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

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S Supporting Information

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 ($\sim 42\%$) may reach the atmosphere via direct bubble transport ($0\text{--}2\text{ kt yr}^{-1}$) and via diffusive exchange of methane dissolving in the surface mixed layer ($1\text{--}5\text{ kt yr}^{-1}$), 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.

INTRODUCTION

Gas leakage from hydrocarbon infrastructure is a major concern because the primary fugitive component of petroleum and natural gas is methane (CH_4), which has a significant global warming potential.¹ However, regular monitoring of wells is only mandatory during the active lifetime of the well and is solely targeted at the leakage of thermogenic gas and formation fluids from the deep reservoir.^{2,3} As such, emissions reported by the industry currently can only provide a lower estimate of atmospheric CH_4 emissions because not all leakages are identified and quantitative data on release rates are rare. This is supported by growing evidence for increased CH_4 emissions in hydrocarbon production areas^{4–11} that are generally attributed to leakage of the produced fossil fuel from several infrastructure parts during various operation steps^{4,11} and after well abandonment.^{12–15}

Conventionally, the petroleum industry considers the potential failure of well material (e.g., casing steel, cement), typically identified by sustained casing pressure (SCP),¹⁶ that is expected to lead to uncontrolled migration of reservoir gas to the surface installations (wellhead, pumps, and controllers, etc.). Available data on such well integrity issues provide an uncertain estimate of 2–75% of all wells² being compromised

and potentially at risk for leakage (Figure 1). Additional emissions of reservoir gas arise through the millions of abandoned wells^{10–15} and/or via gas migration along the well paths which is known to occur due to certain soil/sediment conditions or cementing issues in both active and abandoned sites. Both of these emission sources are not addressed in conventional well integrity surveys, so that the number of leakages and their emission rates are highly uncertain. In the Province of Alberta Canada, the only region where testing for gas migration through the soil is obligatory,¹⁷ 0.6–45% of wells showed soil gas leakage,^{18,19} but solely the discharge of reservoir fluids is targeted.

Here, we focus on the so-far unconsidered migration of biogenic CH_4 gas along the borehole originating from shallow gas accumulations that are penetrated when drilling into the underlying deep hydrocarbon reservoirs.²⁰ Drilling disturbs and fractures the sediment around the wellbore mechanically, thereby creating highly permeable pathways for the buoyancy-

Received: May 26, 2017

Revised: July 31, 2017

Accepted: August 1, 2017

Published: August 1, 2017

Figure 1. Industry and government reported data on loss of well integrity of onshore (gray) and offshore (blue) wells (compiled data based on Davies et al.²). Footnotes refer to the number of wells investigated in each survey. Such regulatory observations provide an uncertain estimate of 2–75% of all wells being compromised and potentially at risk for reservoir leakage. Additional emissions may arise from abandoned wells and/or via (shallow) gas migration along the well paths, which are not addressed in conventional well integrity surveys. Here, we study shallow gas migration along oil and gas wells in the North Sea (red star).

Table 1. Summary of Data from the Three Leaky Abandoned Wells^a

well	$\delta^{13}\text{C}_{\text{CH}_4}$ (‰ VPDB)	$\text{C}_1/\Sigma\text{C}_{2+}$ (L)	r_{MOx} (nM d ⁻¹)	$\text{CH}_{4\text{max}}$ (nM)	peak r_e (mm)	no. of seeps	Q_{SF} (t yr ⁻¹ well ⁻¹ of CH ₄)
15/9-13	−75.9	11 131	b.d. ^c	1014 ^c	2.4	2	1
16/4-2	−71.2	7254	n.d.	n.d.	2.7	8	4
16/7-2	−73.1	2320	0.19–1.4 ^d	10 579–17 294 ^d	5.7 ^b	39	19

^aStable carbon isotope signature ($\delta^{13}\text{C}_{\text{CH}_4}$) and hydrocarbon composition ($\text{C}_1/\Sigma\text{C}_{2+}$) of the free gas, as well as results of video-analysis of active gas bubble venting, i.e. the peak radius of the bubble size distribution (peak r_e), the number of bubble streams per well (seeps), and the per-well leakage rate from the seabed (Q_{SF}) are compiled from ref 20. Newly obtained data include CH_4 oxidation rates (r_{MOx}) and peak concentrations of dissolved CH_4 ($\text{CH}_{4\text{max}}$) in the bottom water. b.d.= below detection limit; n.d.= not determined. ^bAt well 16/7-2 bubbles with significantly larger radii were expelled into the water column, where gas accumulated below a carbonate rock, compared to direct release from the sandy sediments.²⁰ ^cData from CE12010 1-ROV1 and 31-CTD7. ^dData from CE12010 20-ROV6. ^eBased on an average gas flow of 1.4 L min⁻¹ seep⁻¹ at STP (25 °C, 1 bar).²⁰

