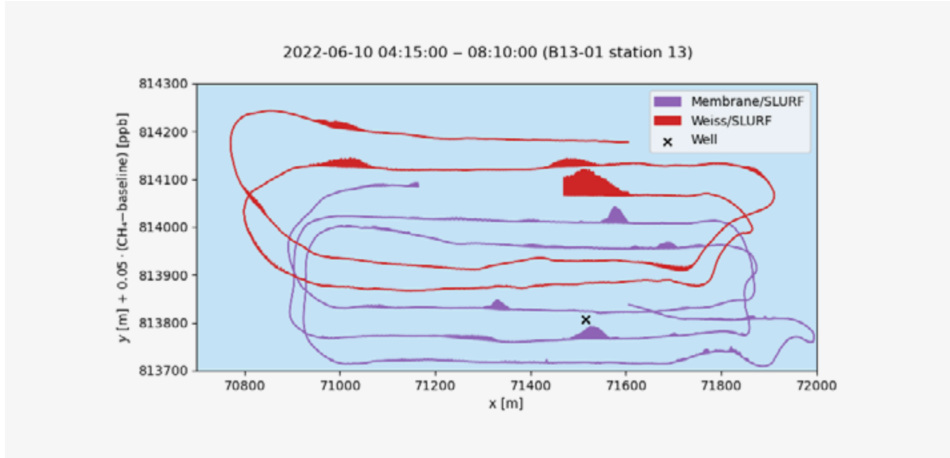


Figure 8-21: *Concentration CH_4 and C_2H_6 measured by using the SLURF and the membrane, around B17-04 (pointed with x).*

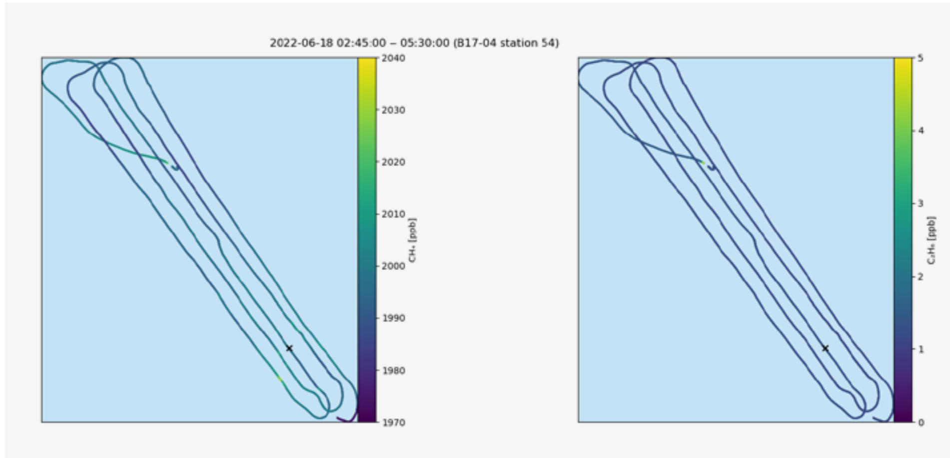
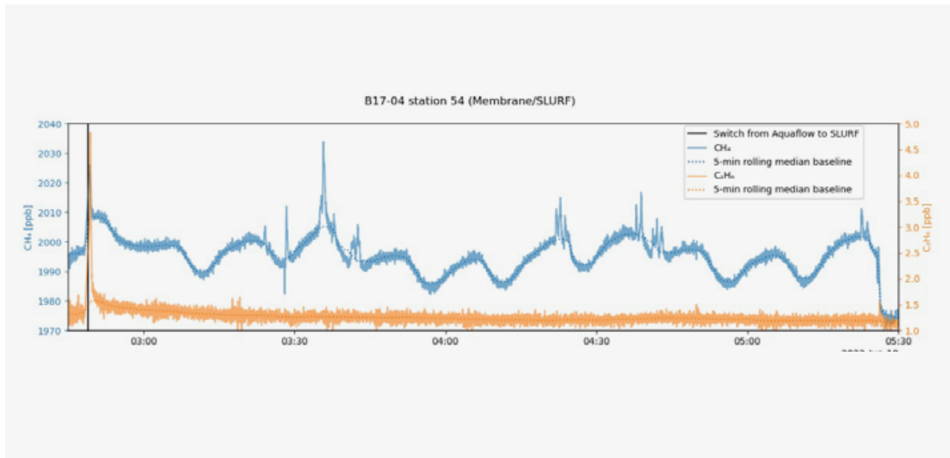


Figure 8-22: *Concentration CH_4 and C_2H_6 around B17-04, with the peaks on top of the background atmospheric concentration showing CH_4 enhancements.*



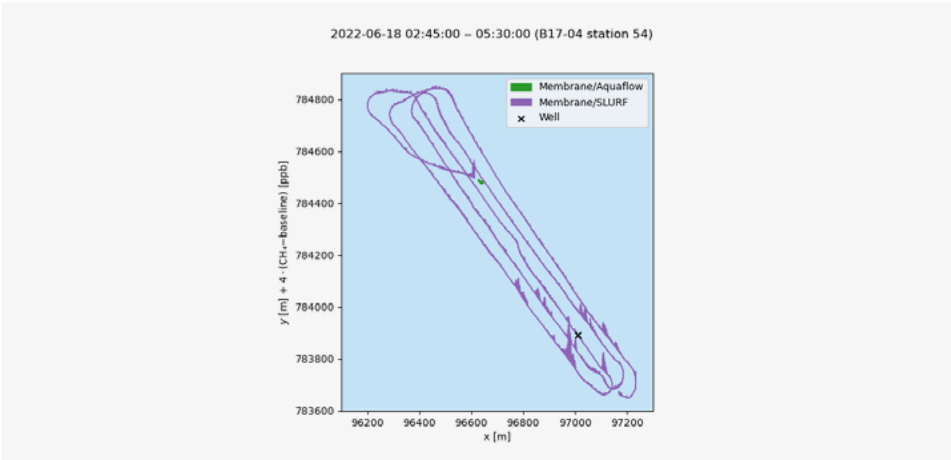


Figure 8-23: *Concentration CH_4 plotted at the track around B17-04. Every ppb at the baseline is projected as 4m.*

Figure 8-24: *Concentration CH_4 and C_2H_6 measured by using the SLURF and the membrane, around F17-14.*

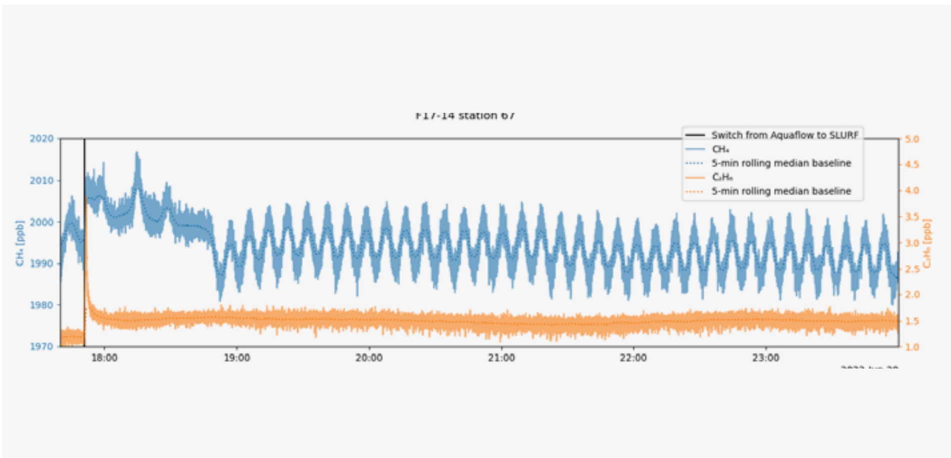


Figure 8-25: *Concentration CH_4 and C_2H_6 around F17-14, without peaks on top of the background atmospheric concentration indicating no CH_4 enhancements.*

8.4 CTD results

In contrast, methane concentrations determined with the head space technique were often one order of magnitude lower than the LMS data, in particular for high methane concentrations. We investigated the cause of these rather counterintuitive results and found that the pH of the head space samples was that of regular sea water (i.e. ~8) providing evidence that the samples were not fixed appropriately, i.e., they did not contain the required sodium hydroxide. At this point, we cannot explain why this crucial step was missed out at sea and for now decided to omit data obtained on the discrete samples. In the following campaigns, we will impose more strict control mechanisms to avoid this.

