Shallow Gas Migration along Hydrocarbon Wells—An Unconsidered, Anthropogenic Source of Biogenic Methane in the North Sea

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ABSTRACT: Shallow gas migration along hydrocarbon wells constitutes a potential methane emission pathway that currently is not recognized in any regulatory framework or greenhouse gas inventory. Recently, the first methane emission measurements at three abandoned offshore wells in the Central North Sea (CNS) were conducted showing that considerable amounts of biogenic methane originating from shallow gas accumulations in the overburden of deep reservoirs were released by the boreholes. Here, we identify numerous wells poking through shallow gas pockets in 3-D seismic data of the CNS indicating that about one-third of the wells may leak, potentially releasing a total of 3–17 kt of methane per year into the North Sea. This poses a significant contribution to the North Sea methane budget. A large fraction of this gas (~42%) may reach the atmosphere via direct bubble transport (0–2 kt yr⁻¹) and via diffusive exchange of methane dissolving in the surface mixed layer (1–5 kt yr⁻¹), as indicated by numerical modeling. In the North Sea and in other hydrocarbon-proliﬁc provinces of the world shallow gas pockets are frequently observed in the sedimentary overburden and aggregate leakages along the numerous wells drilled in those areas may be signiﬁcant.
driven migration of the gas.\textsuperscript{20} We present new and important data on the probability of shallow gas migration along hydrocarbon wells in the North Sea, including the extensive analysis of an industrial 3-D seismic data set that covers an area of \(\sim 2000\) m\(^2\), and provide the first estimates on its regional relevance, including comprehensive modeling, literature review, and GIS analysis. On the basis of this information, we reinvestigated the CH\(_4\) budget of the North Sea, indicating that shallow gas migration is likely of regional significance.

### MATERIALS AND METHODS

#### Data Analysis in the Central North Sea (CNS)

Evidence for shallow gas migration along offshore hydrocarbon wells was first reported by Vielstädte et al.\textsuperscript{20} who investigated three leaky abandoned wells (15/9-13, 16/4-2, and 16/7-2) located in water depth of 81–93 m in the CNS. For the extrapolation analysis of CH\(_4\) leakage to the North Sea scale presented here, we used relevant data on shallow gas migration that has been published in this earlier study\textsuperscript{20} including geochemical data that characterized the origin of the emanating gases, leakage rates, initial gas bubble size distributions (Table 1), and the analysis of industrial 3-D seismic data (ST98M3, Statoil ASA) for shallow gas pockets in the area around the three wells by mapping high amplitude anomalies in the upper 1000 m of sediment using Petrel (Schlumberger). We additionally analyzed CH\(_4\) oxidation rates in the water column at wells 15/9-13 and 16/7-2 (Table 1) and total organic carbon and sulfate concentrations in near surface sediments obtained during cruise CE12010 (July–August 2012; Figure S4). In addition, we estimated the leakage probability of wells in an area of \(\sim 2000\) km\(^2\) in the Norwegian Sector of the CNS by identifying 18 out of 55 wells (i.e., 33\%) that poke through shallow gas pockets in 3-D seismic data (ST98M3, Statoil ASA). Assuming a binomial distribution from a Bernoulli process, a sample size of 55 wells, investigated during seismic analysis, produces an uncertainty in the leakage frequency of 10\%.

#### Extrapolation of CH\(_4\) Leakage to the North Sea Scale

CH\(_4\) leakage from wells into the North Sea and the atmosphere was calculated by applying results of a numerical bubble dissolution model\textsuperscript{109} to the EMODNet North Sea bathymetry (available at http://www.emodnet-bathymetry.eu) and combining publicly available data on drilled wells (see SI Table S3 for details) using the geographical information system software ArcGIS 10.1. In total, 1122 active and inactive wells were selected for the CH\(_4\) flux quantification excluding sidetracks of wells (see SI Table S4). The North Sea was subdivided into equal area polygons of 25 km\(^2\) using a Cylindric Equal Area projection.
projection, and the seabed CH$_4$ flow ($Q_{sfp}$) was calculated for each of these polygons multiplying the determined leakage probability of 33 ± 6% for the wells, the number of wells located inside each polygon, and the range of per-well CH$_4$ leakage rates of 1−4 t yr$^{-1}$ (sample range, $N = 2$) observed in the CNS. Note, we only consider the two lower gas flows measured at wells 15/9-13 and 16/4-2 because they are believed to be more typical for shallow gas migration than the larger gas flow measured at well 16/7-2, which was drilled through a seismic chimney (for details see Discussion and SI Section 2.1.1). For each polygon, the resulting CH$_4$ flow from the surface water into the atmosphere was then estimated applying a transfer function describing the CH$_4$ bubble transport efficiency to the sea surface and to the SML of the North Sea as a function of the seabed CH$_4$ flow and water depth (SI Section 2.2.2). All determined flow estimates and the effective uncertainty in the leakage frequency of wells were added to calculate the potential range of total CH$_4$ ebullition from the seafloor and into the atmosphere. Reported values of CH$_4$ leakage into the North Sea and the atmosphere are expressed in kilo tonnes of CH$_4$ per year (kt yr$^{-1}$ of CH$_4$), considering the potential range of per-well leakage rates of 1−4 t yr$^{-1}$ of CH$_4$ (sample range, $N = 2$) and an uncertainty in the leakage frequency of 6% for the wells ($N = 5$). Full methodology and a discussion of associated uncertainties are provided in the Supporting Information.

