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Research paper

Ongoing methane discharge at well site 22/4b (North Sea) and discovery of a spiral vortex bubble plume motion

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A B S T R A C T

First direct evidence for ongoing gas seepage activity on the abandoned well site 22/4b (Northern North Sea, 57°55′ N, 01°38′ E) and discovery of neighboring seepage activity is provided from observations since 2005. A manned submersible dive in 2006 discovered several extraordinary intense seepage sites within a 60 m wide and 20 m deep crater cut into the flat 96 m deep seafloor. Capture and (isotope) chemical analyses of the gas bubbles near the seafloor revealed in situ concentrations of methane between 88 and 90%Vol. with $\delta^{13}C–CH_4$ values around −74‰ VPDB, indicating a biogenic origin. Bulk methane concentrations throughout the water column were assessed by 120 Niskin water samples showing up to 400.000 nM CH_4 in the crater at depth. In contrast, concentrations above the thermocline were orders of magnitude lower, with a median value of 20 nM. A dye tracer injection into the gas seeps revealed upwelling bubble and water motion with gas plume rise velocities up to ~1 ms^{-1} (determined near the seabed). However, the dissolved dye did not pass the thermocline, but returned down to the seabed. Measurements of direct bubble-mediated atmospheric flux revealed low values of 0.7 ± 0.3 kty^{-1}, much less than current state-of-the-art bubble dissolution models would predict for such a strong and upwelling in situ gas bubble flux at shallow water depths (i.e. ~100 m).

Acoustic multibeam water column imaging data indicate a pronounced 200 m lateral intrusion at the thermocline together with high methane concentration at this layer. A partly downward-orientated bubble plume motion is also visible in the acoustic data with potential short-circuiting in accordance to the dye experiment. This observation could partly explain the observed trapping of most of the released gas below the well-established thermocline in the North Sea. Moreover, 3D analyses of the multibeam water column data reveal that the upwelling plume transforms into a spiral expanding vortex while rising through the water column. Such a spiral vortex motion has never been reported before for marine gas seepage and might represent an important process with strong implication on plume dynamics, dissolution behavior, gas escape to the atmosphere, and is considered very important for respective modeling approaches.

1. Introduction

1.1. Natural and man-made subsea methane release in the North Sea

Natural methane release from the seafloor by seep processes is observed virtually on all continental margins (Judd and Hovland, 2007). Estimates suggest marine seeps may contribute ~10–30 Tg yr^{-1} (Kvenvolden et al., 2001) to global geological methane emissions of 30–45 Tg yr^{-1} (Etiope and Klusman, 2002). However, the significance of marine methane seepage for the total atmospheric methane budget and global warming is still under debate (Ciais et al., 2013).

Methane hosted in interstitial water of marine sediments can enter the water column by diffusive porewater transport, convective fluid flow, or gas bubble release. The latter process is a common phenomenon in the North Sea especially along its central geological graben (Fig. 1), and is subject to research since decades (e.g. Hovland and Sommerville, 1985; Judd et al., 1997; Schroot et al., 2005; Schneider von Deimling et al., 2010, 2011). Methane transported into the water column by bubbles efficiently bypasses the

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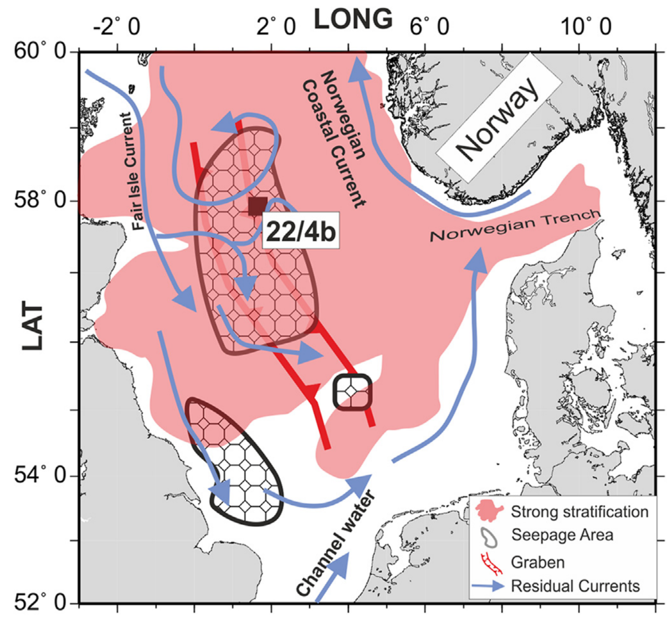

Fig. 1. (a) Schematic main flow pattern in the North Sea adapted from Turrell et al. (1992). Three gas seepage regions (purple polygons) surrounding the study area 22/4b were compiled from various sources (Judd et al., 1997; Judd, 2001; Schroot et al., 2005). Shaded polygon with orange border shows the spatial extent of strong stratification (ΔT 6K) between surface and bottom water in the North Sea modeled for June–August after Holt and Umlauf (2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

microbial filter of the shallow seabed (e.g. Sommer et al., 2006). Those bubbles subsequently undergo dissolution during transport through the water column due to under saturation of methane in the surrounding seawater.

