Contents

Comment on “Greenhouse gas emissions from marine decommissioned hydrocarbon wells: leakage detection, monitoring and mitigation strategies” by Christoph Böttner, Matthias Haeckel, Mark Schmidt, Christian Berndt, Lisa Vielstädte, Jakob A. Kutsch, Jens Karstens & Tim Weiß

Martin Wilpshaar*, Geert de Bruin*, Noortje Versteijlen*, Kaj van der Valk* & Jasper Griffioen*~

* TNO Geological Survey of the Netherlands, Princetonlaan 6, 3584 CB Utrecht, The Netherlands

~ Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, the Netherlands

1 Introduction

Böttner et al. (2020) acquired hydroacoustic water column imaging data at 43 gas wells in the UK sector of the North Sea. They observed so-called flares (bubble plumes) at 28 well head locations. Böttner et al. (2020) related these flares to leakage of natural gas along the outside of the well from shallow gas accumulations in the upper 1,000 m below the seabed through supposed drilling-induced fractures surrounding the well path. Therefore, they labelled the flares from the seabed as anthropogenic methane leakage. Moreover, if the distance between the well and the nearest shallow gas accumulation is shorter than 300 m, leakage is “highly likely (100%)” and for a distance of more than 1,000 m not likely. Based on a probability of leakage and leakage fluxes as deduced from two wells in the Norwegian sector, the authors estimated the methane leakage rate for all 1,792 wells in their study area and concluded that gas release from decommissioned wells is a major source of methane in the North Sea.

Hydrocarbon gas emissions from marine - decommissioned or not - hydrocarbon wells have received considerable attention in the past years (Vielstädte et al., 2015; 2017; Leifer, 2015). This publication by Böttner et al. (2020), is a successor of Vielstädte et al. (2015; 2017) by the same research group and originally part of the PhD thesis (Ch. 3) of Böttner (2020). Methane leakage from shallow gas accumulations through drilling-induced fractures surrounding the borehole was earlier proposed by Vielstädte et al. (2017).

The topic of methane emissions associated with oil and gas production is not only scientifically interesting, it also raises considerable attention in society and politics. Vielstädte et al. (2017) triggered questions from Dutch parliament members to the minister of Economic Affairs and Climate[1], who is politically responsible for oil and gas production in the Netherlands. TNO Geological Survey Netherlands was asked to address these questions during which the scientific findings of Vielstädte et al. (2017) were evaluated as well. TNO (TNO, 2019; 2018) formulated fundamental critique to Vielstädte et al. (2015; 2017). The TNO reports, in which the anthropogenic methane leakage as described in Vielstädte et al. (2015; 2017) is insufficiently validated and overestimated (TNO, 2019), were input for the ministerial answering of the parliamentary questions.

Again, parliamentary questions in the Netherlands were asked to the minister[2] in which reference is made to this successor publication of Böttner et al. (2020). Once more, we have the scientific

---

[1] https://zoek.officielebekendmakingen.nl/ah-tk-20182019-250.html

[2] https://zoek.officielebekendmakingen.nl/ah-tk-20192020-3955.html

opinion that fundamental shortcomings can be noted in the publication of Böttner et al. (2020). We feel the urge not only to share our critical response to this publication with the Dutch parliament and the ministry of Economic Affairs and Climate but also with the readers of the “International Journal of Greenhouse Gas Control”.

2 Topics of critique

Böttner et al. (2020) used hydroacoustic water column imaging to identify gas flares from the bottom of the North Sea in a part of the U.K. continental shelf. Our fundamental critique is that two logical explanations for the flares as observed were hardly considered or researched: natural leakage and leakage caused by well-integrity issues.

Instead Böttner et al. (2020) proposed an alternative leakage mechanism of drilling-induced fractures creating migration pathways for shallow gas accumulations along the borehole whereby the distance to these shallow gas accumulations determines the leakage probability. As elaborated below, this leakage mechanism is questionable since drilling-induced fracturing will not likely be created in the unconsolidated marine sediments where shallow gas accumulations exist. Moreover, the implied lateral migration from shallow gas accumulations to wells over large distances (< 1000 m) is unrealistic.

Moreover, no differentiation of natural and anthropogenic leakage is made and the ease in which the conclusions become transferred to methane leakage from onshore gas wells is not substantiated.

Finally, each subsection (seismic interpretation, water column imaging, statistical analysis, and assessment of leakage rates) contains errors and/or hiatuses. Hence, the line of reasoning of Böttner et al. (2020) and the related conclusions are not properly supported by the results and leave room for alternative interpretations and improvements.

3 Natural methane leakage

Böttner et al. (2020) labelled all flares considered as anthropogenic leakage while natural methane leakage is hardly discussed nor considered as a potential source. Natural methane leakage is abundantly present in the study area from (1) shallow gas accumulations, (2) pockmarks, (3) subsurface salt domes, (4) ‘gas chimneys’ and/or (5) peat layers (Verweij et al. 2018; Römer et al., 2017; Schroot et al., 2005; Fyfe et al., 2003; Böttner et al., 2019; Schneider von Deimling et al., 2015; Hovland et al., 1993, 2012; Heggland, 1998; Karstens & Berndt, 2015; Cartwright & Santamarina, 2015; Vielstädte et al. 2015; Brekke et al., 1997; Borges et al., 2016; Missiaen et al., 2002). More specifically:

1. Böttner et al. (2020) showed that the measured flares are sourced by shallow gas accumulations without discussing or realizing that these accumulations are naturally leaking systems (Verweij et al. 2018, Römer et al., 2017, Schroot et al., 2005). In short shallow gas accumulations are near hydrostatic pressure which indicates that the seals cannot hold a large gas column. Leakage (so called seal breach) occurs when the pressure exceeds a few bar above hydrostatic pressure, allowing the gas to migrate upwards. Furthermore, the accumulations are not filled to the spill point, and are sometimes found in multiple reservoir layers stacked vertically. These stacked reservoirs can be explained by a decreasing seal strength upward due to the decreasing effect of compaction upwards and the increased buoyancy of gas moving upward. Ultimately natural methane leakage occurs when a portion

of the gas reaches the seabed and is vented into the sea and possibly the atmosphere, too (Verweij et al. 2018).

2. In the northern part of the Böttner et al. (2020) study area lies the Scanner Pockmark Special Area of Conservation (SAC)[3]. Pockmarks are geomorphological features that form in response to (explosive) venting of natural gas from the seafloor. Fyfe et al. (2003) showed that the Scanner Pockmark area is part of a much larger area where pockmarks exist. The Scanner Pockmark area was also intensively studied by Böttner (2020) in his PhD thesis (Ch. 2) and published by Böttner et al. (2019). Böttner et al. (2019) documented > 1500 pockmarks over an area of 225 km² where a limited number have active vents. Böttner et al. (2019) showed a direct relation to shallow gas accumulations (bright spots) in the subsurface. Remarkably, these findings were not mentioned in Böttner et al. (2020) when discussing natural leakage.
3. In the southern part just across the border on the Norwegian side (concession block 1/9) lies the well-known Tommeliten seep area (Schneider von Deimling et al., 2015; Hovland et al., 1993) situated above a subsurface salt dome. Subsurface salt domes as indicated on Figure 3C of Böttner et al. (2020) like Tommelitin "are notoriously leaky geologic megastructures and are often associated with surface seep manifestations on land and on the seafloor" (Hovland et al, 2012).
4. Böttner et al. (2020) refer to "*pre-existing fracture networks may favor the vertical migration of fluids through the overburden (Karstens & Berndt, 2015; Vielstädte et al., 2015)*". Gas chimneys are not uncommon in the North Sea (e.g. Heggland, 1998; Schroot et al., 2005; Karstens & Berndt, 2015) and are considered to indicate vertical fluid conduits for shallow and/or deep thermogenic gas accumulations (Cartwright & Santamarina, 2015). Measurements by Vielstädte et al. (2015) showed that one of the three investigated wells was drilled through such a seismic chimney structure. Böttner et al. (2020) was using the data from Vielstädte et al. (2015; 2017) but did not investigate if chimneys are present in the study area, if wells were drilled through a seismic chimney and what the role of these chimneys is in natural and anthropogenic leakage. Further see Appendix C.
5. Apart from the above discussed natural leakage or seeps, gas can escape from shallow layers such as buried Holocene peat (Brekke et al., 1997; Borges et al., 2016; Missiaen et al., 2002), which were not considered by Böttner et al. (2020) as potential source.

