Marine and Petroleum Geology 68 (2015) 848–860

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

# Quantification of methane emissions at abandoned gas wells in the Central North Sea

Lisa Vielstädte[a,*], Jens Karstens[a], Matthias Haeckel[a], Mark Schmidt[a], Peter Linke[a], Susan Reimann[a], Volker Liebetrau[a], Daniel F. McGinnis[b,c], Klaus Wallmann[a]

[a] GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
[b] IGB, Leibniz Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany
[c] Institute F.-A. Forel, Earth and Environmental Sciences, Faculty of Sciences, University of Geneva, Geneva, Switzerland

ARTICLE INFO

*Article history:*
Received 24 March 2014
Received in revised form 22 July 2015
Accepted 30 July 2015
Available online 4 August 2015

*Keywords:*
Methane
Seepage
Abandoned wells
Seismic chimney
Cold vents

ABSTRACT

As a result of extensive hydrocarbon exploration, the North Sea hosts several thousand abandoned wells; many believed to be leaking methane. However, how much of this greenhouse gas is emitted into the water column and ultimately reaches the atmosphere is not known. Here, we investigate three abandoned wells at 81–93 m water depth in the Norwegian sector of the North Sea, all of which show gas seepage into the bottom water. The isotopic signature of the emanating gas points towards a biogenic origin and hence to gas pockets in the sedimentary overburden above the gas reservoirs that the wells were drilled into. Video-analysis of the seeping gas bubbles and direct gas flow measurements resolved initial bubble sizes ranging between 3.2 and 7.4 mm in diameter with a total seabed gas flow between 1 and 19 tons of $CH_4$ per year per well. Estimated total annual seabed emissions from all three wells of ~24 tons are similar to the natural seepage rates at Tommeliten, suggesting that leaky abandoned wells represent a significant source of methane into North Sea bottom waters. However, the bubble-driven direct methane transport into the atmosphere was found to be negligible (<2%) due to the small bubble sizes and the water depth at which they are released.



## 1. Introduction

Methane contributes significantly to the atmospheric pool of radiative (greenhouse) gases, suspected to induce global climate change (Crutzen and Zimmermann, 1991; Hartmann et al., 2013; Lelieveld et al., 1993). Marine methane emissions may contribute around 20 Tg $yr^{-1}$ (Etiope et al., 2008; Kvenvolden and Rogers, 2005; Bange et al., 1994) to the global atmospheric methane budget (i.e. 542 ± 56 Tg $yr^{-1}$ based on top-down estimates, Ciais et al., 2013), most of it, about 75%, being released from coastal and shelf areas (e.g. Bange et al., 1994). The highest amount of marine methane is produced by methanogenesis in the deeper sediment layers of productive coastal areas (Scranton and McShane, 1991; Hovland et al., 1993), which may result in the build-up of free-gas accumulations in the shallow subsurface (Hovland and Judd, 1988; Judd and Hovland, 2007). Such gas pockets constitute a potential risk in connection with drilling operations, because they may be associated with high pore pressures. In 1990, Mobile North LTD created a massive gas blowout in the central UK North Sea (57.922°N, 1.6325°E, WGS84) after drilling into an over-pressurized gas pocket about 360 m below the seafloor. The drilling site had to be abandoned after the incident and methane emissions ("leakage") from the created seabed depression persisted over several decades (Rehder et al., 1998; Schneider von Deimling et al., 2007; Schneider von Deimling et al., in this issue) representing the strongest gas seepage quantified to date (Leifer, in this issue). Smaller methane leaks can result from drilling through less-pressurized gas pockets and the numerous abandoned offshore wells penetrating such gas accumulations may constitute efficient pathways to release gas from the sedimentary strata to the hydrosphere and finally to the atmosphere (Gurevich et al., 1993; Gasda et al., 2004). Although leakage rates are probably orders of magnitude lower compared to a blowout scenario like well 22/4b, leaks along abandoned wells are much more likely to occur. As monitoring generally is not required after proper well abandonment (Gasda et al., 2004), quantitative data on both, the number of leaking wells, and their leakage rates are rare. Most of the available data are related to well integrity surveys that are performed by operating companies and governmental authorities to reduce the risk of major accidents, primarily for the population, environment and economic values, however their focus is mostly on

