Spatial and temporal analysis of gas seep activity in Eckernförde Bay and assessment of its linkage to pockmark morphology and sub-bottom strata using marine acoustic methods

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Key words: Eckernförde Bay, pockmark morphology, shallow gas, gas ebullition, in situ monitoring, hydroacoustic detection

SUMMARY

Highly elevated methane concentrations in Eckernförde Bay bottom waters during campaign AL447 raised attention. Earlier studies focused on pockmarks and groundwater seepage to be the main driver for enhanced methane concentration in the water column. This paper 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 (1) analyse pockmark morphology, (2) estimate the spatial distribution of shallow gas accumulations, (3) examine the spatial and temporal activity of gas seepage, (4) find possible trigger mechanism and (5) estimate a gaseous methane flux to the water column of Eckernförde Bay.

High-resolution bathymetry data indicate the formation of micro-scale intra-pockmark structures on the seafloor with 20 to 50 cm depth and less than 5 m in diameter. Comparison with bathymetric data acquired eight years earlier suggests a stability of the pockmark rims over decades.

Shallow sub-bottom data suggest the presence of free methane gas accumulations in the sediments at water depths exceeding approx. 20 m surrounding the biggest pockmark close to the shoal Mittelgrund. Surface sediment methane concentrations appear to be higher at pockmark rims and the pockmark floor and lower in the central part of the bay.

Single beam data show gas seepage to occur in wide areas of the bay, especially in the southwestern extent of the survey area. Gaseous methane flux estimations using gas bubble ebullition rates derived from *in situ* monitoring and radius estimations derived from single beam echo sounding suggest a significant contribution to enhanced methane concentrations in the water column.

1. INTRODUCTION

The basis for the paper is a multi data set acquired at Eckernförde Bay during research campaign AL447 in 2014 (Figure 1), led by Dr. Jens Schneider von Deimling. The campaign was conducted from 20th October to 04th November 2014 using the research vessel 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 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 basins. 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 sea floor of Eckernförde Bay (Richardson, 1998): (1) the organic flux to the sea floor is highest in late spring and autumn (separated by long periods of low flux), (2) anoxic conditions occur near the sea floor 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 sea floor eventually lead to the anaerobic production of methane in near surface sediments due to biochemical processes, (3) stratification of the water column is generally high due to more saline and denser oceanic North Sea water flowing in at depth overlain by brackish (less saline) 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 events. High organic flux to the seafloor, high rates of sedimentation, slow bottom currents, the net sedimentation environment, occasional anoxic conditions at depth represent ideal conditions for the production of methane (Richardson, 1998). CT-Scans of sediment cores showed the presence of free gas in the porous sediments and methane gas bubbles were found from 80 cm below seafloor 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 Kongsberg EM2040c multibeam echo sounder. In addition, 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 by deploying an Imagenex Delta T 837b multibeam echo sounder on the seafloor. 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 were customised. Water column data has been analysed using the Sonar5-Pro fishery research software. Similar to acoustic tracking of individual fish, this software enabled the automation of single gas bubble release detection and distinction between fish – based on the tracking of single echo detections (SED) – and systematically upward rising gas bubbles (Figure 2). Software scripts have been developed to analyse and visualise the location, target strength and gas bubble releases using Mathworks MATLAB. *In situ* acoustic 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 such as water level changes (Schneider von Deimling et al., 2010).

2. RESULTS

Bathymetric data show three clusters of pockmarks (Figure 1): (1) close to the Mittelgrund shoal, elongated along its flanks (PM1); (2) close to the southern boundary of the bay, clustered along a SW–NE direction trend (PM2); (3) 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 (Figure 3). PM3 on the other hand shows rather concentric intra-pockmark depressions 0.5 m deep and a few meters wide (Figure 3).

Shallow sub-bottom data show acoustic blanking in very shallow depths due to shallow gas hindering deeper penetration of the signal in most parts of the survey area (acoustic turbidity). Lamination of sediments is therefore hidden in most parts of the profiles, which indicates the presence of shallow gas in wide areas of the bay. This acoustic turbidity hides most features of the sub-bottom, except for very shallow sediments north of PM1. The top of the acoustic blanking appears 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: (1) low spatial density single gas bubble seepage, which can clearly be discriminated against each other, (2) high spatial density single gas bubble seepage, where tracking of single gas bubbles is hindered by the high number of gas bubbles and (3) 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 at 20 m water depth), gas bubble releases have been found in wide areas of the bay (Figure 4).