4 Anthropogenic methane leakage at wells

Integrity issues of hydrocarbon wells have been intensively studied in the past years. The issue is pointed out by Böttner et al. (2020): *"…leakage may occur through faulty, damaged or corroded well casings and/or annuli commonly referred to as "well integrity issues" (Celia & Bachu, 2003; Gasda et al., 2004; Vrålstad et al., 2019).* For abandoned wells, well integrity problems are obvious causes of leakage (Bachu, 2017). Nevertheless, Böttner et al. (2020) do not present well integrity issues as a candidate for the observed flares. Instead, they present an alternative process as most likely: *"… for shallow marine sediment, we also consider that fluid migration may occur along the outside of the well through drilling-induced fractures surrounding the well path (Harrison et al., 1954; Gurevich et al., 1993; Aadnøy & Bell, 1998; Kårstad & Aadnøy, 2008; Bohnhoff & Zoback; 2010; Osborn et al., 2011; Vielstädte et al., 2015, 2017, 2019)".*

Böttner et al. (2020) focused on drilling-induced fractures as the cause of methane leakage. This leakage mechanism was not further researched by the authors for the study area but based on

---

[3] https://jncc.gov.uk/our-work/scanner-pockmark-mpa/

publications describing fracturing around the borehole in (deep) consolidated brittle rocks. At the North Sea, shallow gas is only present in unconsolidated, Pleistocene sediments (Verweij et al., 2018, Veen et al., 2018, Boogaard & Hoetz, 2018), with different geological and geomechanical properties. There is no evidence provided that these fracturing mechanisms that could occur in deep brittle rocks can also be applied to shallow unconsolidated sediments. Fracturing of unconsolidated sediments is not likely or even impossible and consequently the leakage mechanism of drilling-induced fracturing is not realistic for the geographical settings at hand. Böttner et al. (2020) assumed that drilling induced fractures create a potential pathway for methane migration behind the casing and this pathway is always present at a well. After all, 100% of the wells that are closer than 300 m from a shallow gas pocket are leaking. One hundred percent change of leakage is unrealistically high when compared to other studies (Bachu 2017, Boothroyd et al. 2016, Kang et al. 2016, Townsend-Small et al. 2016, Schout et al. 2019), where most of these studies refer to onshore wells.

The authors confusingly conclude that “*currently little quantitative data exist for leakage through drilling-induced fracture networks outside of the borehole, most information is related to blowout scenarios (e.g. Leifer & Judd, 2015; Landrø et al., 2019).”* We point out that the large fractures that originate from a catastrophic blowout cannot in any way be compared to the small fractures that would be created during drilling through brittle rock, let alone drilling through unconsolidated sediments. Any comparison between these two types of fractures is invalid (Kaiser, 2017). This is obvious when we recall that the methane flux at the blowout UK22/4b is still 15,000 – 41,000 ton y^{-1} (Table 1) and that the methane flux at a recent blowout in Ohio (USA) was 120 tons hr^{-1} for a few months (Pandey et al., 2019).

Finally Böttner et al. (2020) stated “*Our results show that if the distance between the well and the most proximal bright spot (...) is shorter than 300 m, leakage is highly likely (100%, 20/20 wells) and for a distance of more than 1,000 m not likely (0/5 wells)*”. This means that methane must migrate laterally over large distances (300 to 1000 m). Böttner et al. (2020) explains that *“... lateral gas migration may be favored by dipping beds (up to 1.2-1.4 km distance; Landrø, 2011).”* Gas will move upward in dipping beds because of buoyancy and gets stuck at a trap. It is impossible that gas migrates down structure and away from its trap except when accumulation is going on and the spill point is surpassed. Böttner et al. (2020) do not address why a nearby well will initiate gas to migrate laterally down dip when gas tend to move upward due to buoyancy. As mentioned before, shallow gas accumulations are near hydrostatic pressure (Verweij et al. 2018) which indicates that the seals cannot hold a large gas column, allowing the gas to migrate upwards. This is confirmed by the fact that shallow gas is sometimes found in multiple reservoirs layers stacked vertically (Verweij et al. 2018, Boogaard & Hoetz, 2018). Hence, a negligible lateral pressure gradient is present between the well and the shallow gas accumulation at 300 – 1000 m away.

5 Comparing natural and anthropogenic methane leakage

Böttner et al. (2020) concluded that gas release from decommissioned wells is a major methane source where they compared their calculated rate with the leakage rates at five natural seep sites in the UK continental shelf (and not strictly the North Sea as suggested in their Table 2) to illustrate this. Remarkably, Böttner et al. (2020) and also Vielstädte et al. (2017) did not recognize that natural seeps are frequently found at the North Sea (or associated UK continental shelf (UKCS)) as researched by Judd et al. (1997) and Tizzard (2008). Judd et al. (1997) estimated that 173,003 seeps are present at the UKCS with high densities in parts of the British sector of the North Sea including the area studied by Böttner et al. (2020). Furthermore, Krämer et al. (2017) concluded that a pockmark field (covering 915 km^2) in the German offshore emitted a conservative estimated 5000 ton of methane gas in an episodic event of 3 months.

Table 1 presents a more complete list of estimates for methane fluxes from the seabed of the North Sea. One may note that the total fluxes from the natural seeps at the UKCS are considerably higher than the total leakages along wells as estimated by Vielstädte et al. (2017) and Böttner et al. (2020). The following conclusion of Böttner et al. (2020) is thus not supported by literature: "*In comparison to the natural release of greenhouse gas (methane) into the water column of the North Sea, the release of greenhouse gases from marine decommissioned hydrocarbon wells is (…) larger than all known natural seepage sites combined.*" Moreover, the highest referenced natural methane emission (of Böttner et al., 2020) of 478 ton per year (Römer et al., 2017) is less in absolute numbers compared to the findings of Böttner et al. (2020) but it occurs in a much smaller area. The natural leakage occurs in an area of 8 km^2 while the study area of Böttner is over 20,000 km^2.

Table 1 Literature estimates of the methane fluxes from the seabed of the North Sea as deduced from field measurements and calculations. Grey cells refer to natural leakage and orange cells to leakage along wells or at a historical blowout site.

Methane flux from the seabed	Methane flux (ton(methane) y^{-1})	reference
Pockmark G11, off-shore Mid-Norway	0.151	Chen et al., 2010
Scanner pockmark macroseep	4.2	Hovland & Sommerville, 1985
Scanner pockmark	1,600-2,700	Li et al. (2020)
Pockmark field German offshore	5.000 (in 3 months)	Krämer et al. (2017)
Anvil Point, UK	68	Hinchcliffe, 1978
Gas chimney at Tommeliten	26	Schneider von Deimling et al., 2015
Tommeliten wider seep area	5.64	Hovland et al., 1993
seep area at UK Block 15/25	17	Hovland et al., 1993
seep area at UK Block 15/25	6.8	Judd, 2004
Average of individual seeps at UK continental shelf	1.25 – 35.8	Judd et al., 1997
major seeps at the Dutch Dogger Bank (B13)	273-593	Römer et al., 2017
Total of seeps at UK continental shelf	87,000 – 2,900,000	Tizzard, 2008
Total of seeps at UK continental shelf	216,000 – 6,200,000	Judd et al., 1997
Total natural leakage from North Sea seabed	200	Vielstädte et.al., 2017
blowout UK22/4b	15,000 – 41,000	Leifer, 2015
Range in leakage along 3 wells in the Norwegian Central North Sea	1 – 19	Vielstädte et al., 2015
total leakage along wells in the North Sea	3,000 – 17,000	Vielstädte et al., 2017
Total leakage along wells at UK Central North Sea	900 – 3,700	Böttner et al., 2020

In our view the article could have been improved when more focus was given to (natural) flare locations (e.g. Römer et al., 2017) also at locations where no wells exist to indicate natural leakage.

6 Transfer of conclusions to potential leakage on land

Bottner et al. (2020) transfer their findings to potential leakage from hydrocarbon wells on land: ''*An identification of shallow gas in correlation with drilled wells is needed on a regional to global scale to update the estimates of methane emissions from fossil fuels. This is particularly important on land as drilling-induced leakage along wells in this setting emits the methane directly into the atmosphere, because the mitigating water column is absent. Thus, decommissioned wells may play a key role in methane gas emissions from hydrocarbon provinces, particularly on land.*'' In our opinion, this extrapolation is not justified for a combination of reasons. First, the presence of pockmarks, shallow gas accumulations and bright spots is not self-evident for terrestrial areas. For the Netherlands, it holds that these features are frequently found offshore (Schroot & Schuttenhelm, 2003; Schroot et al., 2005) but TNO Geological Survey Netherlands is not aware of these features on land, where half of the Netherlands has been covered by seismic investigations. Second, horizontal groundwater flow is a common process in terrestrial environments as driven by spatial differences in hydraulic heads. Dissolution of upward migrating methane may occur in along flowing groundwater and this may completely remove upward migrating methane under appropriate conditions (Schout et al., 2020; Taherdangkoo et al., 2020). Third, methane oxygenation in the unsaturated zone (or shallow groundwater) may prevent methane leaking from gas wells to reach the surface (McMahon et al., 2018; Schout et al., 2019; Yin et al., 2020). Last, onshore hydrocarbon wells have a lower probability to show well integrity failure compared to offshore wells (King & King, 2013). This is due to the fact that onshore drilling is technically less difficult than offshore drilling, which may result in higher frequencies of well barrier failure and well integrity failure for the latter.