8.5 Estimation of methanotrophic activity

Aerobic methane oxidation was measured using a radio isotope approach (Niemann et al., 2015). For this, discrete water samples were filled headspace-free into glass vials and capped with halogenated butyl stoppers. After the campaign we then added trace amounts of tritium-labelled methane and determined first order rate constants from the fractional turnover of the added tracer (the framework of the campaign did not allow to take the required personnel and technical equipment on board that is required for working with radio isotopes at sea; this will be done in the following campaigns).

The measurements of the potential for aerobic methane oxidation revealed first order rate constants varying from 0 to 0.051 d-1 (Figure 8-26). These values are in comparison to highly active seeps relatively low (Menoud et al., in review). We could not find a correlation between ambient methane concentration and first order rate constant. This might simply be related to the fact that the samples were incubated ~2 weeks after sampling, or that indeed the potential for methane oxidation at the wells is rather low, which would be in line with the limited ebullition observed. In the upcoming campaigns, we will address this by incubating samples immediately after recovery of seawater.

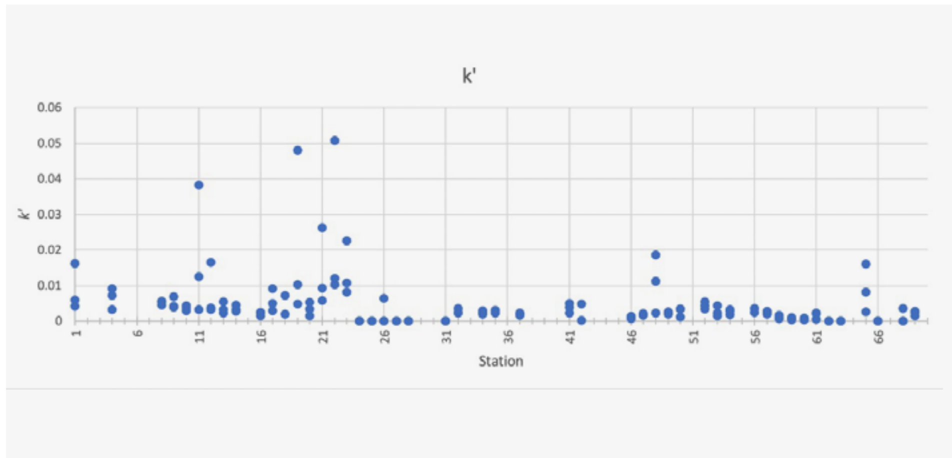


Figure 8-26: *Potential for aerobic methane oxidation depicted as first order rate constants*

9 Methane in the atmosphere

Methane and carbon dioxide were measured continuously during the expedition using a Picarro G2301 (Figure 9-1). The goal was to detect methane in the atmosphere as a background. This set-up is not capable of measuring methane coming from natural seepage or well leakage. Transport of methane from land, depends on the wind direction and is expected to be larger than methane emission from the seawater, as this is much more diffuse.

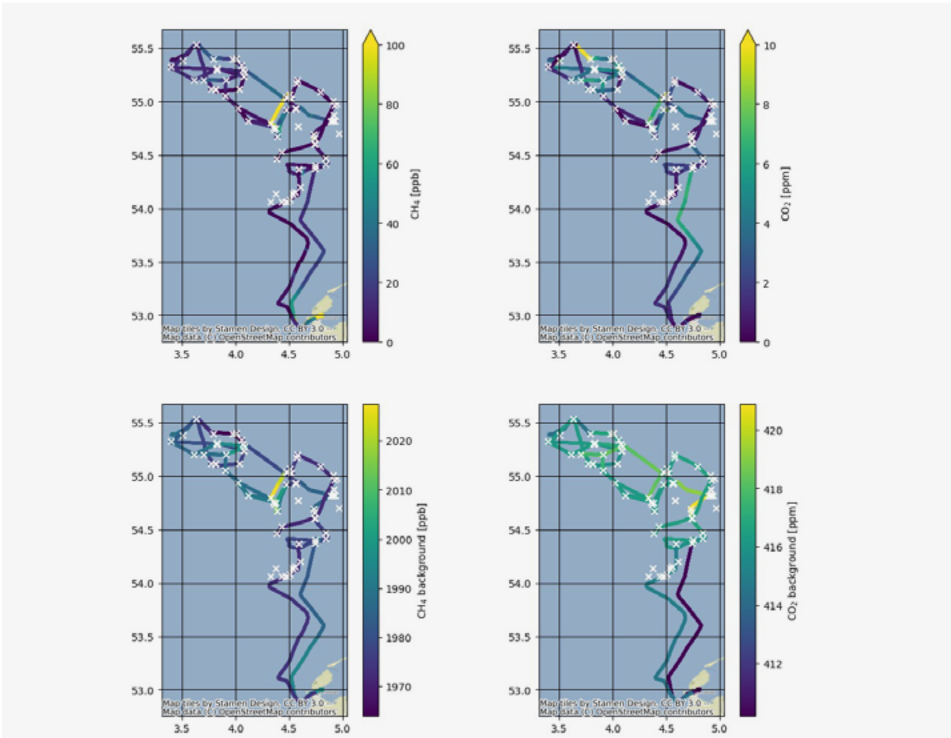


Figure 9-1: *Overview of atmospheric CH_4 and CO_2 concentrations during the cruise, including the visited locations. The upper figures show the concentrations with subtractions of the background concentrations. The lower figures show the total measured concentration (including the background concentrations).*

When we plot (Figure 9-2) the methane concentrations in parts per billion (ppb) over time we see that the background values are around 1980 to 2000 ppb, and that several broad peaks and numerous spikes are measured. When we highlight the bubble plumes locations in this plot, we don't see a correlation between the atmospheric methane concentration and bubble plume observations.

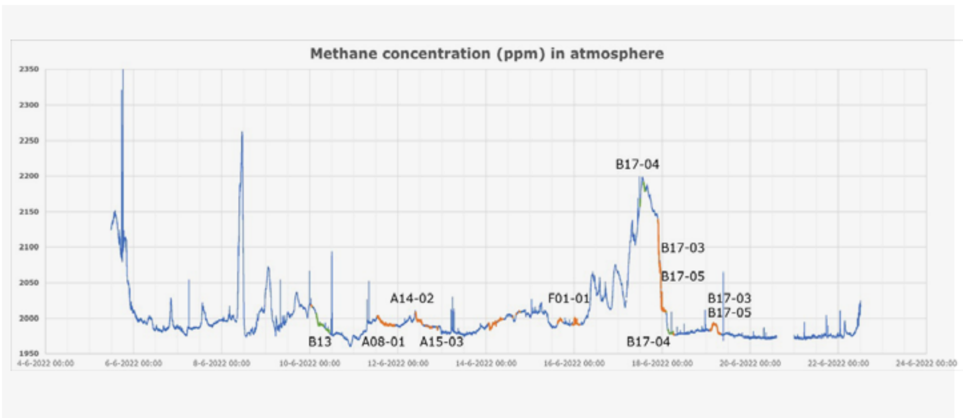


Figure 9-2: *Atmospheric methane concentration as a function of time. The orange highlighted parts are measured in the vicinity of wells with a bubble plume at the well head and not in the surrounding area. The green highlights are measurements in the neighborhood of wells that have no bubble plume at the wellhead, but bubble plumes are found in the vicinity.*

The broad peaks in the methane concentration are probably linked to transport of methane from land. Therefore a transport model could be used for better clarification, but that is outside the scoop of this study. The cause of the spikes is unknown at this point. In some case spikes in the methane concentration could be linked to spikes in CO_2, which corresponds to the ships exhausts gasses being measured.