Overall the acoustic analyses of free gas bubble release in this study demonstrate that gas seepage is clearly not restricted to pockmarked areas (Figure 4a). 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 (Figure 4b).

Target strengths of single echo detections (SED) of single gas bubbles for different rising heights above the seafloor show (1) an increasing trend for roughly the first meter of their rising height and (2) an overall decreasing trend for maximum tracked rising heights. An inversion of target strengths based on an estimated acoustical backscattering cross-section of gas bubbles leads to gas bubble radii ranging from 1.44 to 3.51 mm with a mean of 2.26 ± 0.53 mm.

In situ monitoring data inside PM1 show gas bubble ebullition frequencies between approx. 1 to 6 gas bubbles per minute at an active gas seep site. The data indicate a strong link between hydrostatic pressure changes and gas bubble release activity. An anti-correlation of the gas bubble event count with the gradient of the total hydrostatic bottom pressure was found with a short phase shift between pressure release and gas bubble ebullition (Figure 5).

3. 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 sector scanning sonar to monitor the water column close to the sea floor. 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 paper:

- Modern high-resolution broadband multibeam echo sounding can resolve small-scale ripple-like structures and micro depressions within pockmarks
- High correlation between hydrostatic pressure changes and gas seepage activity suggests that weather driven events trigger gas seepage in the Baltic Sea
- Gas seepage is widespread and not restricted to pockmarked areas; however, it is restricted to gas bearing muddy sediments and likely linked to anaerobic methanogenesis due to oxygen depletion during late summer and autumn
- Derived methane flux from the sediment–water interface in Eckernförde Bay can explain highly elevated methane concentrations in the water column close to the sea floor for typical dissolution rates of gas bubbles

Figures:

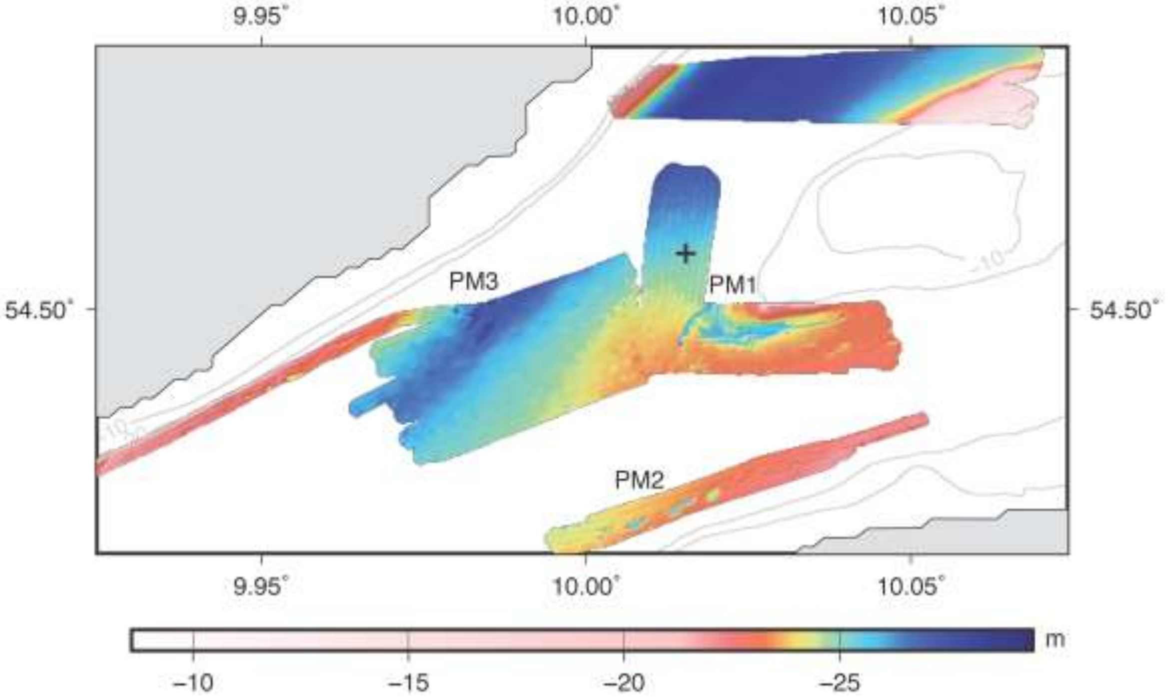

Figure 1: Overview map of Eckernförde Bay showing the extent of the surveyed area. Gray areas indicate landmasses; gray lines indicate depth contour lines. The black cross marks the recording position of Figure 2.