We agree with Böttner et al. (2020) that - decommissioned or not – hydrocarbon wells on land need proper attention when it comes to well leakage issues. However, it is not self-evident that leakage of shallow gas should be the primary focus. The focus should also be on well barrier integrity and well integrity (Davies et al., 2014; King & King, 2013). It is worth to point out that leakage along wells may also be at hand for groundwater wells as they also provide a short circuit between buried, methane-rich geological formations and the surface.

7 Errors and hiatuses in Böttner et al., 2020

When studying the presented findings in order to see whether we could come to the same conclusions, we found that each subsection in the line of reasoning contains errors or hiatuses. The errors and hiatuses we found are discussed in Appendices A, B, and C. They can be summarized as follows:

A. *Seismic interpretation*
   The geophysical data interpretation is not up to standard and the reported distances (wells to bright spots) are not always in line with the presented images.
B. *Selective well usage*
   15 additional wells were measured (Water Column Imaging) but were not taken into account for their conclusions for unclear reasons.
C. *Statistical analysis and potential leakage of wells*
   The statistical analysis (e.g. the claim that the distance to shallow gas accumulations determines the leakage probability of wells) is contradicted by themselves (e.g. Böttner et al. (2019) studied a well with a 0 to 0,2 leakage probability that is located 100 m from a bright spot).
   For the computation of regional leakage rates, they used flux data for a well for which they previously concluded that the measured methane leakage was not related to bright spots but to seismic turbidity (Vielstädte et al., 2015; 2017).
   There are inconsistencies between Böttner et al. (2020) and Böttner (2020). Both publications use the same data set but present, interpret and calculate it different and nevertheless come to the same total methane leakage estimate.

Hence the data handling shows serious shortcomings which leaves room for alternative interpretations and improvements

8 Conclusions

We value the measurements made by Böttner et al. (2020) since measuring methane emission is an important scientific and social issue. However, the authors are too much focused on proving a relation between flares and shallow gas. In order to prove this relationship they use unproven and unlikely migration pathways for shallow gas and migration over considerable distances. This all results in unsupported assumptions, analyses that are not in accordance with standard geological and geophysical interpretation practices, data-handling errors and non-reproducible results.

As indicated in our Introduction, readers should keep in mind that this is more than only a purely academic exercise since it is closely followed in the political arena how to combat climate change. How much, and under what conditions, methane is leaking from the sea bottom and ultimately to the atmosphere has consequences for greenhouse effects as well as the associated political debate. In that regard, resources to diminish anthropogenic methane leakage should be targeted at the right places.

9 References

Aadnøy, B.S., Bell, J.S., 1998. Classification of drilling-induced fractures and their relationship to in-situ stress directions. The Log Analyst 39(06).

Abrakasa, S., 2011. Cuttings and Mud gas data: A new perspective for Caprock Leakage in the North Sea. Archives of Applied Science Research, 3(4), 518-526

Bachu S., 2017. Analysis of gas leakage occurrence along wells in Alberta, Canada, from a GHG perspective – Gas migration outside well casing. International Journal of Greenhouse Gas Control. Volume 61, June 2017, Pages 146-154

Berndt, C., Elger, J., Böttner, C., Gehrmann, R., Karstens, J., Muff, S., Pitcairn, B., Schramm, B., Lichtschlag, A., & Völsch, A. , 2017. RV MARIA S. MERIAN Fahrtbericht/Cruise Report MSM63-PERMO, Southampton–Southampton (UK) 29.04.-25.05. 2017.

Bohnhoff, M., Zoback, M.D., 2010. Oscillation of fluid-filled cracks triggered by degassing of CO2 due to leakage along wellbores. Journal of Geophysical Research: Solid Earth 115(B11)

Boothroyd, I.M., Almond, S., Qassim, S.M., Worrall, F., Davies, R.J., 2016. Fugitive emissions of methane from abandoned, decommissioned oil and gas wells. Sci. Total Environ. 547, 461–469. https://doi.org/10.1016/j.scitotenv.2015.12.096

Borges, A. V. et al., 2016. Massive marine methane emissions from near-shore shallow coastal areas. Sci. Rep. 6, 27908; doi: 10.1038/srep27908.

Böttner, C., 2020. Natural and anthropogenic fluid migration pathways in marine sediments. (PhD/ Doctoral thesis), Christian-Albrechts-Universität, Kiel, Germany, 198 pp.

Böttner, C., Berndt, C., Reinardy, B.T.I., Geersen, J., Karstens, J., Bull., J.M., Callow, B.J., Lichtschlag, A., Schmidt, M., Elger, J., Schramm, B., Haeckel, M., 2019. Pockmarks in the Witch Ground Basin, Central North Sea. Geochemistry, Geophysics, Geosystems, 20(4), 1698-1719.

Böttner, C., Haeckel, M., Schmidt, M., Berndt, C., Vielstädte L., Kutsch, J.A., Weiss, T., 2020. Greenhouse gas emissions from marine decommissioned hydrocarbon wells: leakage detection, monitoring and mitigation strategies International Journal of Greenhouse Gas Control. Volume 100, September 2020, 103119

Brekke, T., Lonne, O. & Ohm, S.E., 1997. Light hydrocarbon gases in shallow sediments in the northern North Sea. Marine Geol., 137, 81-108.

Brown, A. R., 2011. Interpretation of three-dimensional seismic data. Society of Exploration Geophysicists and American Association of Petroleum Geologists.

Cartwright, J., & Santamarina, C., 2015. Seismic characteristics of fluid escape pipes in sedimentary basins: implications for pipe genesis. Marine and Petroleum Geology, 65, 126-140.

Celia, M.A., Bachu, S., 2003. Geological sequestration of CO2: is leakage unavoidable and acceptable? GreenhouseGasControlTechnologies-6thInternationalConference. Pergamon, pp.477–482 (January).

Chen, Y., Ussler III, W., Haflidason, H., Lepland, A., Rise, L., Hovland, M. & Hjelstuen, B.O., 2010. Sources of methane inferred from pore-water δ13C of dissolved inorganic carbon in Pockmark G11, offshore Mid-Norway. Chem. Geol. (275), 127-138.

Davies, R.J., Almond, S., Ward, R.S., Jackson, R.B., Adams, C., Worrall, F., Herringshaw, L.G., Gluyas, J.G., Whitehead, M.A., 2014. Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. Mar. Pet. Geol. 56, 239–254. https://doi.org/10.1016/j.marpetgeo.2014.03.001

Doornenbal, J. C., Kombrink, H., Bouroullec, R., Dalman, R. A. F., De Bruin, G., Geel, C. R., Houben, A.J.P., Jaarsma B., Juez-Larré J., Kortekaas M., Mijnlieff, H. F., Nelskamp, S., Pharoah, T.C., Ten Veen, J.H., Ter Borgh M., Van Oijk K., Verreussel, R.M.C.H., Verweij, J.M., & Vis, G-J., 2019. New insights on subsurface energy resources in the Southern North Sea Basin area. Geological Society, London, Special Publications, 494, SP494-2018.

Fyfe J. A., Gregersen U, Jordt H, Rundberg Y, Eidvin T, Evans D, Stewart D, Hovland M, Andresen P., 2003. Oligocene to Holocene. In: Evans D, Graham C, Armour A, Bathurst P (eds) The

Millennium Atlas: petroleum geology of the Central and Northern North Sea. Geological Society of London, London, pp 279–287

Gasda, S.E., Bachu,S., Celia, M.A., 2004. Spatial characterization of the location of potentially leaky wells penetrating a deep saline aquifer in a mature sedimentary basin. Environmental Geology 46 (6-7), 707–720.

Gurevich, A.E., Endres, B.L., Robertson Jr., J. O., Chilingar, G. V., 1993. Gasmigration from oil and gasfields and associated hazards. Journal of Petroleum Science and Engineering 9(3),223–238.

Harrison, E., Kieschnick, W.F., McGuire, W.J., 1954. The Mechanics of Fracture Induction and Extension. AIME Petroleum Transactions 201, 252–263.

Heggland, R., 1998. Gas seepage as an indicator of deeper prospective reservoirs. A study based on exploration 3D seismic data. Marine and Petroleum Geology Volume 15, Issue 1, February 1998, 1-9

Hovland, M. & Sommerville, J.H., 1985. Characteristics of two natural gas seepages in the North Sea. Marine and Petroleum Geology (2), 319-326.

Hovland, M., Judd, A.G. & Burke, R.A., 1993. The global flux of methane from shallow submarine sediments. Chemosphere (26), 559-578.

Hovland, M., Jensen, S. & Fichler, C., 2012. Methane and minor oil macro-seep systems – Their complexity and environmental significance. Marine Geol. (332-334), 63-173.