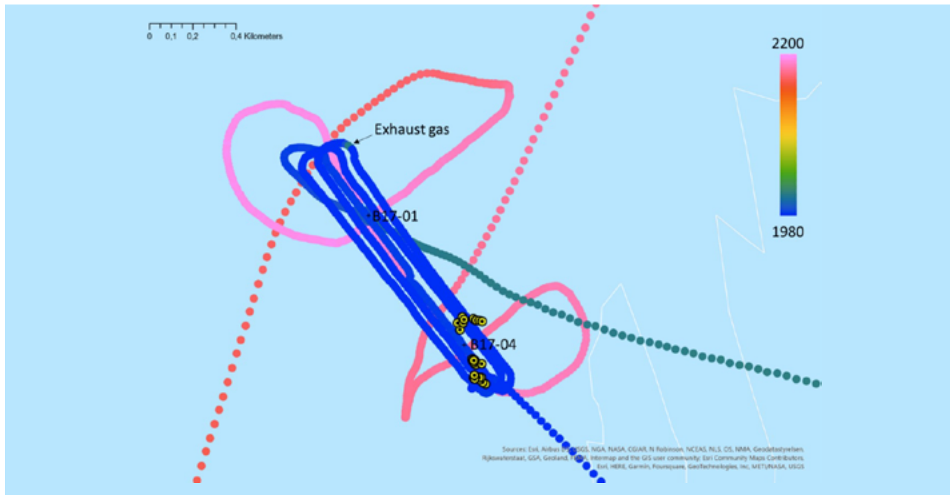


Figure 9-3: *Methane concentrations were measured twice at B17-01 and B17-04. During the first visit the concentrations were high during the entire visit, and low during the entire second visit. No local elevated methane concentration above the many plumes was detected.*

Figure 9-4: *Methane concentrations around the A08-01 well are not varying a lot over time. Left: methane concentrations with the color bar scaled to the lang term maximum and minimum of the methane concentration. Right: the same methane concentration data with the color bar scaled to the data range around A08-01. Note that the methane values are very slowly changing and only about 15 ppm.*

At the bubble plume locations we do not see a local rise in methane concentration around the plume(s). For example, we measured the methane concentrations at B17-01 and B17-04 twice (Figure 9-3). During the first visit the methane concentrations were high (around 2200 ppb) the entire time and during the second visit the methane concentrations were low (around 2000 ppb) the entire time. Small peaks were caused by the exhaust gasses of the ship, but no elevated methane concentrations are found around the bubble plumes. This is also the case at all the bubble plume locations. At A08-01 for example (Figure 9-4) we find that the methane concentrations slowly changes about 15 ppb (1985 to 2000), but no detectable change of methane concentrations are found near the bubble plume. This confirms that the atmospheric measurements at 10 m above sea level (which are not Eddy Covariance measurements) cannot detect the fluxes from the sea surface. It shows transport of methane from other sources (mostly land based or from offshore production platforms).

10 Synthesis and discussion

10.1 Presence of methane sources at wells with bubble plumes

At the 6 wells (see Table 3-1) that have only a bubble plume at the wellhead, only shallow gas has been identified as a potential source (Figure 10-1). The sub bottom profiler results show that Holocene peat layers are not present at these 6 wells. The wells are not drilled through tunnel valleys, but in case of A15-03 a tunnel valley is located in the vicinity. Four of the wells were targeting deep strata that could in theory leak thermogenic gas. However, only methane was observed with the laser spectrometer at all bubble plume locations and ethane, an indicator for the presence of thermogenic gas, was not encountered. Moreover, 2 wells only targeted the Middle North Sea Group, so the chance for encountering thermogenic gas in these wells is low (de Bruin et al, 2022).

Figure 10-1: *Potential biogenic and deep sources encountered at the wells with a bubble plume, the relationship between the well and the bubble plume and the working hypothesis.*

			Relation well to plume		
Well	**Sources**	**Deep**	**Distance**	**At well**	**Away from**
A08-01	● ○ ○	●	8	●	○
A14-02	● ○ ○	●	3	●	○
A15-03	● ○ ○	○	2	●	○
B17-03	● ○ ○	●	23	●	○
B17-05	● ○ ○	○	2	●	○
F01-01	● ○ ○	●	5	●	○
B13-01	● ● ●	●	150	○	●
B17-04	● ○ ○	●	74	○	●
F17-14	○ ○ ●	?	240	○	●

● Shallow Gas
● Tunnel Valleys
● Peat (to be confirmed)
● Present
○ Absent

10.2 Hypotheses for the six wells with bubble plume at the wellhead

We start with the six wells (see Table 3-1) that have a bubble plume only at the wellhead and not further away from the well (Figure 10-2). By power of deduction, well leakage of shallow gas is the only remaining hypothesis. We disprove the other hypothesis based on the following findings.

Natural Seepage

We disprove natural seepage because the pre-drilling surveys showed no evidence of bubble plumes before drilling and the drilling practice is to avoid shallow gas near the seafloor (i.e. a single bubble plume would be very easy to avoid so this would have been done by drillers). Consequently, it is highly unlikely that the bubble plumes at the six wells are caused by natural seepage. Furthermore, natural seepage is characterized by numerous bubble plumes spread over an area. The fact that there are only plumes observed at the well heads disproves the hypothesis that this is natural seepage.

Leakage from peat, tunnel valleys or deep thermogenic reservoirs

All these wells were only drilled through shallow gas, with no other sources encountered. This disproves the hypotheses that the plumes are caused by peat layers, or tunnel valleys. No ethane was measured so this rules out leakage from a deep thermogenic source. Consequently, the only hypothesis that remains is well leakage of shallow gas. The leakage mechanism remains to be proven by studying the well construction, well integrity, well design, drilling practices and abandonment procedures). Böttner et al. (2020) and Vielstädte et al. (2017) propose that "gas migration is likely focused along drilling-induced fractures around the borehole". Wilpshaar et al. (2021) disputes this, and recent literature study (Tsopela et al., 2022) confirms that drilling induced fractures are very unlikely to be the migration pathways for (shallow) gas. The main reason for this is that shallow sediments deform in a ductile manner. Therefore, it is highly unlikely that fractures form. Even when rocks are sufficiently consolidated (brittle), fractures only occur when the drilling fluid (mud weight) is too heavy during drilling. However, these drilling conditions are not typically found at shallow intervals. Finally, no published cases were found of gas migration through drilling induced fractures (in deeper, consolidated intervals).

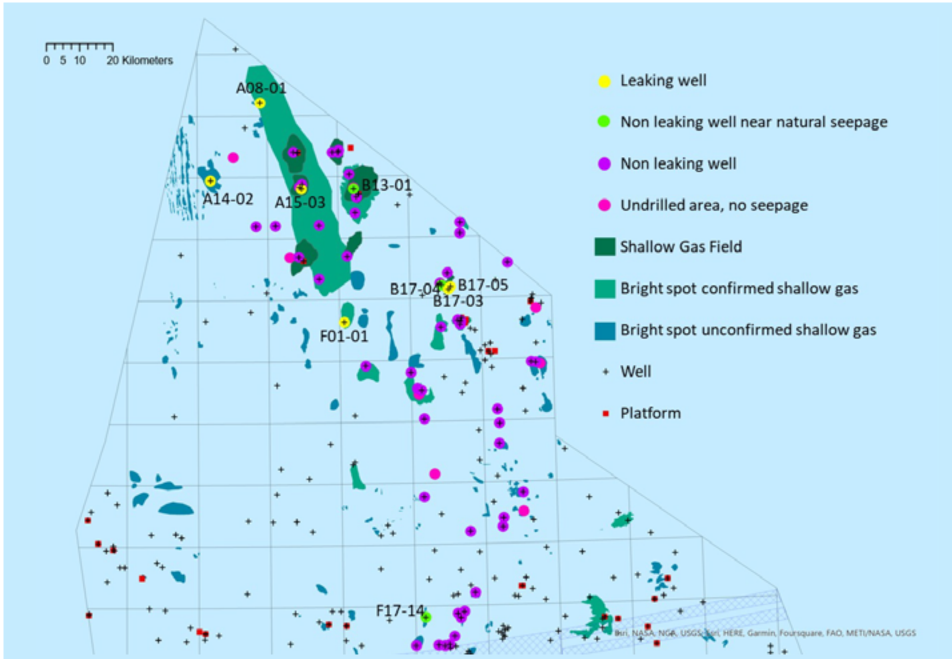


Figure 10-2: *Hypotheses for all surveyed locations.*

10.3 Hypothesis for B13-01

At well B13-01 no bubble plume was observed at the wellhead, but numerous plumes were observed at a distance. These plumes have been studied before by Römer et al 2017, and the consensus is that these plumes are part of a large natural seepage area. We agree that the most likely hypothesis for these plumes is that they are caused by *natural seepage of shallow gas*. We conclude this based on the several observations and falsification of all other hypotheses:

- Multibeam echosounder data: At the well head itself no bubble plume was found. To the north of the well numerous bubble plume were found. The clos-est is 150 m away from the well. We exclude well leakage since it is more like-ly to occur at the wellhead.
- Seismic and wells: The bubble plume clusters are located above a producing shallow gas field. There are several large bright spots related to shallow gas, and shallow gas was encountered during drilling.