driven migration of the gas.²¹ 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 ~2000 m², 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 CH₄ 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.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 CH₄ leakage to the North Sea scale presented here, we used relevant data on shallow gas migration that has been published in this earlier study²⁰ 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 anomalies²² in the upper 1000 m of sediment using Petrel (Schlumberger). We additionally

analyzed CH₄ 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 ~2000 km² 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 wells of 6% (1 – σ). A summary of relevant results published in an earlier study²⁰ and additional geochemical and seismic data are provided in Supporting Information Section 2.1.

Extrapolation of CH₄ Leakage to the North Sea Scale. CH₄ leakage from wells into the North Sea and the atmosphere was calculated by applying results of a numerical bubble dissolution model²⁰ 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, 11 122 active and inactive wells were selected for the CH₄ flux quantification excluding sidetracks of wells (see SI Table S4). The North Sea was subdivided into equal area polygons of 25 km² using a Cylindric Equal Area 116

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 Vielstädte et al.²⁰ (orange line). At well 16/7-2 chaotic reflections indicate the presence of a seismic chimney²⁰ (dashed white lines).

projection, and the seabed CH_4 flow (Q_{SF}) was calculated for each of these polygons multiplying the determined leakage probability of $33 \pm 6\%$ for the wells, the number of wells located inside each polygon, and the range of per-well CH_4 leakage rates of $1\text{--}4 \text{ t yr}^{-1}$ (sample range, $N = 2$) observed in the CNS.²⁰ Note, we only consider the two lower gas flows measured at wells 15/9-13 and 16/4-2²⁰ 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 chimney²⁰ (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 $1\text{--}4 \text{ t yr}^{-1}$ of CH_4 (sample range, $N = 2$)²⁰ and an uncertainty in the leakage frequency of 6% for the wells ($N = 55$). Full methodology and a discussion of associated uncertainties are provided in the Supporting Information.

Figure 3. Sketch of the CH_4 budget of the North Sea. CH_4 sources (black arrows) and sinks (green arrows) are expressed in kt of CH_4 per year. Atmospheric CH_4 emissions comprise direct emissions from leaky wells via bubble transport, predominantly in the shallower coastal and southern regions and the diffusive outgassing of CH_4 from the surface mixed layer. Leaky hydrocarbon wells (orange line) comprising the release of shallow buried gas (gray ellipse) investigated in this study and from the single blowout well 22/4b^{30,41,42} may contribute significantly to the total diffusive emissions. Details on the numbers and recalculation of the budget are provided in SI Section 2.2.5.

143 ■ RESULTS AND DISCUSSION

144 In the North Sea, Pleistocene and Pliocene organic-rich
145 sediments are the most prominent stratigraphic units
146 containing biogenic gas accumulations that are widespread in
147 300–750 m sediment depth.^{23,24} Vielstädte et al.²⁰ identified
148 these units as potential source areas for the CH_4 emitted along
149 three leaky, abandoned wells investigated in the Norwegian
150 Sector of the CNS. CH_4 in the seep gas was isotopically light
151 ($\delta^{13}\text{C}_{\text{CH}_4} < -70\text{‰}$ VPDB) and contained only minor amounts
152 of higher hydrocarbons ($\text{C}_1/\Sigma\text{C}_{2+} > 1000$), clearly pointing
153 toward a biogenic origin²⁰ (Table 1, SI Figure S2). The shallow
154 origin is supported by bright spots (e.g., reverse polarity high-
155 amplitude seismic anomalies) and zones of chaotic signatures in
156 the seismic data surrounding the three well paths²⁰ (Figure 2b).