Judd, A. 2004. Natural seabed gas seeps as sources of atmospheric methane. Environmental Geology 46, 988–996

Judd, A., Davies, G., Wilson, J., Holmes, R., Baron, G. & Bryden, I., 1997. Contributions to atmospheric methane by natural seepages on the UK continental shelf. Marine Geol. (137), 165-189.

Kaiser, M.J., 2017. Rigless well abandonment remediation in the shallow water U.S. Gulf of Mexico. J. Petrol Sci. Eng., 151, 94-115.

Kang, M., Christian, S., Celia, M.A., Mauzerall, D.L., Bill, M., Miller, A.R., Chen, Y., Conrad, M.E., Darrah, T.H., Jackson, R.B., 2016. Identification and characterization of high methane-emitting abandoned oil and gas wells. PNAS 2016 November, 113 (48) 13636-13641. https://doi.org/10.1073/pnas.1605913113

Karstens, J., Berndt, C., 2015. Seismic chimneys in the Southern Viking Graben–implications for palaeo fluid migration and overpressure evolution. Earth and Planetary Science Letters 412,88–100.

King, G.E. and King, D.E., 2013. Environmental Risk Arising from Well-Construction Failure—Differences Between Barrier and Well Failure, and Estimates of Failure Frequency Across Common Well Types, Locations, and Well Age. SPE Prod. Oper. 28, 323–344. https://doi.org/10.2118/166142-PA

Krämer, K., Holler, P., Herbst, G., Bratek, A., Ahmerkamp, S., Neumann, A., Bartholomä, A., Beusekom van, J.E.E., Holtappels, M. & Winter, C. (2017). Abrupt emergence of a large pockmark field in the German Bight, southeastern North Sea. Scientific Reports https://www.nature.com/articles/s41598-017-05536-1.pdf

Landrø, M., 2011. Seismic monitoring of an old underground blowout– 20 years later. First Break 29 (6),39–48.

Landrø, M., Wehner, D., Vedvik, N., Ringrose, P., Løhre, N.L., Berteussen, K., 2019.Gas flow through shallow sediments—A case study using passive and active seismic field data. International Journal of Greenhouse Gas Control 87, 121–133.

Leifer, I., 2015. Seabed bubble flux estimation by calibrated video survey for a large blowout seep in the North Sea. Marine Petrol. Geol. (68), 743-752.

Leifer, I., Judd, A., 2015.The UK22/4b blowout 20 years on: Investigations of continuing methane emissions from sub-sea bed to the atmosphere in a North Sea context. Marine and Petroleum Geology 68 ,706–717

Li, J., Roche, B., Bull, J. M., White, P. R., Leighton, T. G., Provenzano, G., et al. , 2020. Broadband acoustic inversion for gas flux quantification— Application to a methane plume at Scanner Pockmark, central North Sea. Journal of Geophysical Research: Oceans, 125, e2020JC016360.

Linke, P., Haeckel, M., 2018. RVPOSEIDON Fahrtbericht/CruiseReport POS518: Baseline Study for the Environmental Monitoring of Subseafloor CO2 Storage Operations, Leg 1: Bremerhaven–Bremerhaven (Germany) 25.09.-11.10.2017, Leg2: Bremerhaven–Kiel (Germany) 12.10.-28.10.2017.

McMahon, P.B., Thomas, J.C., Crawford, J.T., Dornblaser, M.M., Hunt, A.G., 2018. Methane in groundwater from a leaking gas well, Piceance Basin, Colorado, USA. Sci. Total Environ. 634, 791–801.

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

Osborn, S.G., Vengosh, A., Warner, N.R., Jackson, R.B., 2011. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proceedings of the National Academy of Sciences 108(20), 8172–8176.

Pandey S., Gautam R., Houweling S., Denier van der Gon H., Sadavarte P., Borsdorff T., Hasekamp O., Landgraf J., Tol P., van Kempen T., Hoogeveen R., van Hees R., Hamburg S.P., Maasakkers J.D. and Aben I. 2019. Satellite observations reveal extreme methane leakage from a natural gas well blowout. PNAS December 26, 2019 116 (52) 26376-26381; first published December 16, 2019; https://doi.org/10.1073/pnas.1908712116

Römer, M., Wenau, S., Mau, S., Veloso, M., Greinert, J., Schluter, M. & Bohrmann, G., 2017. Assessing marine gas emission activity and contribution to the atmospheric methane inventory: A multidisciplinary approach from the Dutch Dogger Bank seep area (North Sea). Geochem., Geophys., Geosyst., 10.1002/2017GC006995.

Schneider von Deimling, J., Linke, P., Schmidt, M. & Rehder, G., 2015. Ongoing methane discharge at well site 22/4b (North Sea) and discovery of a spiral vortex bubble plume motion. Marine Petrol. Geol. (68), 718-730.

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

Schout, G., Hartog, N., Hassanizadeh, S.M., Helmig, R., Griffioen, J., 2020. Impact of groundwater flow on methane gas migration and retention in unconsolidated aquifers. J. Contam. Hydrol. https://doi.org/10.1016/j.jconhyd.2020.103619

Schroot, B.M. & Schuttenhelm, R.T.E., 2003. Expression of shallow gas in the Netherlands North Sea. Netherlands Journal of Geosciences / Geologie en Mijnbouw 82 (1): 91-105 (22), 499-515.

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

Taherdangkoo, R., Tatomir, A., Sauter, M., 2020. Modeling of methane migration from gas wellbores into shallow groundwater at basin scale. Environmental Earth Sciences, 79 (18), art. no. 432,

Ten Veen J, De Bruin G., Donders T., Verweij H. & Geel K., 2018. Shallow gas traps in the Cenozoic Southern North Sea delta, offshore Netherlands. First Break, Volume 36, December 2018, 30-36.

Tingdahl, M.K., Bril, A.H. and De Groot, P.F.M., 2001. Improving seismic chimney detection using directional attributes. Journal of Petroleum Science and Engineering, 29(3):205-211.

Tizzard, L., 2008. The Contribution to Atmospheric Methane from Sub-seabed Sources in the UK Continental Shelf. PhD-thesis, University of Newcastle upon Tyne, UK.

TNO, 2018. Emissie van het broeikasgas methaan gerelateerd aan de olie- en gassector in Nederland met nadruk op exploratie en productie. TNO2018 R11080 https://www.nlog.nl/methaanemissies

TNO, 2019. Inventory of wells through shallow gas layers in the Dutch North Sea. TNO2019 R11562; https://www.nlog.nl/en/papers

Townsend-Small, A., T. W. Ferrara,D. R. Lyon, A. E. Fries, and B. K. Lamb, 2016, Emissions of coalbed and natural gas methane from abandoned oil and gas wells in the United States, Geophys. Res. Lett., 43, 2283–2290

Van den Boogaard M. & Hoetz G., 2018. Prospectivity analysis of shallow gas in the Netherlands. First Break Volume 36, December 2018, 47- 54

Verweij, J.M., Nelskamp, S.N., Ten Veen, J.H., De Bruin G., Geel, K., Donders T.H. (2018). Generation, migration, entrapment and leakage of microbial gas in the Dutch part of the Southern North Sea Delta. Marine Petrol. Geol. (97), 493-516

Vielstädte L., Karstens J., Haeckel M., Schmidt M., Linke P., Reimann S., Liebetrau V., McGinnisb D.F., Wallmann K., 2015. Quantification of methane emissions at abandoned gas wells in the Central North Sea. Marine and Petroleum Geology Volume 68, Part B, December 2015, Pages 848-860.

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

Vielstädte L., Haeckel M., Karstens J., Linke P., Schmidt M., Steinle L., and Wallmann K., 2017. Shallow Gas Migration along Hydrocarbon Wells – An Unconsidered, Anthropogenic Source of Biogenic Methane in the North Sea. Environ. Sci. Technol. 2017, 51/17, 10262–10268.

Vielstädte, L., Linke, P., Schmidt, M., Sommer, S., Haeckel, M., Braack, M., Wallmann, K., 2019. Footprint and detectability of awell leaking CO2 in the Central North Sea: Implications from a field experiment and numerical modelling. International Journal of Greenhouse Gas Control 84, 190–203.

Vrålstad,T., Saasen,A., Fjær,E., Øia,T., Ytrehus,J.D., Khalifeh,M., 2019. Plug & Abandonment of offshore wells: Ensuring long-term well integrity and cost-efficiency. Journal of Petroleum Science and Engineering 173, 478–491.

