Spatial and temporal analysis of gas seep activity in Eckernförde Bay

An article by ARNE LOHRBERG

Highly elevated methane concentrations in Eckernförde Bay bottom waters during a ship cruise with RV »Alkor« (AL447) raised attention. Earlier studies focused on pockmarks and groundwater seepage to be a possible driver controlling methane concentration in the water column. This thesis presents high-resolution bathymetry data for three pockmark clusters, high-frequency sub-bottom profiles for methane-rich sediments, a spatial activity distribution grid of gas seepage and a time series of in situ monitored gas seepage events. It aims to analyse pockmark morphology, estimate the spatial distribution of shallow gas accumulations, examine the spatial and temporal activity of gas seepage, find possible trigger mechanism and estimate a gaseous methane flux to the water column of Eckernförde Bay.

Gas seepage | methane | multibeam bathymetry | pockmarks | water column data

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Introduction

The basis for the thesis is a multi data set acquired during research campaign AL447 in 2014, led by Dr. Jens Schneider von Deimling. The campaign was conducted from 20th October to 4th November 2014 using the research vessel RV »Alkor« with a focus on »Controls on methane seepage in the Baltic Sea«. Eckernförde Bay was one of the main study areas as well as the Kattegat (Denmark) and parts of Kiel Bay.

The Eckernförde Bay is one of the most extensively studied shallow water areas in the world. Numerous authors studied characteristics of several aspects of the bay; e.g. pockmarks, shallow gas accumulations and methane flux (Schüler 1952; Whiticar 1978; Bange et al. 2010). Two special research programs (the Coastal Benthic Boundary Layer, CBBL, and SFB95) focused on the sediment-seawater interactions as well as on the seawater-atmosphere interactions.

The Eckernförde Bay is located in the southwestern Baltic Sea, which has been shaped by the last glaciation. It resulted in a system of subglacial channels and semi-enclosed bays forming a large fjord system. The Eckernförde Bay, in particular, is characterised by a landwards advance of an ice ›tongue‹, which is divided into a northern and a southern part by the moraine Mittelgrund at the mouth of the bay.

The Coastal Benthic Boundary Layer research program conducted from 1992 to 1998 found several key characterisations of the seafloor of Eckernförde Bay (Richardson 1998):

- The organic flux to the seafloor is highest in late spring and autumn (separated by long periods of low flux).
- Anoxic conditions occur near the seafloor due to the lack of vertical mixing of the water column, which leads to small amounts of benthic fauna. Subsequent very limited mixing of the sediment as well as a high energy potential due to high organic flux to the seafloor eventually lead to the anaerobic production of methane in near surface sediments due to biochemical processes.
- Stratification of the water column is generally high due to higher salinity higher density oceanic North Sea water at depth overlain by lower salinity lower density Baltic Sea water. It is further enhanced in summer months by the formation of a strong thermocline, thus leading to minimal vertical mixing and sediment transport restricted to storm-induced waves. High organic flux to the seafloor, high rates of sedimentation, slow bottom currents, the net sedimentation environment, occasional anoxic conditions and the shallow depth of bioturbation cause ideal conditions for the production of methane (Richardson 1998). CT-Scans of sediment cores showed the presence of free gas in the porous sediments. Methane gas bubbles are present from 80 cm into the sediment with bubble radii ranging from 0.4 to 5 mm (Abegg and Anderson 1997). The tidal effect is insignificant, while wind, storm surges and baroclinic seiches control the sea level with oscillations of a main periodicity of 26–28 hours, which is called the Baltic Seiche (Richardson 1998).

High-resolution multibeam bathymetry data have been acquired using a fifth generation Kongsberg EM2040c multibeam echo sounder; the water column has been surveyed using a Simrad EK60 single-beam echo sounder; the shallow sub-bottom has been surveyed using an Innomar SES 2000 parametric echo sounder and in situ monitoring has been accomplished using an Imagenex Delta T 837b multibeam echo sounder mounted on a deployment system.

