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Reply to comment on "Greenhouse gas emissions from marine decommissioned hydrocarbon wells: Leakage detection, monitoring and mitigation strategies"

Christoph Böttner[a,b,*], Matthias Haeckel[b], Mark Schmidt[b], Christian Berndt[b], Lisa Vielstädte[b], Jakob A. Kutsch[a], Jens Karstens[b], Tim Weiß[b]

[a] Christian-Albrechts-Universität zu Kiel, Christian-Albrechts-Platz 4, 24118 Kiel, Germany
[b] GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstr. 1-3. 24148 Kiel, Germany

Hydrocarbon gas emissions from decommissioned wells are an underreported source of greenhouse gas emissions in oil and gas provinces and the associated emissions may partly counteract efforts to mitigate greenhouse gas emissions from fossil fuel infrastructure (Böttner et al., 2020). We presented a new approach for assessing and predicting methane leakage from marine decommissioned wells based on a combination of existing regional industrial seismic and newly acquired hydroacoustic water column imaging data from the Central North Sea. By combining available direct measurements for methane release from marine decommissioned wells (worldwide up to now only a single published data set consisting of measurements at three wells by Vielstädte et al., 2015, exists) with our leakage analysis, we found that gas release from the investigated 1792 decommissioned hydrocarbon wells in the UK sector of the Central North Sea could amount to 0.9–3.7 kt yr^{-1} of methane (Böttner et al., 2020) .

This research article has undergone full peer-review by four anonymous reviewers and a very careful editor in three iterations over the time span of more than a year. Especially the reviewers with industry background made very valuable suggestions for the improvement of the manuscript. All this helped to clarify the main aspects and avoid errors or incomplete reasoning in the manuscript. The article has reached a large readership of stakeholders, academics, and industry, and already spawned scientific investigations by the neighboring countries of the North Sea (e.g. by the German Federal Institute for Geosciences and Natural Resources (BGR) or the Norwegian Petroleum Directorate (NPD)).

We are therefore surprised to read the comment by Wilpshaar et al. (2021) which offers fundamental criticism of our study on behalf of TNO, the Geological Survey of the Netherlands. Therefore, we would like to clarify the aspects of our manuscript that they have obviously misunderstood and misinterpreted. Unfortunately, the vast majority of their comments is unwarranted and unsubstantiated and we would like to take the opportunity to reply to their main topics of critique.

Natural methane seepage is of course an important topic and needs further investigation in order to constrain its contribution to global and local methane budgets. However, it is beyond the scope of our article to go into more depth on this topic as we have done in the introduction. For a proper context, we have provided a sufficient number of references as exemplary background information on natural methane leakage in the North Sea (e.g. Böttner et al., 2019; Crémière et al., 2016; Dumke et al., 2014; Römer et al., 2017; Schneider von Deimling et al., 2011). We acknowledge that we have not mentioned Holocene peat as another source of methane in coastal areas (Borges et al., 2016; Missiaen et al., 2002).

Anthropogenic leakage pathways associated with wells can be grouped into two possible scenarios, well integrity issues and drilling-induced fractures, which we have discussed extensively in our manuscript. In shallow sediments (less than 2–3 km depth), fractures may form laterally and vertically and hydraulically connect subsurface layers (Bohnhoff and Zoback; 2010; Gurevich et al., 1993; Kårstad and Aadnøy, 2008; Dugan and Sheahan, 2012). Such fractures are frequently encountered in cases where the drilling mud is overbalanced (Edwards et al., 2002; Guha et al., 2006). Drilling-induced fractures mechanically weaken the sediment and increase the permeability with regard to the surrounding and represent potential leakage pathways. We would like to note that this leakage type has also been widely described, discussed, and accepted in the context of carbon dioxide capture and storage in geologic formations that are penetrated by oil & gas wells (e.g., IPCC CCS Report in 2005 and references therein: Metz et al., 2005). Hence, the repeated claim of Wilpshaar et al. (2021) that this leakage type "is

* Corresponding author.
E-mail address: christoph.boettner@ifg.uni-kiel.de (C. Böttner).

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not realistic", has no scientific basis.

The comment's opinion on seismic interpretation comprises a number of assertions and unsubstantiated claims making this critique questionable. We would like to note that large parts of our manuscript have been ignored and parts of our figures have been cut out, thereby leaving the deceptive impression of incorrect work.