- Slurf spectrometer data: Peaks of methane were observed. Only methane (no ethane) was observed in the water, excluding a thermogenic source.
- Sub bottom profiler data: The SBP focused on the well. No peat layers were found at the well and SBP data was not available for the bubble plume loca-tions.
- Literature: The B13 seepage site has been studied intensively and the con-sensus is that the bubble plumes are caused by natural seepage from shallow gas. However, peat layers and tunnel valleys are potentially present too.

Based on these observations we concluded that *natural seepage of shallow gas* is the most likely hypothesis for this location.

10.4 Hypothesis for B17-04

At well B17-04 no bubble plume was observed at the wellhead, but numerous plumes were found surrounding it. B17-04 hosts an interesting geological history (see section 4.4). The well is drilled through a chimney, originating from a naturally leaking shallow gas reservoir. The most likely hypothesis for these plumes is that they are caused by *natural seepage of shallow gas*. We conclude this based on the several observations and falsification of all other hypotheses:

- Multibeam echosounder data: At the well head itself no bubble plume was found. Surrounding the well numerous bubble plume were found. The closest is 74 m away from the well. We exclude well leakage since it is more likely to occur at the wellhead.
- Seismic and wells: The bubble plume clusters are located above a seismic chimney (vertical disturbed zone, indicating vertical gas migration). Natural seepage from shallow gas is therefore a valid hypothesis. No tunnel valleys were encountered and therefore they are not considered the source for the bubble plumes.
- Slurf spectrometer data: Peaks of methane were observed. Only methane (no ethane) was observed in the water, excluding a thermogenic source.
- Sub bottom profiler data: No peat layers were encountered, excluding peat as a source.
- Literature: The B17 seepage has not been studied to our knowledge.

Based on these observations we concluded that *natural seepage of shallow gas* is the most likely hypothesis for this location.

10.5 Hypothesis for F17-14

In the vicinity of F17-14 several plumes were observed. The most likely hypothesis for these plumes is that they are caused by *natural seepage of peat layers*. We conclude this based on the several observations and falsification of all other hypotheses:

- Multibeam echosounder data: At the well head itself no bubble plume was found. Several bubble plume were found in the vicinity. The closest is 240 m away from the well. Well leakage is more likely to occur at the well and is therefore unlikely. The number and the size of the bubble plumes is small in comparison to the B13 and B17 seepage site.
- Seismic: The bubble plume clusters are not located above a bright spot, and shallow gas is therefore not a likely source.
- Well data: the well data was confidential at the time of writing.
- Slurf spectrometer data: No peaks of methane were observed, which is ex-pected when dealing with small bubble plumes.
- Literature: TNO study identified Basisveen in the area.

Based on these observations we concluded that *natural seepage of peat layers* is the best fitting hypothesis. However, this is concluded on limited amounts of data. We recommend obtaining additional data to proof this hypothesis.

10.6 Methane in water and the atmosphere

When we combine the observations of the bubble plumes with the measurements made with the Methane sensor (LMS) and Slurf based measurements, no correlation is observed (Figure 10-3). Only at B13-01 we see many plumes, and high concentrations in both the methane sensor and Slurf data. At five of the six wells for which we concluded that leakage is likely, the methane sensor finds low methane concentrations (background values), or even below the detection limit. It is important to note that bubble plumes are a point-source of methane and the chance that the background methane concertation is measure is very high. Bubble plumes and dissolved methane is transported by currents, so only when the measurements are taken down stream of the plume, higher methane concentrations are detected. This could explain the relatively low methane concentrations in the water. Our measurements are comparable to those of Römer et al. (2021) who measured in the B13 are and in a neighboring area in the German sector of the North Sea.

Atmospheric methane is mainly high at the wells B17 wells, but this is likely to be caused methane transport from land and not by methane from the observed bubble plumes. The current Picarro setup is not capable to differentiate between lateral methane transport and vertical methane transport caused by local emission (natural seepage or well leakage). Laterally methane transported is driving the variations in measured methane concentrations, overshadowing a possible local source. Methane from the sea surface is more diffuse. In order to differentiate between vertical transport (from bubble plumes) and horizontal transport (from land or platforms) Eddy Covariance measurements should be done, but that is quite challenging for a moving vessel (a lot of corrections for motion are needed) and with relatively low methane concentration differences.

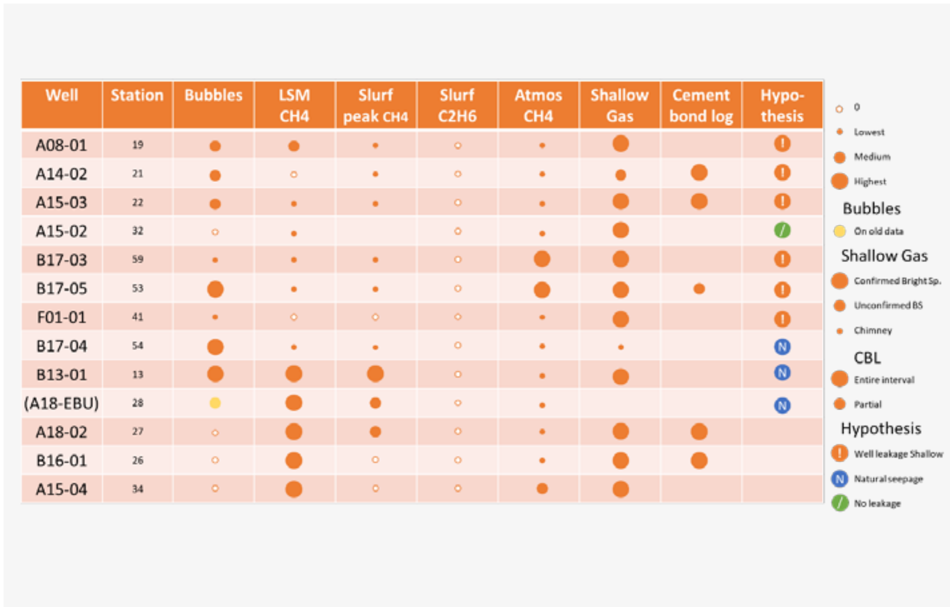


Figure 10-3: *Overview of the main results of phase 1 of the project.*

10.7 Statistical analysis of well leakage

Before extrapolating our observations to a larger area to infer the chance of well leakage to occur, we need to consider the possibility of missing leaking wells (false negative) during the survey and/or misidentifying wells as leaking that are actually not leaking (false positive) as this could potentially introduce a systematic bias that cannot be accounted for by statistics. A false positive could be caused by for instance a school of fish, or another unknown acoustic artefact being interpreted as a bubble plume at a wellhead. Chances on such a false positive are extremely small since the chances of these occurring at exactly the location of a wellhead is small, and it reoccurring during subsequent passes over the wellhead is proportionally more rare. Also, the chance on a false negative, missing an actually leaking well, is small because of the repetitive observations . Temporal changes could still interfere with our observations, but even when a leaking well is not constantly leaking (but has an intermittent flux implying bubble plumes to be present only part of the time) the overlapping MBES-swaths also guarantee at least some temporal coverage. 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. These prolonged recordings (tens of minutes) at the wellhead imply that only intermittency with a very long down time would result in a false negative. Also, Accordingly, the chance that an intermittently leaking well is missed is very small. We are therefore confident that we can rule our both false positives and negatives with regard to the surveys and can treat the data and hence statistics without having to consider a systematic bias.