While bathymetry and shallow sub-bottom data processing and visualisation followed standard routines in MB-System and Seismic Unix, water column data and in situ monitoring data evaluation was customised. Water column data has been ana-

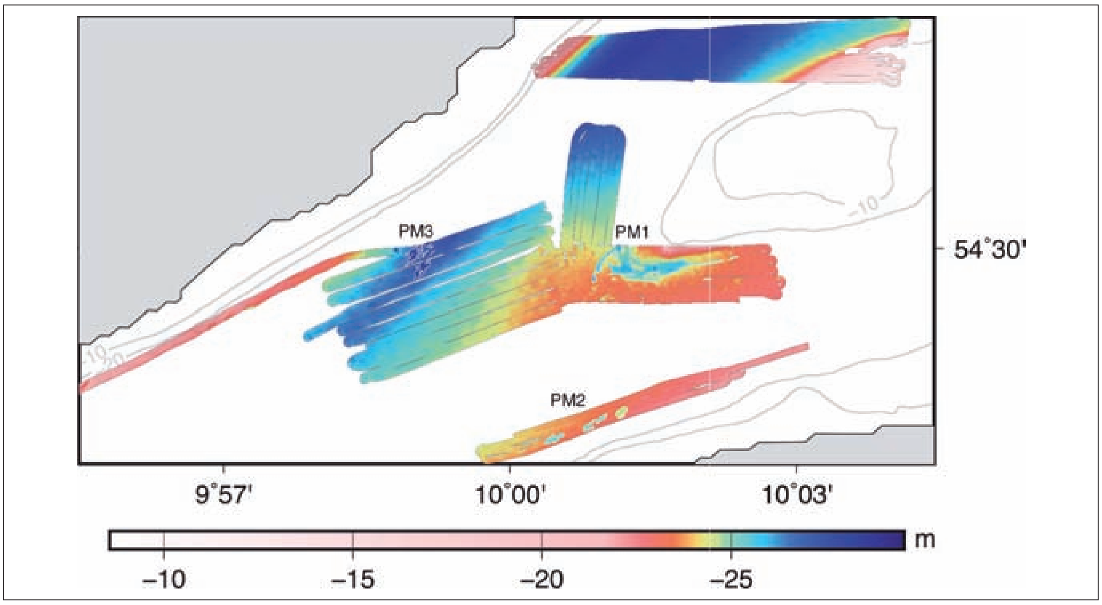

Fig. 1: Overview map of Eckernförde Bay showing the extent of the grid. Grey areas indicate landmasses; grey lines indicate depth contour lines. Pockmark clusters PM1 to PM3 are highlighted with a white contour line

lysed using the Sonar5-Pro fishery research software. Similar to acoustically tracking individual fish this enabled the automation of single gas bubble release detection and distinction from fish based on the tracking of single echo detections (SED) and their evaluation and classification based on characteristics such as the vertical rise velocity and target strength. Scripts have been developed to analyse and visualise the location, target strength and gas bubble releases using Mathworks MATLAB.

In situ monitoring data have been visualised and gas bubble release events have been tracked with high temporal resolution in QPS FMMidwater. The resulting time-series has been analysed to identify potential gas release trigger mechanisms.

Results

Bathymetry data show three clusters of pockmarks (Fig. 1):

- close to the Mittelgrund shoal, elongated along its flanks (PM1);
- close to the southern boundary of the bay, clustered along a SW-NE direction trend (PM2);
- close to the northern shore, with a light tendency of elongation in SW-NE direction (PM3).

The pockmark clusters are composed of bigger interconnected and smaller surrounding depressions. They do not exceed 2.5 m depth. Slope angles at the flanks are steep with up to 46°, while no pockmark cluster shows levees. PM2 shows a cluster of micro-scale depressions right in the vicinity of macro-scale depressions. All pockmark clusters show a sense of elongation. PM1 elongates around shoal Mittelgrund, while PM2 as well as PM3 elongate in a SW-NE direction, which roughly coincides with the direction of the shore. PM1 is the only pockmark to show megaripple-like features (Fig. 2). PM3 on the other hand shows rather concentric depressions inside the main depressions, which look like micro-scale pockmarks (Fig. 2).

Shallow sub-bottom data show blurry high amplitudes in very shallow depths due to shallow gas hindering deeper penetration of the signal in most