* Corresponding author.
*E-mail address:* lvielstaedte@geomar.de (L. Vielstädte).

http://dx.doi.org/10.1016/j.marpetgeo.2015.07.030
0264-8172/

active (production and injection) wells. E.g. on the Norwegian Continental Shelf, 18% of active wells are reported to have integrity issues (Vignes et al., 2006). However, studies in the Gulf of Mexico showed that the majority of integrity issues were related to shut-in or temporarily abandoned wells, rather than to active wells (Wojtanowicz et al., 2001). Thus, even though leakage from abandoned wells poses a lower risk of major accidents for people and economic aspects, it may constitute a relevant source for methane into the ocean.

A large fraction of the released methane will dissolve in the water column, disperse by currents, and is subsequently oxidized by microbes (e.g., Ward et al., 1987; Jones, 1991). Transfer of methane into the atmosphere is possible by both diffusive and turbulent air-sea gas exchange as well as bubble-mediated transport (Leifer and Patro, 2002; Wanninkhof, 1992). The latter is the most efficient way of transferring seabed methane to the atmosphere (McGinnis et al., 2006), which may enhance local sea-air fluxes, particularly in shallow shelf seas. In this study we focus on the North Sea, which acts as a net source for atmospheric methane (Bange et al., 1994). Current flux estimates (Bange et al., 1994; Rehder et al., 1998) seem to be too low, because methane fluxes from estuaries and marine seeps are not adequately represented (Bange, 2006) and possible contributions from abandoned wells have not been studied at all.

To our knowledge, this is the first public study aiming to quantify methane leakage from abandoned wells in the North Sea. For this purpose, we investigated three abandoned wells that show continuous bubble release into the water column during two research cruises in 2012 and 2013. Further, we determine the source of leaking gases and possible migration pathways driving the seabed emissions at leaky wells. Applying a numerical gas bubble dissolution model, we estimate the resulting direct methane flux across the sea surface and finally, methane emissions at the abandoned wells are compared to natural methane seepage as well as other methane sources in the North Sea.

### 1.1. Study area

The three wells are located on the south-western flank of the Utsira High in the Norwegian sector of the North Sea (Fig. 1). The area hosts hydrocarbon-rich Paleocene sediments mainly in the Heimdal Formation, which are charged by Jurassic source rocks (Justwan and Dahl, 2005). The main objectives of the three wells were to delineate hydrocarbon accumulations found in the Heimdal Formation (15/9–13, Normann and Østby, 1982), to prove the presence of a high-risk stratigraphic trap in the Heimdal Formation (16/7-2, Horvig, 1982), and to test a possible small closure at the Top Heimdal Formation (16/4-2, Hydro, 1990). In all cases, the target depths of the wells were deeper than 3000 m below the seafloor (mbsf) corresponding to Jurassic (i.e. 16/4-2, Hydro, 1990) and Permian (i.e. 15/9-13 and 16/7-2, Normann and Østby, 1982, 1982; Horvig, 1982) stratigraphic units. Well 16/4-2 was permanently plugged and abandoned as a dry well (Hydro, 1990), while the other two boreholes proved gas in the Heimdal Formation but were subsequently plugged and abandoned (Normann and Østby, 1982; Horvig, 1982). Shallow gas is mostly present within Nordland Group sediments in the upper Cenozoic sequences. The Utsira Formation, the Top Pliocene, and an 11-m thick sand layer above the Top Utsira Formation constitute important sand layers, which are separated by impermeable layers of shale or mudstones (Fig. 2), thus creating fairly good conditions for the trapping and accumulation of shallow gas (Karstens and Berndt, 2015). The Utsira Formation overlies marine mudstones at the base of the Nordland Group and is dominated by medium-grained sand intersected with some stringers of clay (Eidvin and Rundberg, 2007; Normann and Østby, 1982). While Utsira sands were deposited in a high-energetic shelf environment (Galloway, 2001, 2002), the depositional environment changed from a shallow to a deeper marine environment in the Early Pliocene, which was accompanied by the deposition of finer sediments. The interval from 300 mbsf down to the Utsira Formation thus consist of clay-rich sediments known as Nordland Shales (Fig. 2; Horvig, 1982) largely acting as a seal for upward migrating fluids, except for sections with pre-existing or pressure-induced fractures. The uppermost 300 m of the Nordland Group consists mostly of sand with some inter-bedded clay also containing gas in the vicinity of some wells (Horvig, 1982).