For the interested readership, we would like to summarize shortly our procedure again. The distances between wells and identified gas accumulations (i.e. bright spots with polarity reversal in the seismic data) were measured for all 1792 well locations. As described in our article, we semi-automatically picked the seismic horizons (e.g. Early Pleistocene, Mid Pleistocene, Seafloor), calculated RMS amplitudes for volumes in-between those horizons and identified bright spots (high-amplitude responses of the subsurface). In a second step, we verified that these high-amplitude responses had a polarity reversal (phase shift) in relation to the seafloor to identify the potential locations of free gas. This procedure is the standard technique in seismic interpretation and also discussed in our article in great detail, including pitfalls and shortcomings of post-stack reflection seismic data. This is not a one-size-fits-all approach as we have clearly lined out the boundary conditions, an interpreter is still necessary and we explain why this can be applied to other seismic mega surveys.

We appreciate to read that the comment picked up the recommendations for future work in the PhD thesis of Böttner (2020) with respect to seismic chimney investigations across mega surveys. We kindly refer to Robinson et al. (2021) for further details and the complexity of seismic chimney investigations. We note that the use of seismic attributes such as the "Chimney Cube" (i.e. OpendTect tool) for post-stack mega surveys requires large computational power and storage capacity, which may be available at governmental authorities such as TNO (Meldahl et al., 1999). If these are available, a high signal-to-noise ratio and a homogeneous mega survey would be of great advantage for meaningful results, but a careful quality control by an interpreter would still be necessary (Heggland et al., 1999).

Regarding the unsubstantiated claim on selective well usage by Wilpshaar et al. (2021)*,* we would like to reiterate that in the introduction of (Böttner et al., 2020), we explain in detail that our paper builds on previous investigations, where we have established that the respective leakage is associated with shallow gas. The purpose of our paper is to investigate this topic further. Thus, it is very clear from the start of our paper that random sampling would not have progressed our knowledge. Instead, it was the purpose of our study to investigate if seismic identifiers of shallow gas are indeed a suitable indicator for leakage propensity of wells penetrating through or being drilled close to such seismic anomalies. We have applied high scientific quality standards for the hydroacoustic surveys (e.g. high-resolution imaging, very low survey speed, crisscrossing survey lines) in order to avoid false positive interpretations of water column anomalies (e.g. by shoals of fish, ghost nets, etc.). These very high data quality standards were not achieved during any of the previous surveys (e.g. too high sea-state, no crisscrossing lines, etc.) that investigated other wells for various reasons (also not by Römer et al., 2017, Römer et al., 2021) . In addition, for some of the wells surveyed by us (e.g. wells around Goldeneye) existing seismic data were not made available for scientific publication and thus had to be excluded from the analyses.

The statistical analysis has been falsely displayed and has been incorrectly interpreted by Wilpshaar et al. (2021). Fig. 7 of our article (Böttner et al., 2020) shows the empirical probability density functions (PDF) of the 43 investigated wells. It is obvious that there is no apparent and statistically significant relationship between the propensity to leak and the RMS amplitude and RMS standard deviation, which is why we have excluded it from the leakage propensity analysis.

Instead, we have used the measured distance between all wells of the test group ($n = 43$) and all those who are within the seismic data set ($n = 1792$) and their closest bright spot with polarity reversal. All wells of the test group with a distance to the next bright spot of less than 300 m showed flares in the water column <u>directly above the known well location</u>, i.e. indicating gas release from the well (see Fig. 5, Fig. 7 in Böttner et al., 2020). Wells that are further away than 1 km from such bright spots with polarity reversals showed no leakage (Fig. 5, Fig. 7 in Böttner et al., 2020). We have included a reference to document that gas migration is favored by dipping beds to a proven distance of 1.2–1.4 km *(*Landrø, 2011; Landrø et al., 2019*)*. We agree that geological pre-conditions play a key role in the well's propensity to leak and gas will not move downdip, which is why we have discussed this already in our original article.

Onshore leakage of methane and other hydrocarbon gasses from abandoned wells is evident, but independent emission estimates are scarce. In the U.S., for example, studies have shown that the numbers provided by the industry and authorities are too low (Allen et al., 2013; Miller et al., 2013). In particular, in Pennsylvania abandoned wells contribute 5–8% of the annual anthropogenic methane emissions (Kang et al., 2016), and thus partly counteract efforts to mitigate greenhouse gas emissions from fossil fuel infrastructure (Brandt et al., 2014). In the Netherlands, there is evidence for prolonged leakage of methane from abandoned boreholes on land (Schout et al., 2019) and prolonged leakage of methane from the 1965 blowout SLN-02 (Schout et al., 2018).

We appreciate that Wilpshaar et al. (2021) agree with us that methane emissions from decommissioned on- and offshore hydrocarbon wells require more attention. Wells should be monitored after abandonment and more independent estimates of emission rates from oil and gas infrastructure are needed since these originate almost exclusively from the industry itself. This is particularly necessary to improve current guidelines and regulations and to reduce fugitive emissions of methane – the second most important greenhouse gas – as recommended in the latest IPCC assessment (IPCC, 2021).

Declaration of Competing Interest

The authors declare no conflict of interests.

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