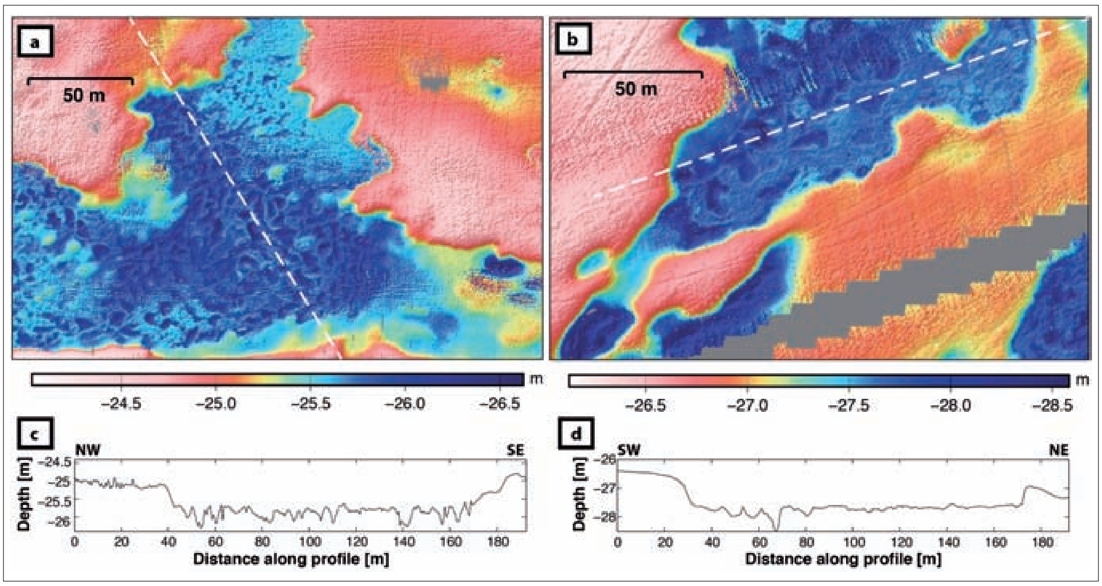

Fig. 2: Close-up of the pockmark floor of main depression of PM1 (a); southwestern depression of PM3 (b); profile over PM1 (c) and profile over PM3 (d). Dashed white line indicates profile line

parts of the survey area. Lamination of sediments is therefore hidden in most parts of the profiles, which indicates the presence of shallow gas in most areas. This acoustic turbidity hides most features of the sub-bottom, except for very shallow sediments north of PM1. Acoustic turbidity reaches closer to the seafloor inside pockmarks and is encountered deeper in the sediments remote of the pockmarks. This is in accordance with earlier investigations by Abegg and Anderson (1997), who found methane concentrations in very shallow sediments to be higher inside pockmarks than remote of them.

Water column data show three different types of gas bubble seepage:

- low spatial density single gas bubble seepage, which can clearly be discriminated against each other,
- high spatial density single gas bubble seepage, where tracking of single gas bubbles is hindered by the high number of gas bubbles,
- multiple gas bubble seepage, where single gas bubbles escape from the seabed in intervals too short for the sonar system to clearly resolve single gas bubbles.

Despite the small footprint of the single-beam echo sounder (roughly 2.5 m for 20 m water depth), gas bubble releases have been found in wide areas of the bay (Fig. 3).

Gas seepage is clearly not restricted to pockmarked areas (Fig. 3a). Gas seepage activity is heterogeneous throughout the bay, but it is increased in the southwest of the survey area and restricted to gas-bearing muddy sediments (Fig. 3b).

Target strengths of single echo detections (SED) of single gas bubbles for different rising heights above the seafloor show an increasing trend for roughly the first metre of their rising height and an overall decreasing trend for maximum tracked rising heights. An inversion of target strengths based on an estimated acoustical backscattering cross-section of near-resonance gas bubbles leads to