Figure 2. Distribution of wells and shallow gas in the North Sea. (a) Areal distribution of shallow gas pockets that have been mapped by high-amplitude anomalies in industrial 3-D seismic data (ST98M3, Statoil ASA) and the seafloor location of wells in the Norwegian CNS. The seismic correlation of 55 well paths revealed that one-third of the wells were drilled through shallow gas accumulations in Miocene/Pliocene (green), Lower Pliocene (red), Top Pliocene (blue), and Pleistocene (orange) stratigraphic units. Upper left corner: Bathymetric map of the North Sea showing the location of the study area (white rectangle) and the distribution of wells (black dots). (b) Seismic profiles indicating shallow gas pockets in the subsurface around the well paths of the three leaky abandoned wells investigated by Vielstädt et al. (orange line). At well 16/7-2 chaotic reflections indicate the presence of a seismic chimney (dashed white lines).
In the North Sea, Pleistocene and Pliocene organic-rich sediments are the most prominent stratigraphic units containing biogenic gas accumulations that are widespread in 300–750 m sediment depth. Vielstaedt et al. identified these units as potential source areas for the CH₄ emitted along three leaky, abandoned wells investigated in the Norwegian Sector of the CNS. CH₄ in the seep gas was isotopically light (δ¹³CCH₄ < −70‰ VPDB) and contained only minor amounts of higher hydrocarbons (C₁/CΣC₄ > 1000), clearly pointing toward a biogenic origin (Table 1, SI Figure S2). The shallow origin is supported by bright spots (e.g., reverse polarity high-amplitude seismic anomalies) and zones of chaotic signatures in the seismic data surrounding the three well paths (Figure 2b).

Here, we further hypothesize that leakage from existing wells in the North Sea is likely to constitute an important part of the respective regional CH₄ budget due to the large number of wells (i.e., ~11 122, discounting extra sidetracked wellbores) and ubiquitous gas accumulations in the shallow subsurface (Figure 2, SI Table S4). In the following, we will thus assess CH₄ leakage along wells into the North Sea and estimate the resulting emission into the atmosphere. Tracking the subsurface well paths of 55 wells in an area of ~2000 km² in the Norwegian Sector of the CNS, where shallow gas accumulations have been identified by bright spots in industrial 3-D seismic data, we examine the likelihood of wells to leak shallow gas: 18 out of 55 wells in this area (about 33 ± 6%) were drilled through shallow gas accumulations and are thus believed to leak CH₄ (Figure 2). Individual leakage rates along three wells (15/9-13, 16/4-2, and 16/7-2) in this area were highly variable, amounting to 1, 4, and 19 t yr⁻¹ of CH₄, respectively (Table 1, SI Table S1). These rates are in the upper range of gas emissions measured from soils around wells in Alberta (i.e., ~ 0.03–16 t yr⁻¹ of CH₄). The highest release rate in the North Sea was measured at well 16/7-2, which was drilled through a seismic chimney (Figure 2b), typically believed to be more permeable than the surrounding sediment. Assuming that the high gas flow at this well is representative for only a small fraction of leaky wells in the North Sea and that the two lower rates of wells 15/9-13 and 16/4-2 are more typical for shallow gas migration, we solely consider the two lower rates in our extrapolation analysis (i.e., sample range, N = 2). Given the small sample size of only three measured wells in the North Sea and the unknown spatial and temporal variability of the ebullition (i.e., CH₄ flow measurements at the three wells covered only a few minutes), we emphasize that the uncertainties in our per-well leakage rates are high.

Using publicly available wellbore data and extrapolating our results to the North Sea scale, we estimate that shallow gas migration along wells may release around 3–17 kt of CH₄ from the North Sea seafloor per year, assuming that 33 ± 6% of the 11 122 wells in the North Sea are leaking. In comparison to other major sources of CH₄ in the North Sea, i.e., rivers (0.5 kt yr⁻¹), the Wadden Sea area (1.1–2.1 kt yr⁻¹), and known natural seep sites (0.2 kt yr⁻¹), leaky wells may constitute a significant input to the CH₄ budget of the North Sea (Figure 3 and SI Table S5). It should, however, be noted that also numerous additional natural gas seeps have been observed at the seabed of the North Sea, but their abundance and contribution to the CH₄ budget are poorly constrained.