## 2. Methodology

Geochemical sampling and video investigations were performed at three leaky abandoned wells during cruises on board the research vessels RV Celtic Explorer (CE12010, July–August 2012) and RV Alkor (AL412, March 2013). In addition, an industrial 3D seismic data set (ST98M3, Statoil ASA) covering the area around the three wells of interest was analyzed for gas accumulations and possible vertical migration pathways in the sedimentary strata around the boreholes. Furthermore, well reports and well-logs of the Norwegian Petroleum Directorate (NPD) were investigated for the characterization of the sediments in the uppermost 1200 mbsf.

### 2.1. Sediment and gas sampling

During the Celtic Explorer expedition CE12010, surface sediments were collected with ROV-deployed push-cores (PC). For dissolved gas analysis, 3 ml of wet sediment was sub-sampled in 2 cm intervals and filled into 20 ml headspace vials. 6 ml of saturated NaCl solution and an additional 1.5 g of NaCl were added and the vials sealed tight with butyl-rubber stoppers. The samples were stored refrigerated for onshore analyses. Prior to storage in the cold room, the vials were shaken vigorously for half an hour to release dissolved gases into the headspace.

In addition, free gas was sampled directly in the bubble stream with ROV-operated special gas samplers as described by Rehder and Schneider von Deimling (2008) and Pape et al. (2010). The gas sampler consists of a stainless steel cylinder with a PVC funnel attached to it to facilitate gas bubble sampling (Fig. 1 and Fig. A1). Onboard, subsamples of pressurized gas were transferred into pre-evacuated headspace glass vials of 20 and 100 ml volume until the pressure in the vials was ~1020 mbar.

In the GEOMAR home laboratory, methane and higher alkane concentrations in the free gas samples and in headspace vials were determined with a gas chromatograph GC 8000top (CE instruments) equipped with a FID detector and a capillary column (RT-Alumina Bond-KCl, 50 m, 0.53 mm). Stable carbon isotope composition of methane was determined by using a continuous flow GC-Isotope Ratio Mass Spectrometer combination. Methane was separated from other hydrocarbons in a Thermo Trace GC (isotherm at 60 °C, He-carrier gas, ShinCarbon 1.5 m packed column). The subsequent conversion of methane to carbon dioxide was conducted in a Ni/Pt combustion furnace at 1150 °C. The $^{13}C/^{12}C$-ratios of the produced $CO_2$ were determined by a Thermo MAT253 isotope ratio mass spectrometer. All isotope ratios are reported in the $\delta$-notation with respect to Vienna Pee Dee Belemnite (VPDB). Analytical precision of the reported concentrations and isotopic composition is ±3% and ±0.3‰, respectively.

Sediment porewater was extracted by squeezing wet sediment at low pressure (<5 bar) through 0.45 $\mu$m Whatman regenerated cellulose filters. 2 ml aliquots were treated with 10 $\mu$L of HgCl to inhibit further microbial degradation and stored cool until analysis. Onshore, the stable carbon isotope composition of dissolved inorganic carbon (DIC), referred to as $\delta^{13}$DIC was determined at the University of Bremen using a Finnigan MAT 251 mass spectrometer