Yin, Y., Mastalerz, M., Lennon, J.T., Drobniak, A., Schimmelmann, A., 2020. Characterization and microbial mitigation of fugitive methane emissions from oil and gas wells: Example from Indiana, USA. Applied Geochemistry, 118, art. no. 104619,

10 Appendix A: Seismic interpretation

10.1 Used method is not suited for mapping shallow gas bright spots

The goal of the seismic analysis presented by Bottner et al. (2020) was to map in a (semi-) automatic way bright spots caused by shallow gas. The “PGSMegaSurveyPlus” 3D seismic dataset was used, that consist of numerous post-stack merged seismic surveys. These seismic surveys are especially used in oil and gas exploration/production for deeper targets. As a consequence of the merging, not all data is zero-phase (Brown, 2010) in the studied interval (Figure 2 of Böttner et al., 2020) and large differences in scaling (amplitude variations) between surveys exist. Next the RMS amplitude is calculated across the entire geological interval of interest. This methodology produces poor results, inaccurate outlines of bright spots, false negatives and (possibly) false positives. Figure 1 shows why this method yields poor results even when applied to a good (quality) seismic volume with shallow gas accumulations. The used method results in amplitude anomalies that do not reflect shallow gas accumulations correctly. When a similar workflow is applied to merged surveys (*e.g.* PGSMegaSurveyPlus) these errors become increased and differences between the seismic processing of the individual surveys is highlighted rather than geological features.

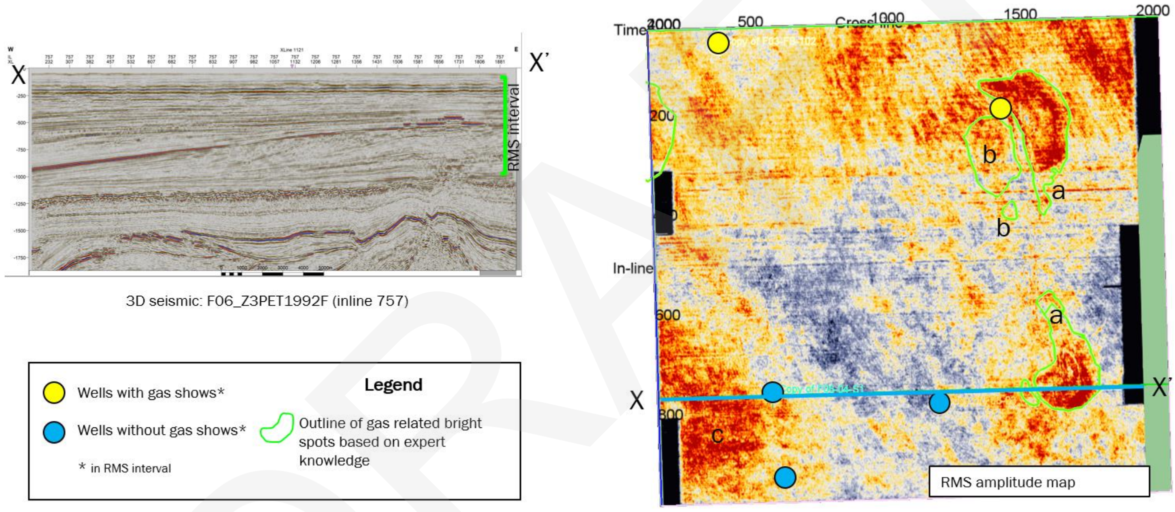


Figure 1: The RMS amplitude map is calculated over a large interval, which creates a stacked image of all seismic anomalies (bright spots related to gas, bright spots related to hard grounds, low energy zones due to chimneys, tunnel valleys, processing artifacts, etc.). This creates poor results: (a) The outlines of bright spots on the RMS amplitude map are not accurate when compared to the outlines of gas related bright spots based on expert knowledge. When measuring the distance of wells to bright spots, this will result in errors. (b) Certain gas related bright spots are not visible on the RMS amplitude map, creating false negatives. (c) Bright spots that are not related to shallow gas are also highlighted on the RMS amplitude map, creating (possible) false positives.

Moreover, the RMS amplitude map (Figures 3D, 5 of Böttner) will highlight the differences in scaling between seismic cubes and not the stacked anomalies. Figure 5 middle right of Böttner et al. (2020), shows that the results are unusable, since well 21/17a-6 is in the middle of a high RMS anomaly (bright spot), while the distance to the shallow gas related bright spot is reported to be 2400 m (appendix Böttner et al., 2020). The observation that “(…) *there is no apparent and statistically significant relationship between the propensity to leak and the RMS amplitude and RMS standard deviation”* indicates that this workflow yields unusable results.

Finally, Böttner et al. (2020) refer frequently to “*bright spots with polarity reversals”.* They suggest that they verified that the bright spots are caused by shallow gas by comparing the top reflector of the bright spot to the reflector of the seabed and that they are opposites (i.e. when the sea bottom reflector is a peak the top of a bright spot caused by gas should be a trough or vice versa). However, a “polarity reversal” (also called phase change, Brown, 2011) is another type of direct hydrocarbon indicator (DHI) (see Figure 2) and therefore Böttner et al. (2020) are effectively saying that shallow gas is causing not only a bright spot but also a phase reversal (i.e. two types of DHI’s combined). This is not the case for the depicted bright spots. Thus, the used terminology is not in accordance with standard geophysical interpretation practices (Brown, 2011).

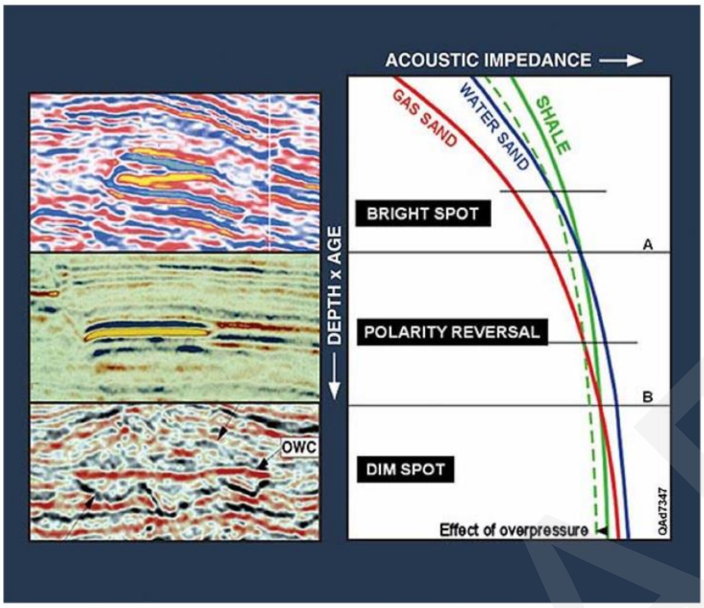


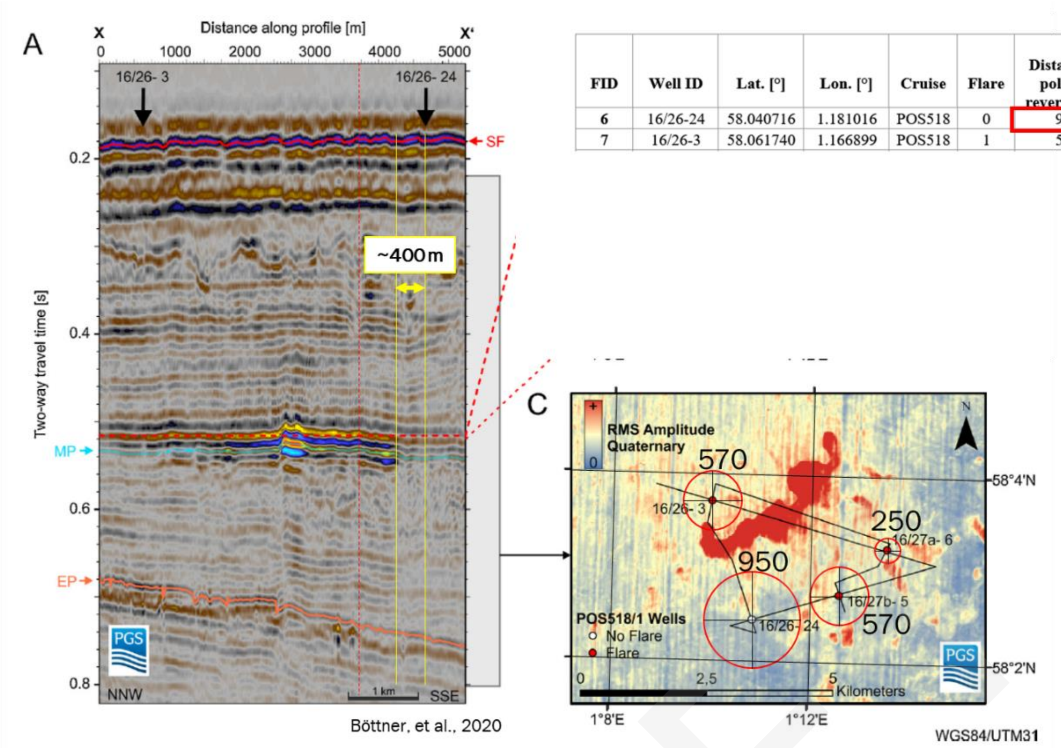
Figure 2: Direct hydrocarbon indicators; bright spot, polarity reversal, and dim spot (Brown 2011)

10.2 Using incorrect data for the polarity attribute

In order to identify if a high RMS response is indeed caused by shallow gas, an “apparent polarity attribute” is used by Böttner et al. (2020). This attribute only works when the data is zero phase and, as stated above, not all data is uniform zero phase. Consequently, this attribute is unreliable for identifying bright spots related to shallow gas. The implication of this finding cannot be ascertained.

