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Marine near-surface electromagnetic signatures of methane gas and palaeorivers in the central North Sea

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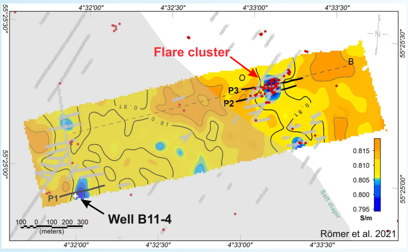
Introduction

Methane seeping from the seafloor, particularly in shallow shelf-regions, is one source of atmospheric methane, but exact amounts are still discussed. This hold for natural seepages, but also for methane, which may escape from active and abandoned oil & gas wells. During research cruise HE537 (July 2019) and MSM98 (January 2021) we studied the seafloor in the “Entenschnabel”, NW part of German North Sea, for signatures of gas seepage - combining hydroacoustics and electromagnetics, gas geochemistry and microbiology.

Sediment-physical properties of the seabed were mapped with marine EM profilers NERIDIS and GOLDEN EYE, both holding a frequency-domain central loop EM system with different loop-diameters and surveying techniques. Two case studies discuss electromagnetic signatures (and approaches for quantification) of methane gas in sediments and porosity/permeability characteristics of the shallow seabed.

Methane gas

The survey area above salt diapir Berta is dominated by fine sands, with up to 20% clay and silt content in the west and medium to coarse sand in the northeast (mean porosity ~40%; sediment 0.8 S/m, seawater 3.7 S/m). Conductivity drops by up to 10% below flare clusters, which could be explained by 5% free gas saturations of the pore-space.



How much gas in sediments?

We calculated gas saturation using Archie’s empirical porosity-resistivity relation (Eq.(1); mod. from Archie 1942), where σ_g is the electric bulk conductivity of the sediment section derived by inversion from EM data, σ_w the conductivity of the pore fluid (usually close to bottom water conductivity of 3.7 S/m measured by the CTD probe), ϕ the sediment porosity and S_g the gas saturation of the pore space.

$$\sigma_g = a\,\sigma_w\,\phi^m\,(1-S_g)^n, \quad (1)$$

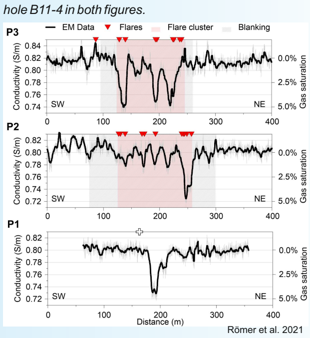
Assuming that the lithology does not change between gas-charged and gas-free sediment sections, Eq. (1) simplifies to Eq. (2). where σ_0 is the background conductivity of the pore water saturated sediment and σ_g the bulk conductivity of the gas-charged sediment section (both derived by inversion from EM data).

$$S_g = 1 - [\sigma_g/\sigma_0]^{\frac{1}{n}}, \quad (2)$$

Assuming a gas saturation parameter n = 2.0 one can estimate the gas-saturation from electric conductivity anomalies without actual porosity determination (right figures). However, local sediment compaction or dilution (i.e. by gas migration) is omitted - can we do better in unraveling gas and porosity effects?

Fig. (top) *Sediment electric conductivity data of the benthic EM Profiler. (A) Gridded 10 kHz EM conductivity data with flare locations (red dots), acoustic blanking from subbottom data (gray lines).*

Fig. (bottom) *Selected profiles crossing conductivity minima (gray: raw data, black: median filtered) with projected flare locations. Background colors indicate areas of high flare density and acoustic blanking. Gas saturation estimates are based on the conductivity contrast (Eq. 1). A white cross marks the location of borehole B11-4 in both figures.*



Palaeorivers

A group of small depressions was detected above salt diapir Britta, lacking water column anomalies but with indications of dissolved fluid release. Electromagnetic mapping with the NERIDIS profiler reveals a continuous, almost hook shaped structure of enhanced electric conductivity and magnetic susceptibility which partly coincides with morphological depressions

Figures:

(A) Bathymetric map of the area at salt diapir Britta, where several pockmarks were detected (Römer et al. 2021).