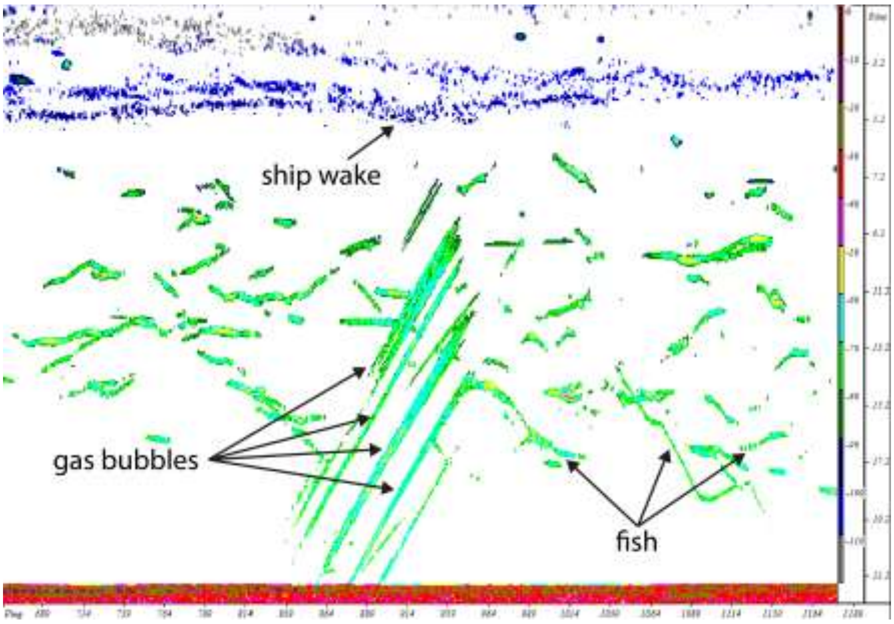

Figure 2: Amplitude echogram of rising gas bubbles. For location see Figure 1.

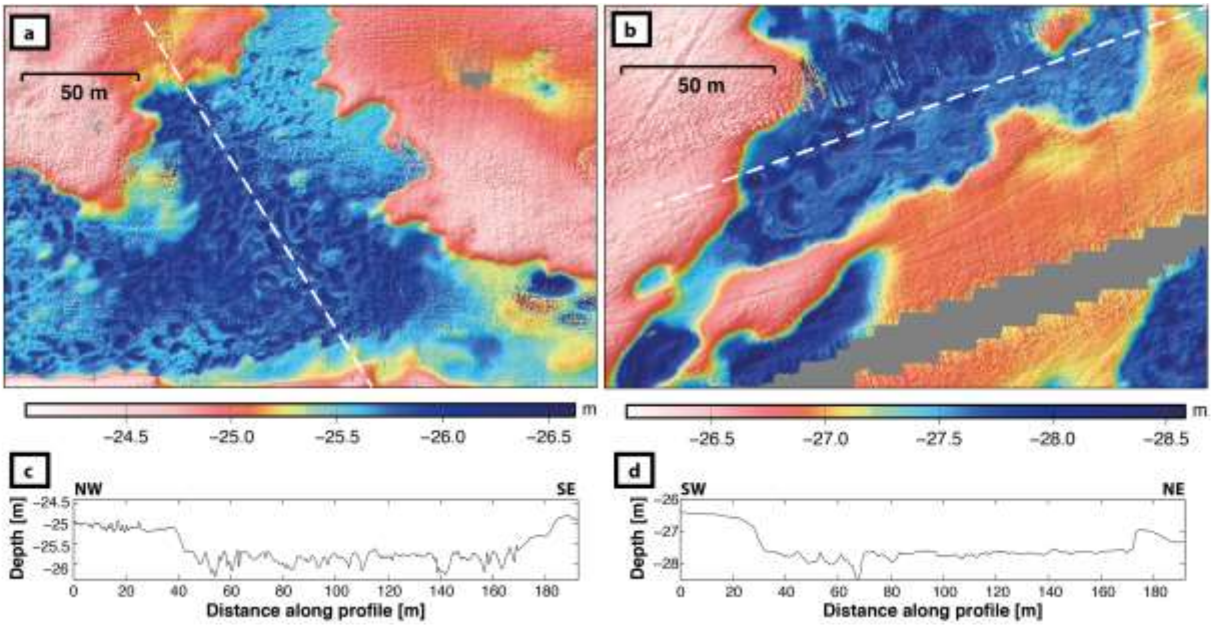

Figure 3: Bathymetric close-up of the pockmark showing (a) main depression of PM1; (b) southwestern depression of PM3; (c) profile over PM1 and (d) profile over PM3 revealing small scale intra-pockmarks. Dashed white line indicates profile line.