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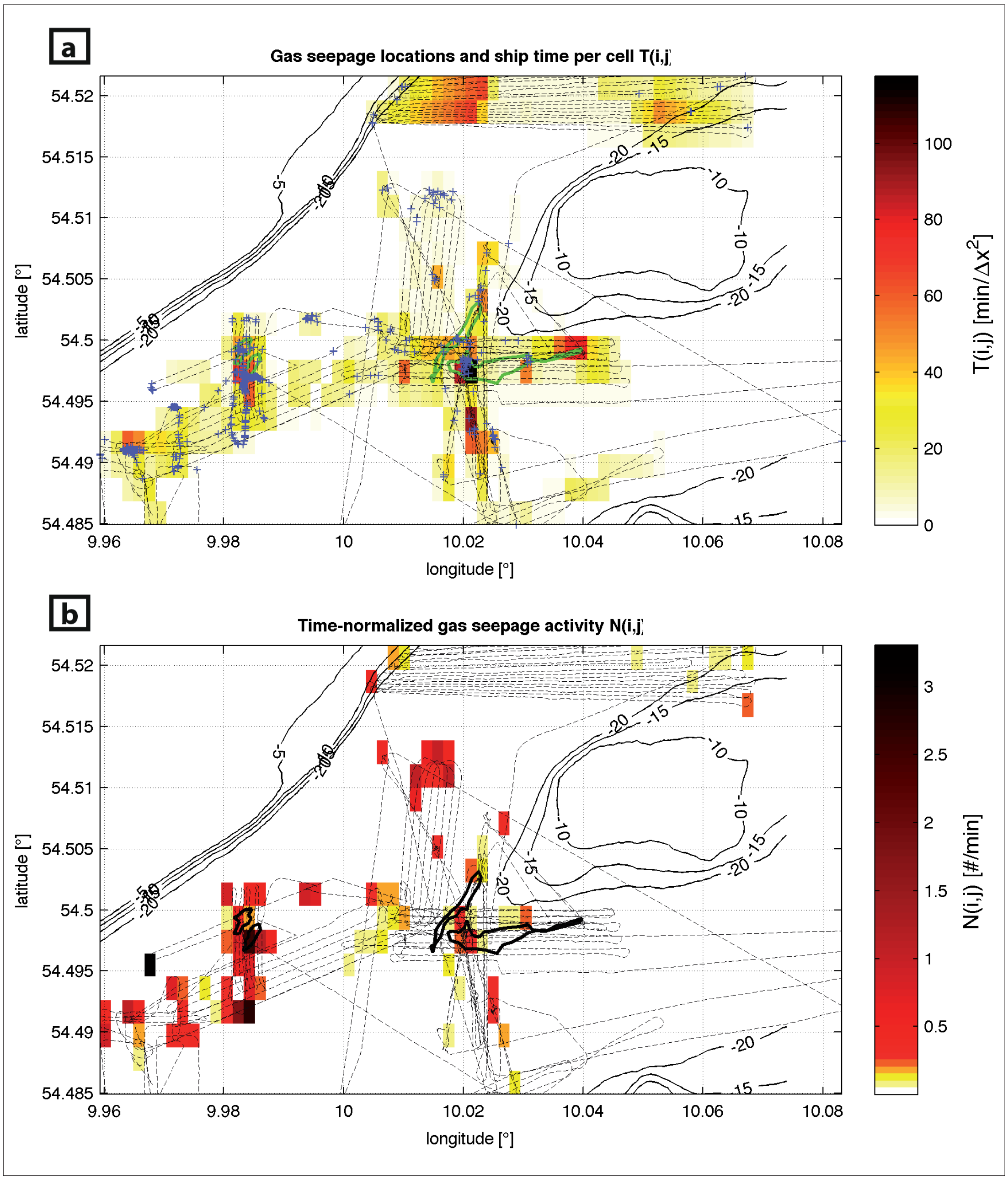

Fig. 3: Grid showing the ship time spent in each cell T(Δx = 200 m) and locations of gas seepage (a); probability density distribution of gas seepage activity N(Δx = 200 m) (b). Thin black lines indicate depth contours; bold green/black lines indicate pockmark clusters PM1 and PM3; dashed lines represent the ship track; blue crosses indicate gas seepage locations. Note that PM2 is not represented due to the lack of gas seepage in the southern extent of the bay

gas bubble radii ranging from 1.44 mm to 3.51 mm with a mean of 2.26 ± 0.53 mm.

In situ monitoring data show gas bubble ebullition frequencies between approximately 1 to 6 gas bubbles per minute at an active gas seep site. The mean ebullition frequency is 2.86 ± 0.91 min^{-1}. Spectral peaks have been found for 21.3, 7.1, 4.7, 3.9 and 1.3 hours, while the 21.3 hours peak shows about two-fold amplitude of the other peaks and is therefore considered the dominant period of gas bubble release (Fig. 4). It shows a strong correlation with the Baltic Seiche main water level oscillation period of 21.8 hours during the time of in situ monitoring.

To investigate the effect of methane flux from the seabed by gas bubble ebullition for a hypothetical stagnant water column, the gas seepage activity N(Δx = 50 m) with a grid cell size of 50 m has been used as the basis to estimate the spatial gas seepage activity. The ebullition frequency of single gas bubbles derived from in situ monitoring data in combination with the bubble volume derived from target strength assessment has been used to estimate the methane flux. It is calculated for the time span of one day assuming 100 % methane concentration at initial release of gas bubbles from the seabed.