Anthropogenic sources for methane gas release from the seabed include pipeline and well leakages, which might be of considerable magnitude if the number of potential leakages in an area of intense hydrocarbon exploration (i.e. North Sea) are taken into account (Vielstaedte et al., in this issue). Judd and Hovland (2007) compiled a series of explosive offshore accidents beginning in 1964 for the North Sea; our study will concentrate on such a blowout that happened at the 22/4b well site in 1990 in the Northern North Sea. In this study, we deliver direct evidence of ongoing gas discharge at site 22/4b since 2005 and provide a comprehensive geochemical and hydroacoustic dataset about this exceptional site.

1.2. History of the well 22/4b blowout and related scientific research

In May 1994, Rehder et al. (1998) identified a pronounced dissolved methane peak in surface waters near 58°N and 1°40′E, about 200 km east off the Scottish coast, with maximum concentrations more than 700 times atmospheric equilibrium. The area was marked in nautical charts as a gas release hazard to marine vessels. Three years before, on the 20th of November 1990, Mobil North Sea Ltd. (MNSL) encountered shallow gas at 360 m below seabed while drilling into the Quaternary section of exploration well UK22/4b. The well blew out, creating a crater on the seafloor and a massive bubble plume (Fig. 2) that rapidly diminished over several days. From 1990 on, this crater and the vigor of the gas plume were monitored by survey vessels and ROV (remotely operated vehicle) operations, showing decreasing plume intensity (Fox, 1995). In 2000, the UK Dept. of Trade and Industry (DTI) determined that further monitoring was not required without a perceived safety threat or environmental harm, and a near future depletion of the gas reservoir was predicted. However, fifteen years after the accident a revisit with R/V ALKOR in 2005 verified a persisting major methane anomaly at the sea surface and provided direct visual and acoustic evidence of a ca. 25 m diameter bubble plume arising from a 60 m wide conical crater at the seabed up to the sea surface (Schneider von Deimling et al., 2007). After a submersible dive in 2006, a press release raised public awareness and political interest for the still continuing massive methane discharge 16 years after the blowout incident. In light of enhanced sensitivity to offshore oil and gas leakage in the wake of the Deep Water Horizon blowout (Gulf of Mexico, 2010), a comprehensive survey with further measuring, monitoring and verification studies at the 22/4b location outlined in Leifer and Judd (in this issue) was initiated by the U.K Department of Energy and Climate Change (DECC).

Fig. 2. 22/4b blowout image 1990. Inset shows blowout location. © MOBIL North Sea Ltd. Rig is approximately 60 by 80 m wide.

1.3. Minor vs. major gas plume release

Marine gas seeps can be classified by their flux rate into minor (mL min^{-1}), major (L min^{-1}) (Leifer and Boles, 2005), and mega (10^6 L day^{-1}) release sites (Leifer, in this issue). Minor seeps are characterized by Gaussian-shaped bubble size spectra peaking around 2–3 mm radii with potential spectra variation depending on gas flux magnitude (Leifer, 2010). Major seeps produce broader bubble size spectra characterized by a power law decrease of probability with bubble radius (Leifer, 2010). Modeling suggests that a clean 3 mm radius bubble of methane would loose 95% of its initial amount of methane during a 100 m rise by dissolution into the water column, while absorbing nitrogen and oxygen during the initial part of its rise (Leifer and Patro, 2002). E.g. Schneider von Deimling et al. (2011) demonstrate for a seep site in the Central North Sea at 70 m water depth by modeling and field data that the release of small bubbles has a very limited vertical transport potential. In turn, larger bubbles released from major seeps are far more efficient in regard to vertical gas transport due to their greater volume to surface area ratio and higher rise velocities (e.g. Leifer et al., in this issue). Leifer and Patro (2002) showed that larger bubbles (r > 5000 μm) released at about 100 m water depth should transport more than 50% of their original CH_4 content into the atmosphere.

Each rising bubble applies drag to the ambient water, inducing a vertical momentum plume (Milgram, 1983). If sufficiently high, the total momentum can induce significant upwelling with 0.3–2 m/s (Leifer et al., 2009), lifting e.g. denser ambient water and even particles upwards. Bubble rise and related methane gas dissolution/equilibration within an upwelling flow causes an enhanced vertical transport due to reduced bubble retention time in