157 Here, we further hypothesize that leakage from existing wells
158 in the North Sea is likely to constitute an important part of the
159 respective regional CH_4 budget due to the large number of
160 wells (i.e., ~11 122, discounting extra sidetracked wellbores)
161 and ubiquitous gas accumulations in the shallow subsur-
162 face^{23,25,26} (Figure 2, SI Table S4). In the following, we will
163 thus assess CH_4 leakage along wells into the North Sea and
164 estimate the resulting emission into the atmosphere. Tracking
165 the subsurface well paths of 55 wells in an area of ~2000 km² in
166 the Norwegian Sector of the CNS, where shallow gas
167 accumulations have been identified by bright spots in industrial
168 3-D seismic data, we examine the likelihood of wells to leak
169 shallow gas: 18 out of 55 wells in this area (about $33 \pm 6\%$)
170 were drilled through shallow gas accumulations and are thus
171 believed to leak CH_4 (Figure 2). Individual leakage rates along
172 three wells (15/9-13, 16/4-2, and 16/7-2) in this area were
173 highly variable, amounting to 1, 4, and 19 t yr⁻¹ of CH_4 ,
174 respectively²⁰ (Table 1, SI Table S1). These rates are in the
175 upper range of gas emissions measured from soils around wells
176 in Alberta (i.e., ~0.03–16 t yr⁻¹ of CH_4).¹⁸ The highest release
177 rate in the North Sea was measured at well 16/7-2, which was
178 drilled through a seismic chimney (Figure 2b), typically
179 believed to be more permeable than the surrounding
180 sediment.²⁰ Assuming that the high gas flow at this well is
181 representative for only a small fraction of leaky wells in the
182 North Sea and that the two lower rates of wells 15/9-13 and
183 16/4-2²⁰ are more typical for shallow gas migration, we solely
184 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., CH_4 flow measure-
ments at the three wells covered only a few minutes),²⁰ 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 CH_4 from
the North Sea seafloor per year, assuming that $33 \pm 6\%$ of the
11 122 wells in the North Sea are leaking. In comparison to
other major sources of CH_4 in the North Sea, i.e. rivers (0.5 kt
yr⁻¹),^{27–30} the Wadden Sea area (1.1–2.1 kt yr⁻¹),²⁷ and
known natural seep sites (0.2 kt yr⁻¹),^{31–34} leaky wells may
constitute a significant input to the CH_4 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,³¹ but their abundance
and contribution to the CH_4 budget are poorly constrained.^{23,35}
Despite the poor characterization of the North Sea CH_4
sources, the patchiness and high spatial variability of CH_4
supersaturation in the surface mixed layer (SML) of the open
North Sea with respect to atmospheric partial pressure, i.e.
103–50 000%,^{27,30,36} suggest that ubiquitous point sources at
the seabed (wells and natural seeps) dominate the regional CH_4
budget. The high supersaturation of the North Sea surface
waters drives a diffusive CH_4 loss to the atmosphere of 10–50
kt yr⁻¹,^{30,36} which constitutes the major sink in the marine CH_4
budget (Figure 3). An additional amount of 8 kt yr⁻¹ is
exported to the Atlantic.³⁰

To examine the extent to which emissions from leaky wells
may contribute to the CH_4 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 CH_4 is considered: (1)
dissolution in the deep stratified layer (>50 m water depth),³⁷
(2) dissolution in the surface mixed layer (SML, <50 m water
depth)³⁷ 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
 CH_4 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 227

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 $5 \times 5 \text{ km}^2$ cells and assuming that $33 \pm 6\%$ of the 11 122 wells leak CH_4 at a rate of $1\text{--}4 \text{ t yr}^{-1} \text{ well}^{-1}$ (sample range, $N = 2$).²⁰ Emission rates are expressed in tonnes of CH_4 per year per cell. A total annual seabed release of $3\text{--}17$ ($N = 11\ 122$) kt of CH_4 is estimated for the North Sea (bottom), of which $\sim 1\text{--}7$ ($N = 11\ 122$) 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 $< 40 \text{ m}$). The map's geographic coordinate system refers to WGS84 and is displayed in Cylindrical Equal Area Projection.

spherical bubble radius, $r_e = 2.6 \text{ mm}$ ²⁰, SI Figure S5) were comparable to those observed at natural seeps in the North Sea (i.e., $r_e = 2.2 \text{ mm}$ at Tommeliten³² and $r_e = 2.5 \text{ mm}$ at the Scanner Pockmark field³¹). This comparability, together with the North Sea wide dominance of fine- to medium-grained clayey sand,²⁶ suggest that initial bubble sizes are similar across the North Sea, because their formation is believed to be controlled by the mechanical properties of the surface sediments.³⁸