Our results show that six of the 33 wells drilled through shallow gas are leaking. This is 18% of the wells drilled through shallow gas. Using the Wilson score interval (Wilson, 1927) compensated for a finite population (i.e. there is a finite number of wells) we calculated the binomial proportion confidence interval for the probability of leakage (see Figure 10-4, Table 10-1). At the 90% confidence level, the estimated range for true probability of leakage is between 9 to 32%, which implies that there is 90% likelihood that the minimum leakage is between these two values. Our statistics show that wells drilled through shallow gas have a higher chance of leakage compared to wells not drilled through shallow gas, which showed no leakage in our survey. However, as the relative amount of wells not drilled through shallow gas was much smaller, some leakage occurring in these wells cannot be fully excluded. In the vicinity of 4 of the 6 presumed leaking wells (A18-01, A15-03, B17-03, B17-05) we found other, non-leaking wells (A12-03, A15-02, A15-05, B17-06), that were drilled through the same shallow gas accumulations. In 3 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 does not necessarily result in wellhead leakage. A properly closed abandoned well, with a good design, drilled, completed, and abandoned, apparently does not have to result in ebullition. The occurrence of wellhead leakage is clearly avoidable. Further investigation is needed what the correct measures are to avoid wellhead leakage.

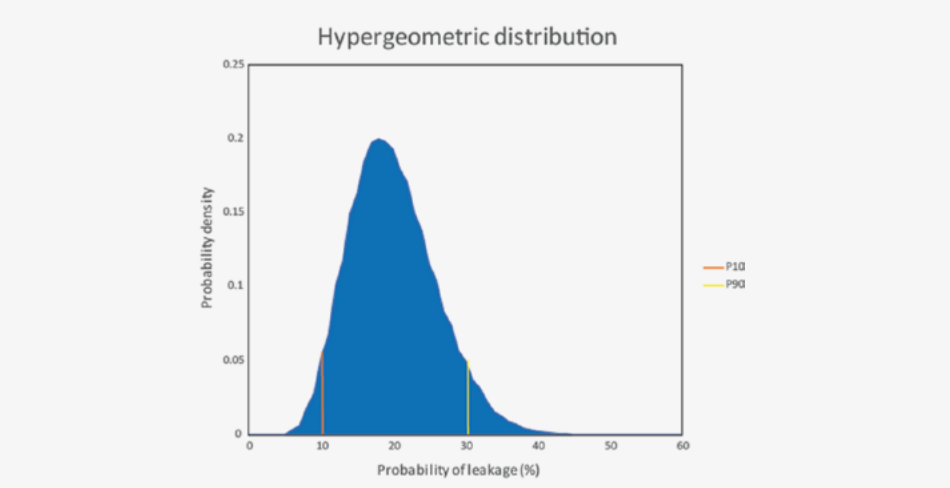


Figure 10-4: *Wilson (1927) distribution curve for the probability of leakage of wells drilled through shallow gas. The confidence interval shows typical skewing towards the positive side, albeit with a limited range.*

	Leakage probability range
Observed	18 %
1 standard deviation (68.2 %)	12 to 26 %
90 % confidence level	9 to 32 %
2 standard deviations (95.4 %)	8 to 35 %

Table 10-1: *Statistical probabilities of leakage of wells drilled through shallow gas found for our sample set.*

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

Table 10-2: *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)*

The fact that wells drilled through shallow gas have a higher chance of leakage needs to be taken into consideration when calculating leakage percentage for all wells. From the surveyed wells 58% is drilled through shallow gas, whereas for the entire Dutch North Sea the percentage of wells drilled through shallow gas is only 11%. Accordingly, since we found that about 18% of all surveyed wells drilled through shallow gas are leaking, we predict that 23 of the 153 wells drilled through shallow gas leak, which is less than 2% of all wells (1450 excluding side tracks) in the Dutch North Sea (see table 2).

10.8 Statistical comparison with previous studies

The here presented research is a direct result of parliamentary questions following publications by Böttner et al. (2020) and Vielstädte et al. (2017). Böttner et al. (2020) found a bubble plume at 28 out of the 43 wells that were investigated by them. These observations are based on investigations in the UK sector of the North Sea. Of the 28 wells with a bubble plume at the wellhead, 8 were drilled through shallow gas, 13 were drilled less than 300 m away from shallow gas, and 7 were drilled more than 300 m from shallow gas (max 1000 m) (Tab. 9-1). The wells that had no bubble plume were drilled at a distance of 300 to 3300 m away from shallow gas. From these findings, the following conclusions were drawn:

1. All wells (100%) drilled through shallow gas leak.
2. All wells (100%) drilled within 300 meters of shallow gas leak at the wellhead
3. Wells drilled up to 1000 m from shallow gas have a high risk of leakage (at the wellhead).
4. Wells drilled more than 1000 m from shallow gas do not leak.

Inspecting 54 wells and 9 references areas we find that of the 33 wells drilled through shallow gas, only 6 are likely caused by well leakage, while 27 wells do not leak (Table 10-1: Summary of results on bubble plume observations at North Sea wellheads from the present study, Böttner et al. (2020) and Römer et al. (2021).). All wells in this survey that were not drilled through shallow gas are not leaking.

There is a striking difference between our findings and those of Böttner et al. (2020). Böttner et al. (2020) did not investigate the cause of the bubble plumes and assumed that they are all caused by drilling induced fractures along the well. Ruling out other possible causes of methane ebullition is essential. In our case, this led to the conclusion that the bubble plumes of 6 wells are most likely caused by (conventional) well leakage, while we categorized 3 wells as a non-leaking well ('No plume' in the table below) since natural seepage was found in the vicinity, but no plume was detected at the well itself. Our statistics show that wells drilled through shallow gas appear to have a higher chance of leakage. However, at 4 of the 6 presumed leaking wells (A18-01, A15-03, B17-03, B17-05) we found other non-leaking wells (A12-03, A15-02, A15-05, B17-06) that were drilled through the same shallow gas accumulations (in 3 cases those were proven shallow gas fields, i.e. large quantities of shallow gas are proven to be present). From this we conclude that the presence of shallow gas itself is not the biggest risk factor, but the way wells are designed, drilled, completed, and abandoned.

Table 10-2: *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)*

	This study			
Well	Number	Plume	No plume	Percentage with plume
Drilled through Shallow gas	33	6	27	18%
Drilled < 1000 m from shallow gas	8	0	8	0%
Drilled > 1000 m from shallow gas	16	0	16	0%
Total	**57**	**6**	**51**	**11%**

	Böttner et al., 2020			
Well	Number	Plume	No plume	Percentage with plume
Drilled through Shallow gas	8	8	0	100%
Drilled < 1000 m from shallow gas	30	20	10	67%
Drilled > 1000 m from shallow gas	5	0	5	0%
Total	**43**	**28**	**15**	**65%**

	Römer et al., 2021			
Well	Number	Plume	No plume	Percentage with plume
Drilled through Shallow gas	6	0	6	0%
Not drilled through shallow gas	4	0	4	0%
Total	**10**	**0**	**10**	**0%**

Römer et al. (2021) found many bubble plumes (166) in the "Entenschnabel" area (Part of the German North Sea, bordering our study area). They concluded that all plumes were natural since no plumes were detected at the wellheads of any of the 10 surveyed wells. The distance from the wellhead to the nearest bubble plume was 125 to 9,500 m. Of these 10 wells, six were "underlain by bright spots (Under German mining laws, all data collected by oil and gas companies stays confidential and cannot be freely accessed as is the case in the Netherlands. Exact well trajectories are likely not available for research). In the vicinity of all the six wells associated with bright spots bubble plumes were observed, while no plumes were observed in the vicinity of the four wells that are not associated with bright spots.

The findings of this study are that 11% off all wells are leaking, while Böttner et al. (2020) finds 65%, and Romer et al. (2021) finds 0% of all wells to be leaking. When we specifically look at wells drilled through shallow gas, we find that 18% is leaking, Böttner et al. (2020) finds that 100% is leaking, while Römer et al. (2021) finds 0% of the wells to be leaking. The fact that these numbers are so different from each other cannot be explained at this moment.