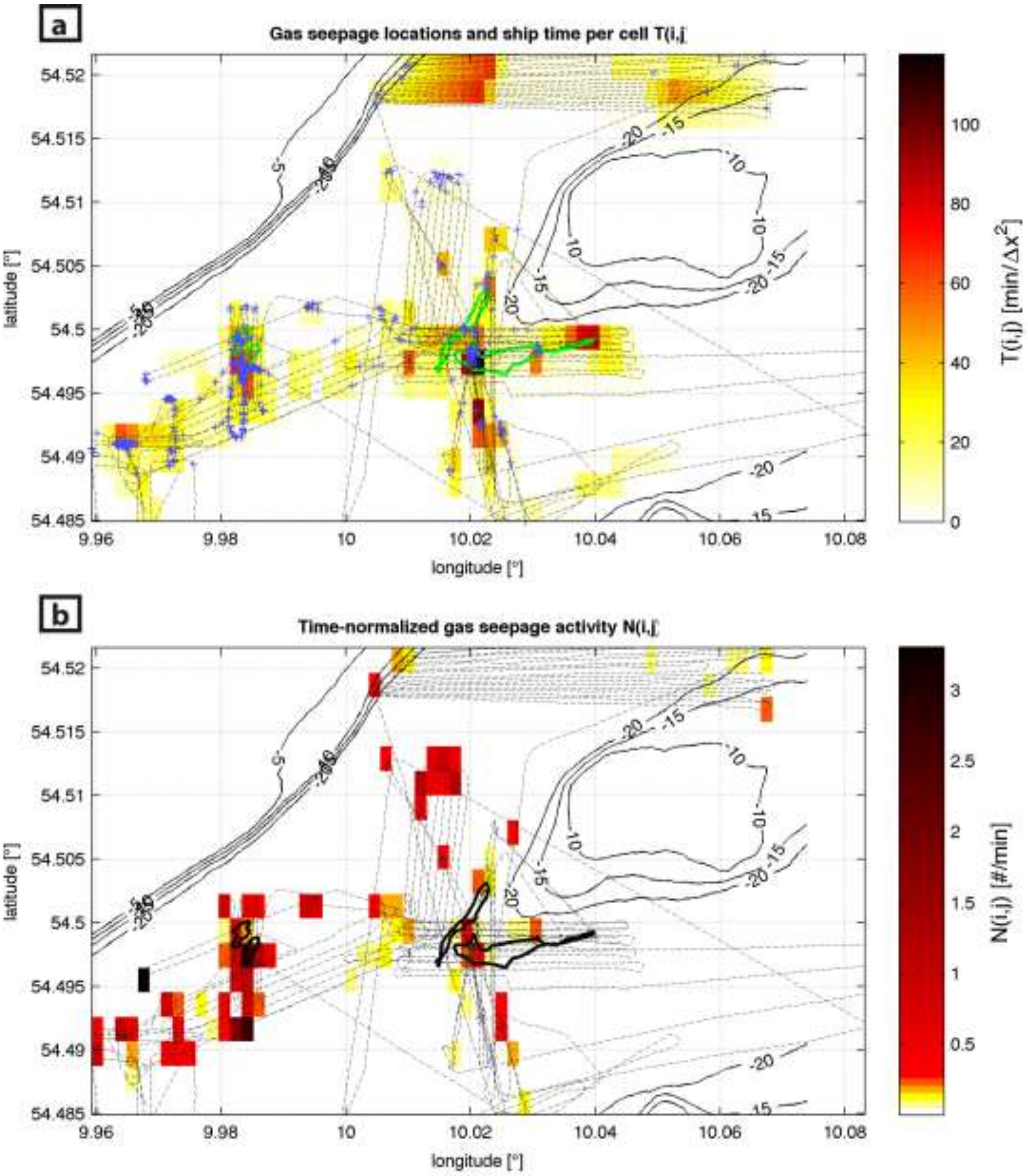

Figure 4: (a) Grid showing the ship time spent in each cell T(Δx=200m) and locations of gas seepage; (b) Probability density distribution of gas seepage activity N(Δx=200m). Thin black lines indicate depth contours; bold green/black lines indicate pockmark clusters PM1 and PM3; dashed lines represent 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.