10.3 Errors in distance wells-to-bright spots

Figure 6 of Böttner et al. (2020) shows a seismic cross-section and two attribute maps, the only illustration where the distance between wells a shallow gas can be verified. The distance between well 16/26-24 and the bright spot is about 400 meters, which is less than half the reported distance of 950 m in the provided additional data (see our Figure 3). It is unclear if this large difference is caused by errors in the figure or by measuring the distance on the (erroneous) RMS amplitude map. In any case, this distance cannot be reproduced by us. Furthermore, figure 6 of Böttner et al. (2020) contains multiple errors. Transect X-X’ is incorrectly depicted on the map B, because it does not cross the two wells when it is plotted on map C. Also, the bright spot that is visible on the transect does not line up with the RMS amplitude anomaly when compared to the map. This is most likely due to the ‘stacking of multiple anomalies’-effect of the RMS attribute but it could also be an error in the position of the transect.



FID	Well ID	Lat. [°]	Lon. [°]	Cruise	Flare	Distance to polarity reversal [m]
6	16/26-24	58.040716	1.181016	POS518	0	950
7	16/26-3	58.061740	1.166899	POS518	1	570

Böttner, et al., 2020

Figure 3: This is Figures 6 of Böttner et al. (2020) which contains a seismic cross-section and two attribute maps. This is the only illustration where we can verify the distance between wells and shallow gas, but we are unable to reproduce their findings. The distance between well 16/26-24 and the bright spot is about 400 meters, which is less than half the reported distance of 950 m.

10.4 Unproven and unlikely shallow gas accumulations

"(…) bright spots likely indicate the presence of shallow free gas (…)" (Figure 2 of Böttner et al., 2020). The indicated bright spots are small, chaotic and located in a low. As indicated, the gas is free to move and is therefore unlikely to conform to lows, unless trapped in a stratigraphic trap (Doornenbal et al. 2019). No explanation is given for the occurrences of bright spots in lows. We are presented with too limited data to confirm that these bright spots are indeed caused by shallow gas. Furthermore, the seismic results are not compared to well data at all. (Gas)logs can give insight into the presence of shallow gas and should be used to confirm the presence of shallow gas. For example, Abrakasa (2011) pointed out that 38% of the wells that he studied in the North Sea (partly overlapping with the study area of Böttner et al.) have thermogenic gas ≥ 1000 m above the reservoir caprock.

11 Appendix B: Selective well usage

Böttner et al. (2020) concluded that 28 out of 43 wells release gas. We note that 15 more wells were measured during the cruises POS534, POS518 and MSM63 (Linke and Haeckel, 2018; Schmidt et al., 2019; Berndt et al., 2017) but were not included. There is no explanation why these wells were not taken into account. It is scientifically unsatisfactory that wells were not included without additional arguments for the reasons behind. Especially, since a group of wells was used to perform a quantitative upscaling of the findings towards the mega-survey area and a qualitative one for the North Sea as a whole. The statistics might change with 15 wells added to 43 ones.

11.1 POS534 and POS518 cruises - 5 wells not used

According to the provided track data of cruises POS534 and POS518, multibeam echosounder data was acquired at four wells (21/02- 07, 21/02- 1, 21/02- 5 and 21/03b- 3) and one well (22/03a- 1), respectively (Figure 4), but not included in the publication. Please note that these wells lie within the study area of the 3D seismic mega-survey.

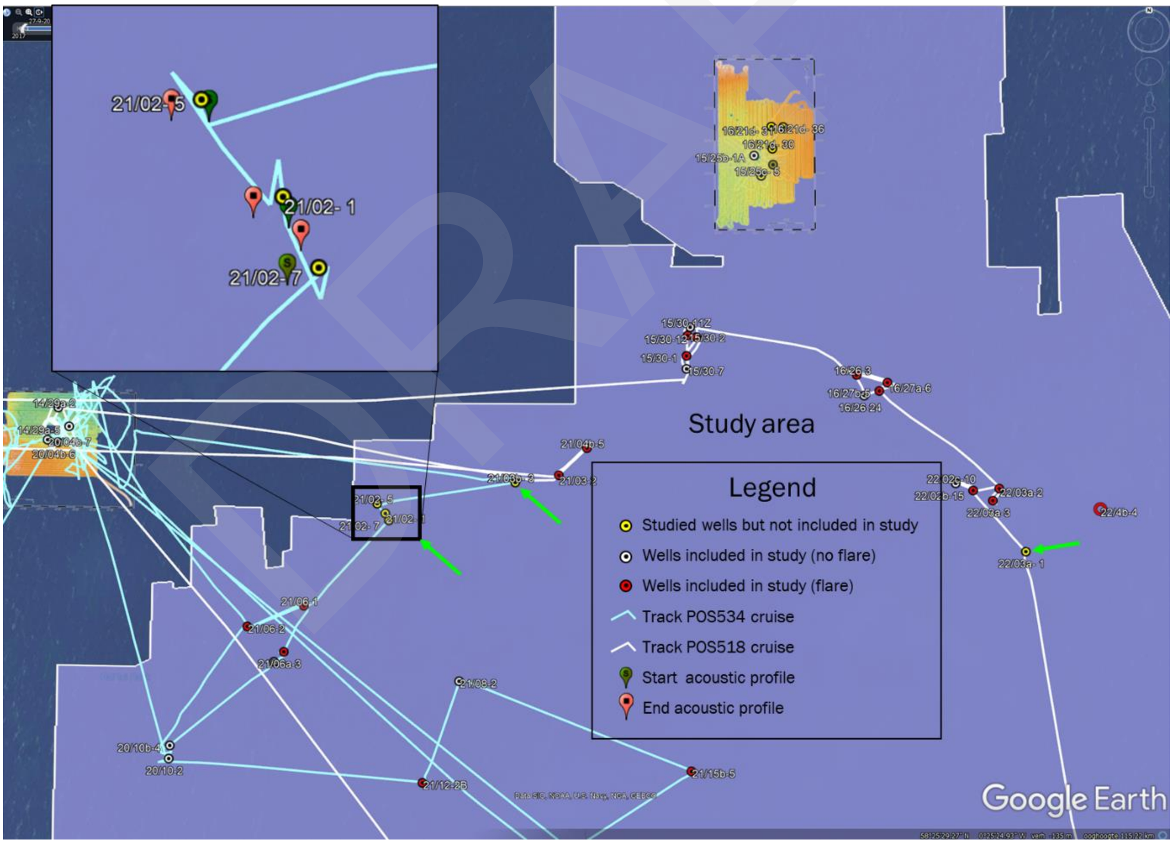


Figure 4: Multibeam echo sounder data at wells of cruises POS534 and POS518 shows that data was acquired at five more wells (21/02- 07, 21/02- 1, 21/02- 5, 21/03b- 3, and 22/03a- 1 indicated with green arrows) than reported by Böttner et al. (2020).

11.2 MSM63 cruise (Scanner pockmark area) – 6 wells not used

Böttner et al. (2019) used data collected by MSM63 cruise (Berndt et al., 2017) in the Scanner pockmark area. Six wells are located in the study area (15/25b-1A, 15/25c- 5, 16/21b- 25, 16/21d-30, 16/21d- 36, 16/21d- 31) and all were imaged by multibeam echo sounder (Figure 5, right side). Well 15/25b-1A in the Scanner Pockmark area is located very close to the Scanner pockmark (being the largest pockmark in the area) where a flare was seen at the pockmark location. It is unclear to us why these 6 wells were not included as data-points (Figure 5, Böttner et al. 2020).