10.9 Well leakage and methane concentration in seawater

The methane concentration in the water at the leaking wells seems not to be elevated in comparison to non-leaking wells. A map plotted by taking the highest value that was measure at each location (in most cases the deepest measurement) and interpolating in between these measurements (see Figure 10-5) shows that the methane concentrations seem to be stable over larger areas. These higher concentrations seem independent of the presence of plumes. For example A15-02 (non-leaking) and A15-03 (plume) are 800 meters apart and have identical methane concentrations of about 11 nM. This is comparable to the background measurements (9 nM) that Römer et al. (2021) found in Germany, roughly 30 km from these wells and slightly above the 6 nM background measurement that we did at F08. Römer et al. (2021) also found that the methane concentrations were stable over larger areas (i.e. over a distance of more than 1 km), also independent of bubble plume occurrences. The B17 wells (B17-03 plume, B17-04 natural seepage, B17-05 plume, and B17-06 no leakage) show all similar numbers. At A14-02 methane concentrations are below the detection limit, which is also true for the 5 locations east of that well. Overall a W-E band of points is observed, characterized by concentrations below the detection limit. These locations are all located within the shallowest part of the Doggerbank (see Figure 10-6). We observed highest methane concentrations in the water column at the B13 natural seepage site and at wells where we could not find bubble plumes in the water column (A18-B16 area). West of the A18-02 well natural seepage has been identified on previous collected side scan sonar data (TNO archives), although at these locations no bubble plumes were identified during the current measuring campaign. This suggests that here methane release may be fluctuating over time.

10.10 Relationship well leakage and generation of shallow gas

When we look at the depth of the base of the Upper North Sea Group (NU), which is a proxy of the thickness of the NU, we find that all wells that are leaking are found in the part were the NU almost is at it thickest (see Figure 10-7). When we model the temperatures within

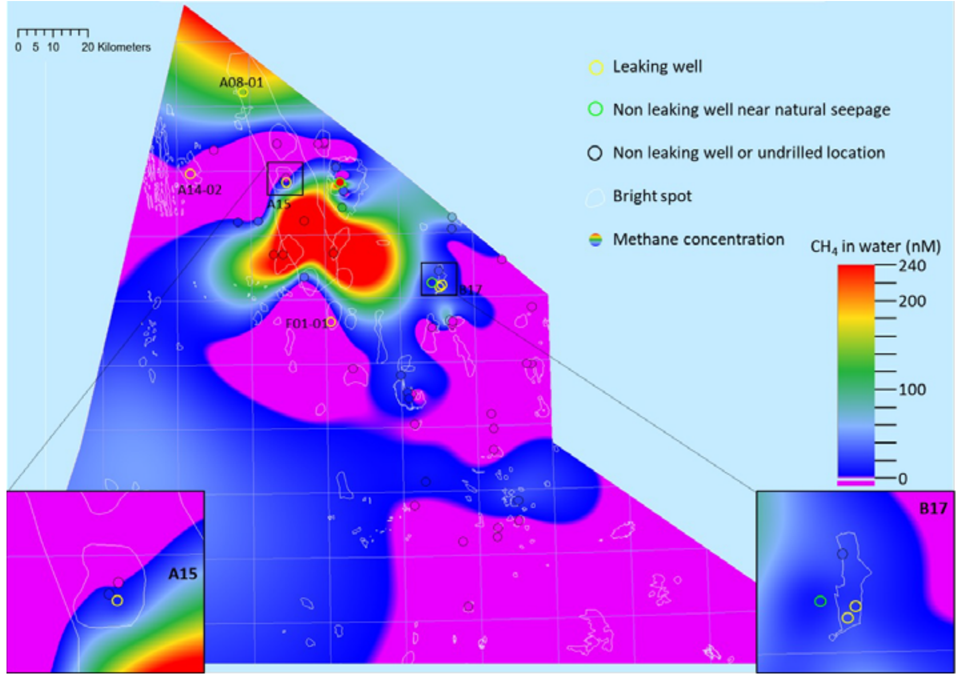


Figure 10-6: *Measured methane concentrations (in nM) measured with the Franatech Methane sensor. We plotted the maximum of the 4 measurements taken at different depth and interpolated in between. The circles show the location of measurement, and the color is representing the methane concentration. Purple is below detection limit, blue is low, red is high. The map is an interpolation (isochore interpolation) in between these points. The leaking wells are indicated by a yellow outline.*

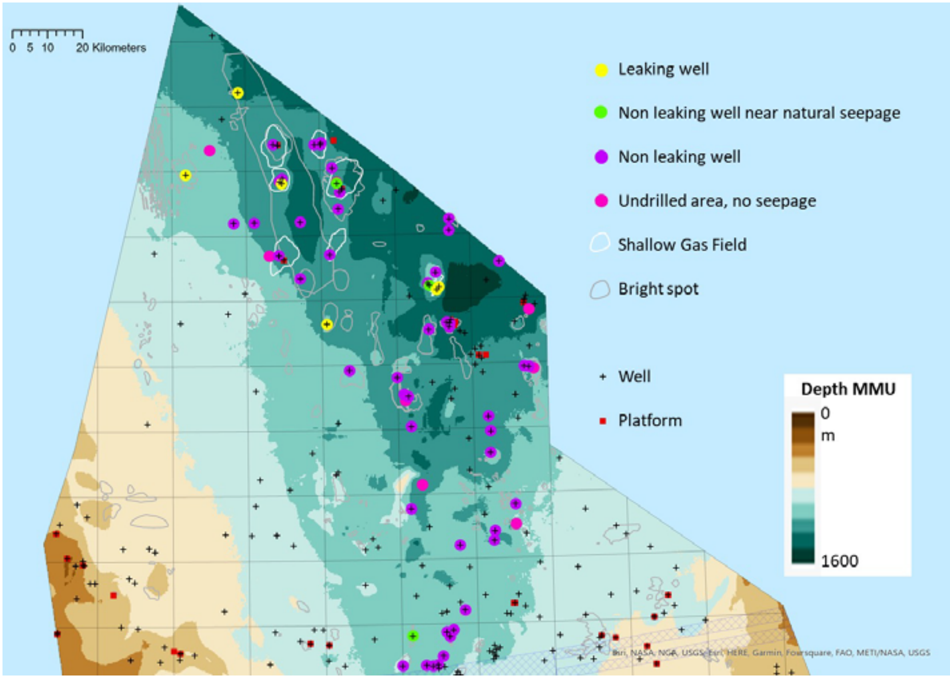


Figure 10-8: *Relation between the depth of the MMU (Base of the Upper North Sea Group) and leaking wells. The depth of the MMU is a proxy for it thickness.*

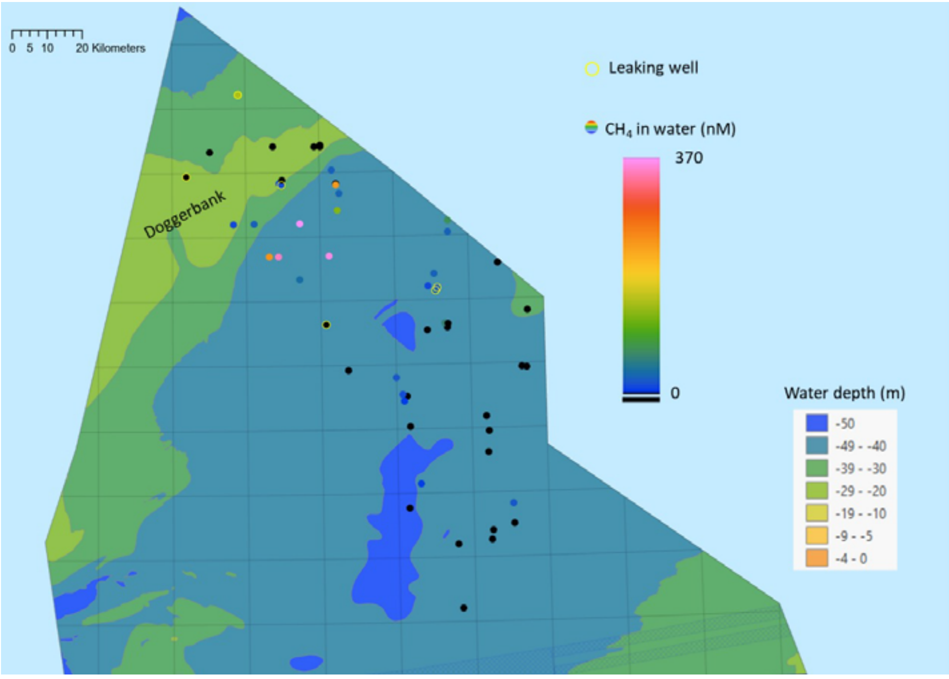


Figure 10-7: *Methane concentration in the water (dots) compared to the water depth (map). Note that the 6 locations in the shallowest part (Doggerbank) are all below the detection limit (black), while the higher methane concentrations are found to the south of the Doggerbank. The Doggerbank could act as a barrier for dissolved methane.*