(B) The backscatter map shows that pockmarks are characterized by high backscatter indications. The area around well B18-4 and the pockmarks have been sampled by Mini-Corer (MIC) and Gravity-Corer (GC).

(C) Profile crossing the pockmarks (marked by red arrows), indicating their sizes, depths, and shapes.

(D) Apparent electric conductivity and

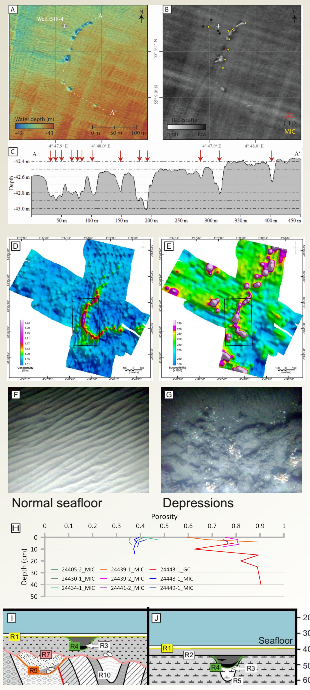
(E) magnetic susceptibility of the NERIDIS EM survey (the square represents the detailed area (Fig, a-b) with equidistant UTM projection).

(F) Normal sandy seafloor with ripples (source: Golden Eye camera)

(G) Sediments in depressions with coldwater corals, sponges, crabs (peat and woods) (Golden Eye camera)

(H) Porosity of MIC and GC samples. Sediments in depressions have high (60-90%) porosity versus ~40% background (mediumfine to coarse sands) (source: M. Römer, pers. comm.)

(IJ) Stratigraphical scheme of palaeorivers in North Sea sediments (modified from Coughlan et al. 2018, doi: 10.1111/bor.12253).



Marine electromagnetic profilers at BGR and MARUM

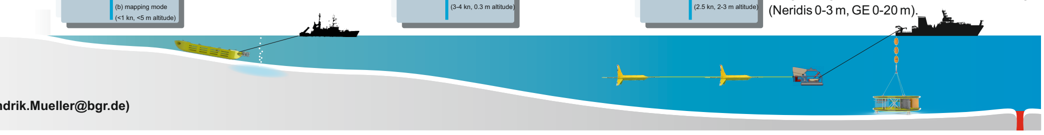
Size (D x H)	3.6 m x 1.25 m
Weight	900 kg (400 kg i.w.)
Depth rating	5000 m
Communication	Optical fibre
Power supply	900 / 24 / 12 V DC
Positioning	USBL
Operation	(a) stationary (b) mapping mode (<1 kn, <5 m altitude)

Size (L x W x H)	5.2 m x 1.2 m x 0.8 m
Weight	850 kg (150 kg i.w.)
Depth rating	500 m
Communication	DSL (coax-cable)
Power supply	24 V DC
Positioning	Triangulation
Operation	towed, bottom contact (3-4 kn, 0.3 m altitude)

Size (L x W x H)	3.1 m x 1.6 m x 1.2 m
Weight	300 kg (100 kg i.w.)
Depth rating	500 m
Communication	DSL or Optical fibre
Power supply	400 V / 24 V DC
Positioning	Triangulation / USBL
Operation	towed, non-contact (2.5 kn, 2-3 m altitude)

The BGR GOLDEN EYE (left) and MARUM NERIDIS (center) EM profilers hold similar EM induction-loop sensors with different TX coil dimensions, operation depths, configuration and tow-speeds. SPECTRE (right) is a new shallow water profiler for faster surveying, and easier transport and handling.

Central loop EM data are measured at 6-12 frequencies (15 Hz – 10 kHz) using a +/- 30A (48V) Geophex transmitter. Half-space inversion provides maps of electrical conductivity and magnetic susceptibility. 1D inversion (or LCI) and 3D gridding is used for subsurface modelling (Neridis 0-3 m, GE 0-20 m).



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Römer M, Blumenberg M, Heeschen K, Schloemer S, Müller H, Müller S, Hilgenfeldt C, Barckhausen U and Schwalenberg K (2021) Seafloor Methane Seepage Related to Salt Diapirism in the Northwestern Part of the German North Sea. Front. Earth Sci. https://doi.org/10.3389/feart.2021.556329