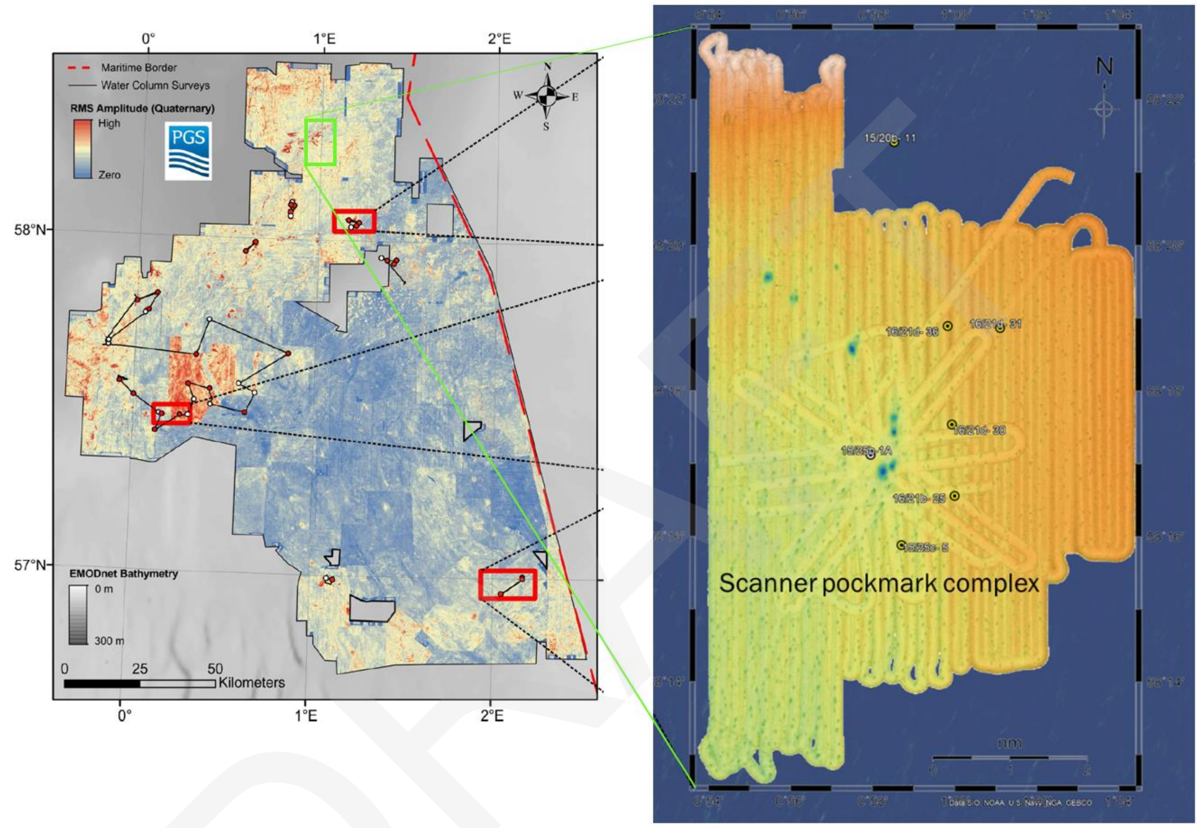


Figure 5: Six wells in the Scanner pockmark complex were studied on the research cruise MSM63 (figure on the right after Berndt et al., 2017; Böttner et al., 2019). Böttner et al. (2020) selected 43 wells but did not include the 6 wells (yellow dots) in the Scanner Pockmark Area (figure on the left, Figure 5 from Böttner et al., 2020). The multibeam bathymetry map of the Scanner pockmark complex area (right) illustrates the intensive measurement campaign and the presence of natural pockmarks (blue spots).

11.3 Wells used outside the mega-survey – 2 used, 4 wells not used

Two wells (22/02c-10 and 22/02b-15) lie within a window that was not covered by the “PGSMegaSurveyPlus” 3D seismic dataset (see Figure 5 of Böttner et al. 2020). Nevertheless, a distance to a bright spot was determined without 3D seismic data at these well locations. We consider this as unjustified: theoretically, a bright spot might be present closer. Remarkably, no leakage probability was plotted for these wells in Figure 8 of Böttner et al. (2020), which seems inconsistent to us.

As part of the POS534, POS518 and MSM63 cruises, four more wells (14/29a-5, 20/04b-6, 20/04b-7, 14/29a-2) were investigated around the Goldeneye Field near the study area (Figure 6). No flares were detected at these wells, while natural flares and pockmarks were observed in the area. These wells (and flares) lie outside the study area of the 3D seismic dataset, like wells 22/02c-10 and

22/02b-15. However, the presence of natural gas leakage at pockmarks and the absence of leakage at gas wells is worth being noted and not in line with their reasoning.

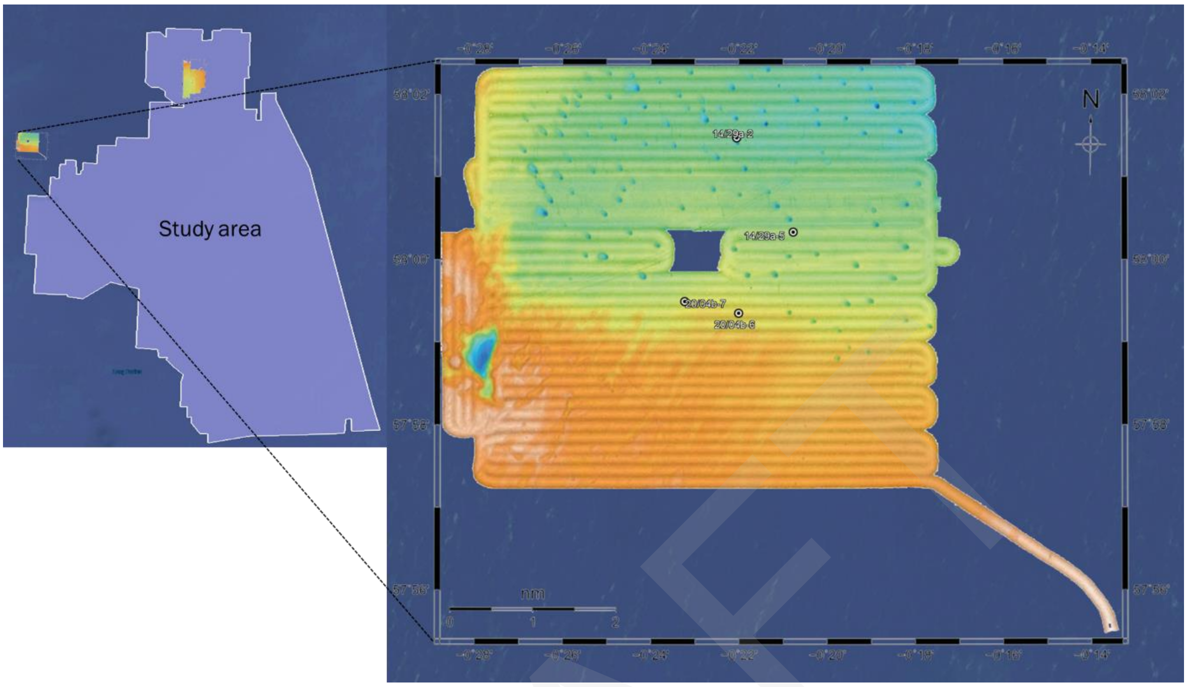


Figure 6: Wells and pockmarks were studied in the Goldeneye area on cruise MSM63 (Modified from Berndt et al., 2017). Right: Multibeam bathymetry map shows pockmarks (blue dots). All wells had no flare. The presence of natural gas leakage at pockmarks and the absence of leakage at gas wells is worth being noted and not in line with the reasoning of Böttner et al. (2020).

11.4 Wells near natural leakage sites

The main challenge is to differentiate between natural and anthropogenic leakage at well locations. While the authors are well aware of natural leakage no effort was made to distinguish the differences. On this subject Böttner et al. (2020) only quotes *"Natural seepage from the seafloor in close vicinity to leaking wells (see wells 23/26a-11 & 30/01a-7 in Fig. 5; Linke and Haeckel, 2018)" suggests that wells are not necessarily cannibalizing natural release of methane from the seafloor but represent a new, anthropogenic fluid migration pathway".* How the differentiation between natural and anthropogenic leakage was made, is not explained. The report of the cruise (POS518) by Linke and Haeckel (2018) state: *"… a natural seep was discovered above a buried salt dome, next to wells 31/01a-7 and 30/01f-8".* Please note that the reported wells by Linke and Haekckel (2018) are not identical to Böttner et al. (2020). As mentioned, natural seeps above salt domes are well known in this area (Tommeliten seep area). Linke and Haeckel (2018) suggest that the differentiation is made based on a distance to the well. Unfortunately, the distances between the wellheads and the flares is not specified and it is unclear what distances Böttner et al. (2020) have classified as leakage "*from the well head location*" and what distances are considered as natural leakage. The article could have improved by specifying flare locations in the study area irrespective of well locations (Römer et al. 2017).