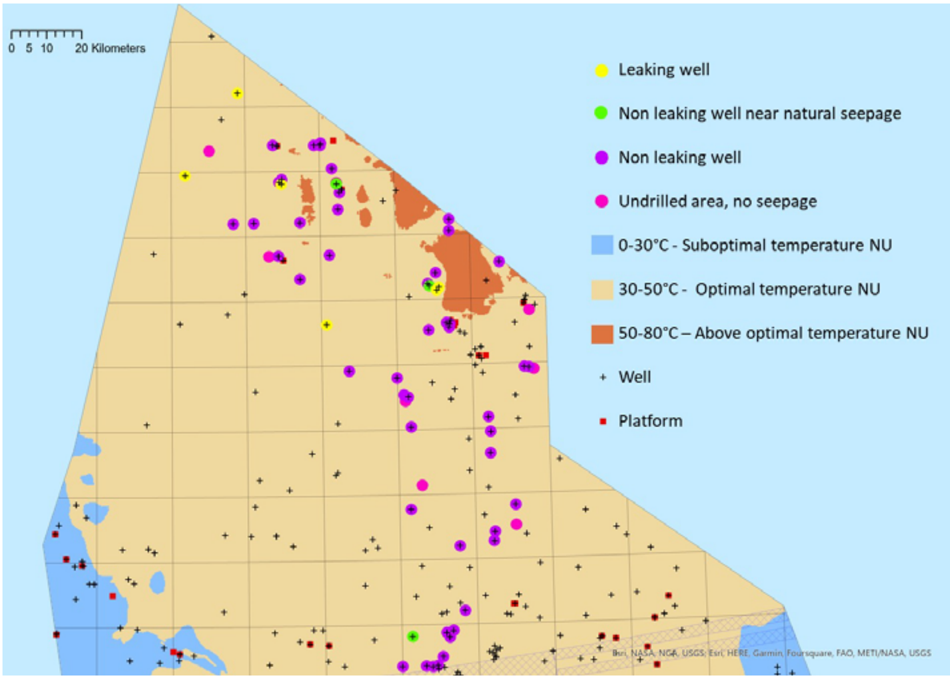


Figure 10-9: *Relationship between the temperatures within the Upper North Sea group and well leakage from shallow gas. Note that all presumed to be leaking wells are found close to the region of above optimal temperatures for biogenic gas generation. Source: https://www.geodeatlas.nl/*

the Upper North Sea Group (NU) (i.e. the sediments in which the biogenic shallow gas is generated), we find that all the wells that are presumed to be leaking are located in the region with optimal temperatures for biogenic methane generation, and all close to the 'above optimal' region (Figure 10-8). This is all in the North of the Dutch sector of the North Sea, and consistent with the distribution of shallow gas fields. Three of the six wells are drilled through a shallow gas field (i.e. A15-A and B17-A), that were not taken into production at the time of measuring. The temperatures decrease southwards, and no leaking wells are found there. This suggests that the amount of shallow gas is decreasing southwards. Consequently, the statistics (i.e. 18% of wells drilled through shallow gas are presumed to be leaking) that were found in the North may not be applicable to the south and only apply to the area were enough shallow gas was generated.

10.11 Bubble plumes and tide cycles

We found no relationship between tidal cycles and the present of bubble plumes. Plumes occurred during high, mid and low tide. Whether the magnitude of the bubble plumes (flux) varies with the tides remains to be researched.

10.12 Relationship with structures and salt

Römer et al. (2021) found that the distribution of natural bubble plumes was not randomly distributed but showed a relationship to Zechstein salt structures. Of the six presumable leaking wells, two (A08-01 and A14-02) have no relation to salt (Figure 10-9). A15-03 has a very small salt pillow below it, while the other 3 wells (B17-03, B17-05, and F01,01) were drilled on large salt structures. All natural seepage sites found are indeed found above salt structures. Salt doming can be instrumental in creating structural traps in the Cenozoic sequence, crestal faults, and higher heat flow that may favor biogenic gas generation and its vertical migration and trapping.

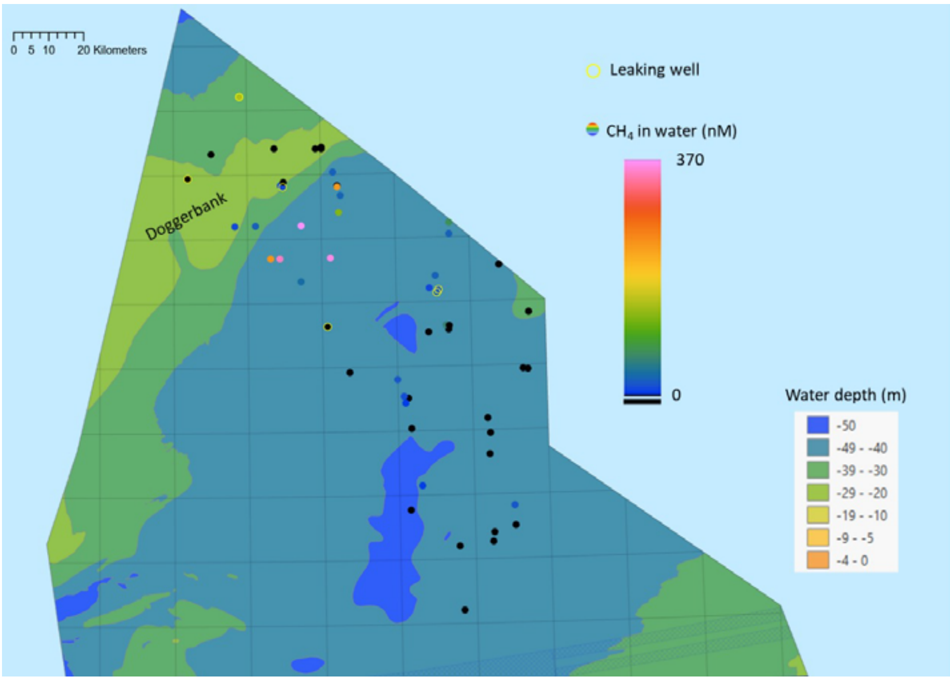


Figure 10-10: *A relationship between deep Zechstein salt and natural seepage was reported by Römer et al., 2021. For the six leaking wells, no such relationship is apparent.*

11 Conclusions

In total 63 locations were surveyed, of which 57 were abandoned wells. Since the aim of the project is to determine ebullition from abandoned wells in the Dutch sector of the North Sea and to place it in perspective of possible natural ebullition and seeps in the North Sea we start with our conclusions on both subjects.

11.1 Well leakage

Six wells (A08-01, A14-02, A15-03, B17-03, B17-05, F01-01) are leaking shallow gas.

All leaking wells are found in the most northern part of the Dutch offshore in an area where shallow gas quantities are the highest (i.e. in an area where the commercial shallow gas fields are found). Three of the six wells were drilled through a shallow gas fields (i.e. A15-A and B17-A) that were not taken in production yet. We conclude from this that significant quantities of shallow gas are present at the leaking wells.

From the fact that we found non-leaking wells drilled through the same shallow gas accumulations as the leaking wells, we concluded that wells can be drilled through shallow gas fields without resulting in leakage. A15-03 is leaking, while A15-02 and A15-05 are not leaking and all three well are drilled through the A15-A field. B17-03 and B17-05 are leaking while B17-06 is not leaking and all three well are drilled through the B17-A field. A08-01 (leaking) is drilled through the same shallow gas accumulation as A12-03 (non-leaking).