The low end of methane flux of 3.5 to 20.1 µMol m^{-2} d^{-1} derived for the minimum ebullition frequency for all cells showing seepage is comparable to fluxes of 5 to 20 µMol m^{-2} d^{-1} estimated by Jackson et al. (1998). However, methane fluxes derived for the mean and the maximum ebullition frequency of 9.9 to 142.5 µMol m^{-2} d^{-1} and 20.1 to 289.3 µMol m^{-2} d^{-1}, respectively, are considerably higher. The range of derived methane fluxes is large, which is owed to the cubic dependence of bubble volume. However, methane fluxes in this range may well explain highly elevated methane concentrations found in the Eckernförde Bay during the campaign.

Estimating the total methane flux of all gas seepage locations for the mean bubble volume and the mean ebullition frequency for in situ conditions yields 181 L d^{-1}, which equals 23 Mol d^{-1}. To put this in perspective: one cow emits approximately 200 L d^{-1}, which corresponds to 9 Mol d^{-1}. Thus, the mean methane emissions derived for all gas seepage locations is about 2.5-fold higher than emissions of one cow. However, the estimations range up to 1185 L d^{-1} corresponding to 150 Mol d^{-1}. This is about 17-fold higher than emissions of one cow.

Subsequently, the methane emissions derived here can be considered to have an insignificant effect on atmospheric methane emissions. Nonetheless, the number of seepage locations in the Eckernförde Bay may be highly underestimated due to limited coverage.

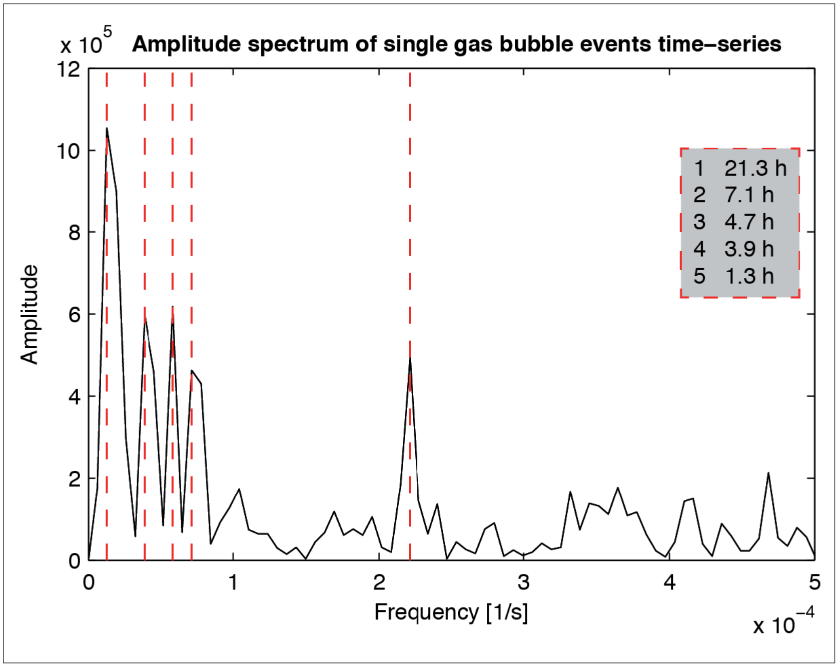

Fig. 4: Amplitude spectrum of gas bubble count time-series

Conclusions

Earlier studies focused on pockmarks and acoustic turbidity due to reverberation of resonating gas bubbles in the sediment, whereas more recent studies focused on methane flux. Most studies used indirect means to quantify the methane flux to the atmosphere by measuring its concentration in the water column and related parameters (Bange et al. 1994, 2010; Lennartz et al. 2014). Jackson et al. (1998) tried to quantify methane flux to the water column by gas ebullition using a circularly scanning sonar to monitor the water column close to the seafloor. However, their resolution was limited and targets were ambiguous. For the first time, the data acquired during research campaign AL447 visualise gas bubbles rising through the water column with additional target strength information.

The following conclusions can be drawn from the results and discussion presented in this thesis:

- Modern high-resolution broadband multibeam echo sounding can resolve small-scale ripple-like structures and micro depressions on the pockmark floor.
- High correlation of sea level oscillations and gas seepage activity suggests fluctuations in hydrostatic pressure due to the Baltic Seiche to be a trigger mechanism of gas seepage.
- Gas seepage is widespread and not restricted to pockmarked areas; however, it is restricted to gas bearing muddy sediments and anaerobic methanogenesis due to oxygen depletion during late summer and autumn.
- Gas seepage activity is heterogeneous but is increased in the West of the survey area.
- Derived methane flux from the sediment–water interface in Eckernförde Bay can explain highly elevated methane concentrations in the water column close to the seafloor for typical dissolution rates of gas bubbles. ⚓

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