12 Appendix C: Statistical analysis and potential leakage of wells

12.1 Probabilities of leakage

We noted some errors in the classification of the wells, which implies that 4 out of the 43 were incorrectly processed. Two of the 43 wells lie outside the PGS "Mega Survey Plus" 3D seismic survey. These wells should not have been used to derive the relationship between leaking at wells and the distance to a bright spot. Although they were used, no leakage probability was computed for these wells (see Figure 8 of Böttner et al. 2020). This leaves 41 of the 43 measured wells for which a "probability of leakage" was computed. Of these wells, well 16/26-3 is located 570 m from a bright spot and falls in the "> 0.6–0.8" leakage probability group (compare Figures 5 and 8 from Böttner et al., 2020). According to the regression function of their Figure 7 (Böttner et al., 2020) it should fall in the "> 0.4-0.6" leakage probability group. Well 16/26-3 has exactly the same distance to a bright spot as well 16/27b-5 (e.g. 570), and this well falls in the "> 0.4-0.6" leakage probability group. Well 21/06b-6 is classified as a "0.2 – 0.4 leakage probability group" while the regression fit of Fig 7 of Böttner et al., (2020) places it in the "0.4-0.6 leakage probability group"

Furthermore, well 15/25b-1A, that was discussed by Böttner et al. (2019), was drilled in close proximity (400 m) of the large Scanner' pockmark (see Figure 5) which brings upon long-lasting seepage with active flares. Underneath this specific pockmark is a large bright spot present (Figure 7), indicative of a shallow gas accumulation. Based on the seismic cross-sections published by Böttner et al. (2019), the well is drilled 100 meters from this bright spot (apparent distance). Although, numerous passes were made over this well during cruise MSM-63 (Figure 5, right), no leakage was reported by Böttner et al. (2019). Furthermore, Böttner et al. (2020) did not include this well in their list of "leaking wells in the vicinity of natural leakage". We, therefore, conclude that this well is not leaking. This is in sharp contrast with their conclusions that all wells drilled within a 300 m distance to a shallow gas bright spot leak. Remarkably, our deduction that the well is not leaking is confirmed by the leakage probability of Böttner et al. (2020) which is > 0.2-0.4 according to their Figure 8. However, this well should fall into the 'high leakage probability' (0.8-1.0) group according to the assumptions made by Böttner et al. (2020) based on its proximity to a bright spot. In conclusion, the probability class of well 15/25b-1A seems erroneous which potentially disproves their conclusion that *"the distance between the well and the most proximal bright spot with polarity reversal is shorter than 300 m, leakage is highly likely (100%, 20/20 wells)"*.

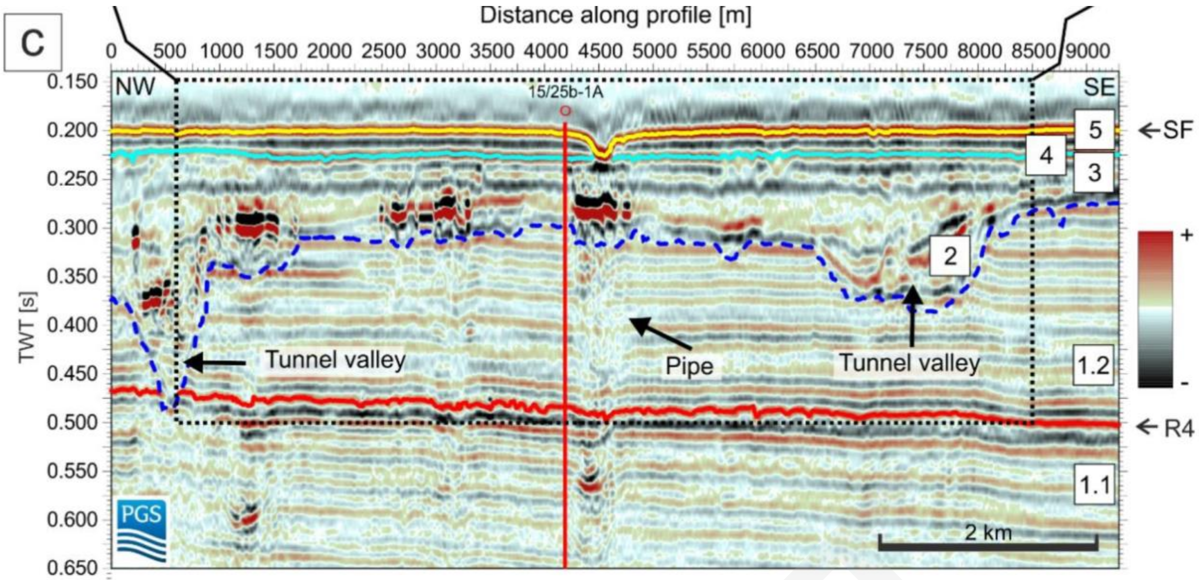


Figure 7: Well 15/25b-1A is located 100 m from a bright spot above which a natural pockmark (Scanner) is present (depression in yellow surface). From Böttner et al., 2019.

12.2 Selection leakage rates from 3 Norwegian well sites

Böttner et al. (2020) use data on gas release at three decommissioned hydrocarbon wells as investigated by Vielstädte et al. (2015) from the same research group. These three wells lie in the Norwegian sector less than 50 km away from the northeastern corner of the area studied by Böttner et al. (2020). Vielstädte et al. (2015; 2017) estimated the annual methane release rate at well 15/9-13 where a bright spot was present as 1 ton y^{-1} , at well 16/4-2 where no bright spot was as 4 ton y^{-1} and at well 16/7-2 where both a bright spot and a seismic chimney were present as 19 ton y^{-1}. Unfortunately, Vielstädte et al. (2015 & 2017) did not provide any error estimates on their release rate estimates as the values play such an important role in subsequent papers. In their regionalization of methane release, Böttner et al. (2020) chose the rates from the first two wells (15/9-13 and 16/4-2) as input in the calculations and excluded well 16/7-2. This is remarkable in different ways.

First, no shallow gas pocket is present at well 16/4-2 according to Fig. 5 of Vielstädte et al. (2015). This is recognized by Vielstädte et al. (2015) and explained as follows: “*near-surface sediments (Fig.5C,.1–0.4 s two-way-traveltime TWT) show seismic turbidity, which might indicate an unfocussed distribution of gas (Judd and Hovland,1992)”*. In other words, the methane leakage at well 16/4-2 is not related to bright spots. However, Böttner et al. (2020) did relate well 16/4-2 to bright spots without giving an explanation why they changed their interpretation. Furthermore, the closest shallow gas bright spot is small (approximately 200 by 100 m) and roughly 950 m away from the well (Fig. 5 of Vielstädte et al. , 2015). This is at the very limit at which Böttner et al. (2020) are claiming that gas release along abandoned wells originates from shallow gas pockets occurs. The fact that this well leaks 4 times more than a well that actually penetrates shallow gas is remarkable. Also, how the gas can migrate from a 200 by 100 m gas pocket laterally over a distance of 950 meters is at least extraordinary and needs explanation.

Second, it is illogical to exclude one well (16/7-2) that shows a seismic chimney and also a bright spot as non-representative. Chimneys are not uncommon in the North Sea (e.g. Heggland, 1998; Schroot et al., 2005; Karstens & Berndt, 2015) and are considered to indicate vertical fluid conduits (Cartwright & Santamarina, 2015). There are various seismic interpretation packages (*e.g.* OpendTect ChimneyCube), that can be used to detect which wells were drilled in a seismic chimney

(Tingdahl et al., 2001). Following their line of reasoning to exclude well 16/7-2 (one out of three), all wells drilled in a seismic chimney (found in the study area) should be excluded. However, the presence or absence of seismic chimneys at abandoned wells was not investigated by Böttner et al. (2020).

Vielstädte et al. (2015) explicitly raised the question what the cause is for the high release rate for well 16/7-2 drilled through a gas chimney: *''to what extent the migrating gas appears to separate from the borehole fracture and uses pre-existing conduits created by the chimney sometime in the geological past.''* In other words: to what extent is the gas release around this well natural and not anthropogenic? In regionalizing the gas release rate from three studied wells, the subsequent question arises what the gas release rate at regional scale is for wells drilled through a chimney? This question did not become addressed by Böttner et al. (2020) which makes any comparison between natural and anthropogenic release of methane in the North Sea incomplete.

12.3 Böttner et al. (2020) and Böttner (2020)

The publication of Böttner et al. (2020) is based upon the PhD thesis of Böttner (2020). Both publications use the same data set but present, interpret and calculate it different and nevertheless come to the same total methane leakage estimate. In Böttner's PhD thesis , only 14 out of 1792 wells have *a high leakage likelihood* (Chapter 3, Table 1 of Böttner, 2020) in contrast to 926 wells which are likely to leak with a 95% confidence interval according to Böttner et al. (2020). Consequently, many wells that were classified as 'low leakage probability' in the PhD thesis, became classified as 'high leakage probability' in the publication. This large difference is clear when Figure 8 of Böttner et al. (2020) is compared with Figure 3.8 from his thesis. Although the leakage probabilities and calculations according to the two publications are entirely different, the methane leakage estimate is the same. These large differences in interpretation of the same data is remarkable and should at least be clarified.