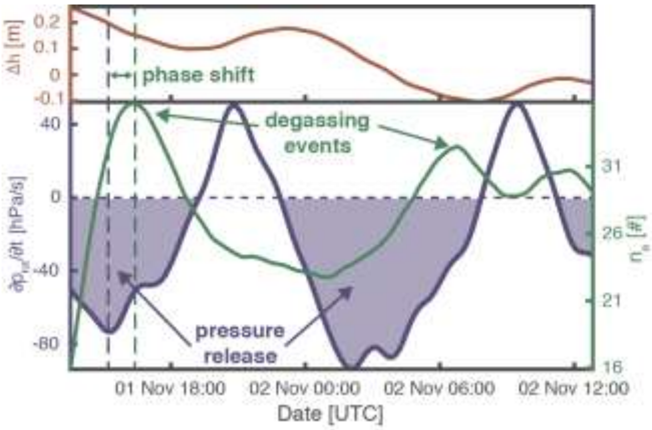

Figure 5: Correlation of water level, bottom pressure changes over time, and gas bubble count time series. Red line shows water level fluctuations Δh (PNP 5.004 m); purple line shows temporal change of total bottom pressure including atmospheric pressure (p_{tot}); green line shows the number of gas bubble events per 10-minute time bin n_e.

REFERENCES

Journal articles:

ABEGG, Friedrich and ANDERSON, Aubrey L.: *The acoustic turbid layer in muddy sediments of Eckernfoerde Bay, Western Baltic: methane concentration, saturation and bubble characteristics*. Marine Geology, 137(1):137–147, 1997.

BANGE, Hermann W., BARTELL, Ulrich, RAPSOMANIKIS, Spiridon, and ANDREAE, Meinrat O.: *Methane in the Baltic and North Seas and a reassessment of the marine emissions of methane*. Global Biogeochemical Cycles, 8(4):465–480, 1994.

BANGE, Hermann W., BERGMANN, Katja, HANSEN, Hans-Peter, KOCK, Annette, KOPPE, Regine, MALIEN, Frank, and OSTRAU, Christian: *Dissolved methane during hypoxic events at the Boknis Eck time series station (Eckernfoerde Bay, SW Baltic Sea)*. Biogeosciences (BG), 7:1279–1284, 2010.

LENNARTZ, Sinikka T., LEHMANN, Andreas, HERRFORD, Josefine, MALIEN, Frank, HANSEN, Hans-Peter., BIESTER, Harald, and BANGE, Hermann W.: *Long-term trends at the Boknis Eck time series station (Baltic Sea), 1957–2013: does climate change counteract the decline in eutrophication?* Biogeosciences, 11(22):6323–6339, 2014.

RICHARDSON, Michael: *Coastal Benthic Boundary Layer: A Final Review of the Program*. NRL Memorandum Report, Marine Geosciences Division-Naval Research Laboratory: Washington, DC, 1998.

SCHNEIDER VON DEIMLING, Jens., GREINERT, Jens., CHAPMANN, N. Ross., RABBEL, Wolfgang., & LINKE, Peter.: *Acoustic imaging of natural gas seepage in the North Sea: Sensing bubbles controlled by variable currents*, Limnology and Oceanography: Methods, *8*(5), 155-171, 2010.

SCHNEIDER VON DEIMLING, Jens: *R/V ALKOR cruise report AL447: Controls on methane seepage in the Baltic Sea, 20th Oct.-04th Nov., 2014*, 2015.

SCHÜLER, Friedrich: *Untersuchungen über die Mächtigkeit von Schlickschichten mit Hilfe des Echographen*. Deutsche Hydrografische Zeitschrift, 5(5-6):220–231, 1952.
WHITICAR, Michael J.: *Relationships of interstitial gases and fluids during early diagenesis in some marine sediments*. Sonderforschungsbereich 95, Univ. Kiel, 1978.

Links:

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BIOGRAPHICAL NOTES

Arne Lohrberg has graduated in Geophysics in April 2016 at Kiel University with prior undergraduate studies in Geosciences. As a student assistant he has worked in the Marine Geophysics and Hydroacoustics departments of both the GEOMAR Helmholtz Centre for Ocean Research Kiel and Kiel University since 2011.

Dr. Jens Schneider von Deimling is a trained geologist that gained his PhD in Geophysics in 2009 at Kiel University. He worked at renowned research facilities (GEOMAR, IOW, Germany), in the private survey industry, and gathered 15 years experience with customised hydroacoustic measurements and marine field work. Since 2016 he works as a research assistant and gives lectures in the Marine Geophysics and Hydroacoustics department at Kiel University.

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