All the leaking wells were drilled through shallow gas. However, of the 33 wells drilled through shallow gas 27 wells were not leaking (i.e. 82% of the wells was not leaking). None of the 16 wells that are not associated with shallow gas were leaking. Therefore, we conclude that drilling through shallow gas is associated with a slightly higher risk of leakage compared to wells that are not drilled through shallow gas.

At the majority of surveyed locations (54 of 63), no bubble plume was encountered. This is true for all undrilled areas (6), all wells that were not associated with shallow gas (16), and all wells drilled close to shallow gas (6).

11.2 Natural seepage

Surrounding 3 wells (B13-01, B17-04, F17-14), natural seepage was concluded. B13-01 and B17-04 are related to natural seepage of shallow gas. The number of bubble plumes at these locations far exceeds the number of plumes encountered at leaking wells (usually 1 or 2). Whether the methane flux is also higher remains to be investigated.

11.3 Slurf workflow and results

The SLURF setup (water situated just above the seafloor was pumped up via a hose and analysed in a laser spectrometer) was experimental, but it showed to be very capable of detecting enhanced methane concentration caused by bubble plumes when sampling water from close to the seafloor. Also enhanced ethane concentrations above a pipeline were observed, demonstrating ethane could be detected too. However, the methane ebullition could not be quantified since the current setup proofed to be sensitive for fluctuations in background concentrations and the temperature of the container. For the upcoming expedition, the setup will be enhanced to quantify the methane ebullition.

12 Recommendation and research questions

The results of the first expedition show that 6 wells that are drilled through shallow gas are leaking and that natural seepage is present in the same region. At this moment we have 3 topics that we would like to investigate further.

1. Methane fluxes
2. Sources of shallow gas
3. Leakage mechanism

Methane fluxes will be investigated during the upcoming expedition in October 2023. We want to investigate how much methane (from well leakage and natural seepage) is released into the water. Furthermore, we want to investigate how much methane is absorbed or oxidated in the water column and whether methane is consumed by organisms. Finally we are interested how much is emitted to the atmosphere?

During that expedition we also want to investigate natural seepage sites and compare the methane emissions from leaking wells to natural seepage. This will aid SodM in the decision if mitigation of leakage is required (i.e. how does the amount of leakage compare to the emission caused by repair operations, and the nearby natural seepage). However, many uncertainties about the methane emissions will remain. We do not know if the methane emission will decline or decrease over time. Leakage could decrease over time due to diminishing methane volumes, but leakage could also increase first 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. For example, above the B13-FA field a large natural seepage site is found. Whether the natural seepage will decrease due to the production of shallow gas is unknown. This also because we do not know what the exact source of the natural seepage is and how the methane migrates through the subsurface. Another example is A15-A field that will be taken in production in the near future. It is unknown if the production will decrease the methane leakage of the abandoned A15-03 well (again, there are several gas bearing interval and it is unclear which interval is the source of the leakage and whether that interval is actually being produced.

To answer some of these questions we need to understand the various sources of shallow gas better and gain knowledge how these gasses migrate to the subsurface (in case of natural seepage). Shallow gas is found at different depth in the subsurface. It is unclear which depth is the source of the leakage and which interval is responsible for the methane leakage. How does the methane migrate through the subsurface in case of natural seepage. Doing isotope measurements could help to differentiate between shallow gas from different depth.

Furthermore, new terminology is needed for the different types of shallow gas. At the moment all gas in the upper 1 km is labeled as shallow gas. However, from studies that are done onshore, we know that biogenic gas can originate from various depth. There, shallow gas is sub dived and for example “swamp gas” and “Brongas” are defined.

Another important topic is the leaking mechanism(s). At the moment we do not know what well-integrity issue(s) can cause the leakage (again, drilling induced fractures are not the leakage mechanism). Understanding this is important for new wells, but also for assessing the risks of leakage of existing (abandoned) wells that are drilled through shallow gas. Gaining more knowledge on this topic is also very important for CO_2 storage. Currently, there is little known about the risks of leakage for legacy wells and the risks of leakage when storing CO_2 in shallow aquifers. We recommend investigating the leakage mechanisms when mitigation actions are taken place. During these operations an ROV could film the dug up well and see where the methane is coming from (i.e. is it leaking from within the well and which annulus or is there migration along the well bore due to bad cement).

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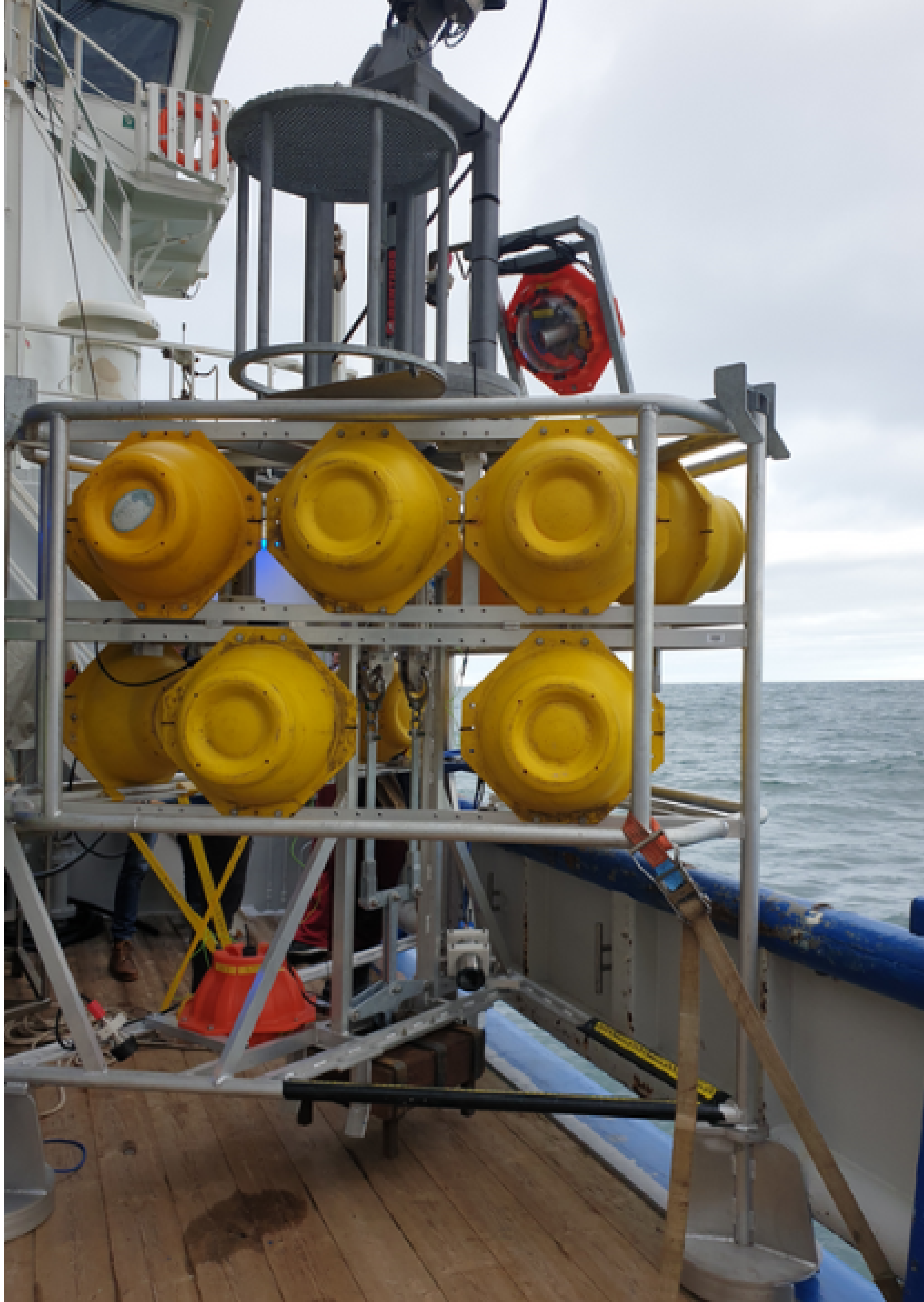

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