Despite the poor characterization of the North Sea CH₄ sources, the patchiness and high spatial variability of CH₄ supersaturation in the surface mixed layer (SML) of the open North Sea with respect to atmospheric partial pressure, i.e. 103–50 000%, suggest that ubiquitous point sources at the seabed (wells and natural seeps) dominate the regional CH₄ budget. The high supersaturation of the North Sea surface waters drives a diffusive CH₄ loss to the atmosphere of 10–50 kt yr⁻¹, which constitutes the major sink in the marine CH₄ budget (Figure 3).

To examine the extent to which emissions from leaky wells may contribute to the CH₄ budget of the North Sea, we apply a numerical bubble dissolution model to the North Sea scale. Each of the three key fates of leaking CH₄ is considered: (1) dissolution in the deep stratified layer (>50 m water depth), (2) dissolution in the surface mixed layer (SML, <50 m water depth) contributing to the outgassing to the atmosphere, and (3) direct gas bubble transport into the atmosphere. Leakage depths and initial bubble sizes play a critical role in transporting CH₄ from the seafloor to the atmosphere, thus defining the magnitudes of diffusive exchange and direct ebullition into the atmosphere (SI Figure S4). Average initial bubble sizes measured at the three investigated leaky wells (equivalent range, N = 2) were 607.5 m.
Figure 4. Potential emissions of shallow CH$_4$ along hydrocarbon wells into the North Sea and into the atmosphere. CH$_4$ emissions were calculated for 5 x 5 km$^2$ cells and assuming that 33 ± 6% of the 11 122 wells leak CH$_4$ at a rate of 1–4 t yr$^{-1}$ well$^{-1}$ (sample range, $N = 2$). Emission rates are expressed in tonnes of CH$_4$ per year per cell. A total annual seabed release of 3–17 (N = 11 122) kt of CH$_4$ is estimated for the North Sea (bottom), of which ~1–7 (N = 11 122) kt may reach the atmosphere (top). Highest CH$_4$ emissions into the atmosphere are expected in the Southern North Sea, where the water depths are shallower (mean water depth <40 m). The map’s geographic coordinate system refers to WGS84 and is displayed in Cylindrical Equal Area Projection.
leakage rates and the assumption that wells poking through shallow gas pockets will leak, which is corroborated by observed ebullition of biogenic gas at wells 15/9-13 and 16/7-2, as well as 15/9-11 and 15/9-16. However, Vielstädt et al. also found leakage at well 16/4-2, where no shallow gas pockets could be imaged in the seismic data (Figure 2b, note that the spatial resolution of the seismic data is ~10 m) but seismic turbidity may suggest the presence of gas in the vicinity of the well (see Figure 2b, 0.1–0.4 s two-way travel time (TWT)). The low TOC concentrations in surface sediments (~0.1 wt %) and high dissolved sulfate concentrations in associated pore fluids (29 mM) document the low potential for biogenic gas formation in CNS surface sediments (see SI Figure S4). These geochemical observations confirm that the biogenic gas emitted at the wells does not originate from microbial gas production in ambient surface sediments but from subsurface gas reservoirs. However, surveying for more leaky wells and quantifying their ebullition rates (including longer time-series) is clearly needed in order to better constrain the North Sea CH₄ budget and the anthropogenic contribution to atmospheric emissions.

Our new findings on human-induced greenhouse gas emissions are relevant to the understanding and future management of human-affected petroleum provinces in the North Sea and elsewhere. Currently, operators and regulators consider only leakage from surface oil and gas installations (wellhead, pumps, controllers, etc.) and stop assessing the well integrity after the well has been abandoned permanently. In addition, the focus of leakage from oil and gas wells is solely on fluids from the hydrocarbon reservoir. Our study indicates that this is not sufficient, and comparing the North Sea leakage rates to those measured from onshore abandoned wells in the U.S. indicates that gas migration along hydrocarbon wells may exceed emissions from the well annulus by 1–2 orders of magnitude, possibly because onshore studies miss significant gas fluxes from the soil surrounding the well. Our larger leakage rates are more comparable to those measured from active surface installations in the U.S., which give a similar value of ~2 t of CH₄ per year per well. Our and other recent studies clearly document strongly increased CH₄ emissions in areas with oil and gas operations, which may counteract our efforts to reduce greenhouse gas emissions by switching energy supply from coal to gas. Therefore, it is important to improve our surveying and monitoring efforts and adapt the respective regulatory frameworks (national and international), because the regional aggregate of thousands of wells with fairly low gas supply from coal to gas. Therefore, it is important to improve our surveying and monitoring efforts and adapt the respective regulatory frameworks (national and international), because the spatial resolution of the seismic data is ~10 m but seismic turbidity may suggest the presence of gas in the vicinity of the well (see Figure 2b, 0.1–0.4 s two-way travel time (TWT)).

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