Hence, applying the average bubble size spectrum of the investigated wells²⁰ and extrapolating numerical results to the North Sea scale, we estimate that leaky wells could emit a total of $1\text{--}7 \text{ kt yr}^{-1}$ of CH_4 into the atmosphere (Figures 3 and 4). This is a significant proportion ($\sim 10\%$) of the total CH_4 flow from the North Sea into the atmosphere (for details see SI Table S5). Leakage from the wells into the atmosphere is dominated by diffusive outgassing of CH_4 dissolved in the SML (i.e., $1\text{--}5 \text{ kt yr}^{-1}$), rather than by direct bubble transport (i.e., $0\text{--}2 \text{ kt yr}^{-1}$), because of the large water depths at which the bubbles are released (Figure 2, SI Figure S5). The microbial sink for CH_4 in the water column is expected to be negligible because CH_4 oxidation (MOx) rates at the investigated leaky wells were very low ($< 1.4 \text{ nM day}^{-1}$, Table 1) compared to the fast ventilation of CH_4 in the SML (i.e., days to weeks)³⁶ and the turnover time of 0.75 years of North Sea water masses.³⁷ Strong tidal currents that laterally transport CH_4 oxidizing bacteria away from the CH_4 point source, or hinder the establishment of a large community of CH_4 oxidizing bacteria,^{39,40} may explain the low MOx rates in the water column above the investigated wells. Overall, this suggests that

essentially all of the CH_4 reaching the SML will be transferred into the atmosphere. A larger proportion of the CH_4 will, however, dissolve in the deep water of the North Sea, below the SML, i.e. $2\text{--}10 \text{ kt yr}^{-1}$. Whereas some unknown fraction of this deeply dissolved CH_4 may be mixed into the SML during frequent fall and winter storms and seasonal or interannual deepening and breakdown of the thermocline,^{30,32,37} the deep water CH_4 input (not oxidized by microbes) may contribute to the export of CH_4 into the North Atlantic Ocean (8 kt yr^{-1}).³⁰ Thus, drilling-induced CH_4 leakage originating from shallow biogenic gas accumulations may constitute an important source for CH_4 in the regional budget of the North Sea contributing significantly to the export into the Atlantic and to the observed high diffusive outgassing into the atmosphere (Figure 3). Adding the other anthropogenic CH_4 sources, the blowout well 22/4b in the British Sector^{30,41,42} and wells with reported integrity issues,² leakages from oil and gas infrastructure may determine the North Sea CH_4 budget (see SI Table S.5).

Our extrapolation from the investigated CNS area to the North Sea scale is corroborated by the spatial correlation of boreholes (Figure 2) with areas of frequent shallow gas accumulations and reported hydroacoustic gas flares.^{23,31} Nonetheless, the range of uncertainty in the North Sea-wide leakage estimates based on this work is substantial, as might be expected from the current state of knowledge of shallow gas leakage, mainly depending on the representativeness of data obtained in the Norwegian CNS. A detailed discussion of uncertainties that may affect our calculations is giving in SI Section 2.2.6. Our estimate for CH_4 leakage along hydrocarbon wells in the North Sea is based on the lower two measured

leakage rates²⁰ 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 16/7-2,²⁰ as well as 15/9-11 and 15/9-16.⁴³ However, Vielstädte et al.²⁰ 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 rates²⁰ to those measured from onshore abandoned wells in the U.S.^{12–14} 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.,^{4,7,10} which give a similar value of ~2 t of CH₄ per year per well. Our and other recent studies^{8,9} 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 flows can be substantial. Nevertheless, it should be noted that while it is relatively easy to detect and quantify CH₄ leakage rates as low as the reported ones in the marine realm, for terrestrial environments this is more challenging and may require using highly modern monitoring technologies that are not yet readily available,⁴⁴ and fixing of such leaks may prove difficult.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b02732.

A summary of relevant results published in an earlier study,²⁰ additional geochemical data of CH₄ oxidation rates in the water column at leaky wells, TOC and SO₄ concentrations in near surface sediments at a reference site in the CNS, and seismic data, full details on materials

and methods, details on the North Sea CH₄ budget, and a discussion of associated uncertainties and the generalization of our results (PDF)

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Author Contributions

The paper was written by L.V., M.H., and K.W. Seismic data were analyzed by J.K. Geochemical and optical data were collected and analyzed by L.V., P.L., M.S., M.H., and L.S. Numerical modeling and spatial extrapolation were done by L.V. The study was designed by M.H.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We thank the Captains and crews of RV *Celtic Explorer* and RV *Alkor*, as well as the teams of ROV Kiel 6000 and ROV Phoca for their invaluable support during the cruises CE12010 and AL412. We thank Andrea Bodenbinder and Meike Dibbern at GEOMAR for conducting geochemical analyses and Monika Segl at MARUM/University Bremen for DIC isotope measurements. We thank Statoil ASA for permission to use the 3-D seismic data and the Norwegian Petroleum Directorate for providing the well path data. Figures were created with ArcGIS, Petrel, Mathematica, and Adobe Illustrator. The cruises and scientific work received funding through the European Community's seventh Framework Program (FP7/2007-2013) in the EUROFLEETS program, the ECO2 project (grant agreement 265847), and the DFG funded Cluster of Excellence "Future Ocean".

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