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A low frequency multibeam assessment: Spatial mapping of shallow gas by enhanced penetration and angular response anomaly

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ABSTRACT

This study highlights the potential of using a low frequency multibeam echosounder for detection and visualization of shallow gas occurring several meters beneath the seafloor. The presence of shallow gas was verified in the Bornholm Basin, Baltic Sea, at 80 m water depth with standard geochemical core analysis and hydroacoustic subbottom profiling. Successively, this area was surveyed with a 95 kHz and a 12 kHz multibeam echosounder (MBES). The bathymetric measurements with 12 kHz provided depth values systematically deeper by several meters compared to 95 kHz data. This observation was attributed to enhanced penetration of the low frequency signal energy into soft sediments. Consequently, the subbottom geoacoustic properties contributed highly to the measured backscattered signals. Those appeared up to 17 dB higher inside the shallow gas area compared to reference measurements outside and could be clearly linked to the shallow gas front depth down to 5 m below seafloor. No elevated backscatter was visible in 95 kHz MBES data, which in turn highlights the superior potential of low frequency MBES to image shallow sub-seafloor features. Small gas pockets could be resolved even on the outer swath (up to 65°). Strongly elevated backscattering from gassy areas occurred at large incidence angles and a high gas sensitivity of the MBES is further supported by an angular response analysis presented in this study. We conclude that the MBES together with subbottom profiling can be used as an efficient tool for spatial subbottom mapping in soft sediment environments.

1. Introduction

Methane is considered the most important greenhouse gas on Earth after water vapor and CO_2. Recent studies suggest an even higher impact of CH_4 on global warming (Shindell et al., 2009) compared to earlier assumptions (Lelieveld et al., 1993). Marine methane has been reported to occur worldwide especially on the continental margins, in estuaries and river deltas, where the gas is often hosted in sediments a few decimeters to meters below the seafloor (Judd and Hovland, 2007). Global warming and eutrophication can accelerate natural seabed gas generation by enhancing organic matter accumulation which upon burial is converted to methane. Gas generation and respective bubble formation have a strong impact on the structural integrity and load-bearing capabilities of the sediment (Briggs and Richardson, 1996). Therefore an understanding of presence and distribution of shallow gas in the sediment is of great importance e.g. with regard to offshore construction safety issues. Best et al. (2006) argued that abnormally high levels of methane gas in seafloor sediments could pose a major hazard to coastal populations within the next 100 years through the impact on climate change and sea level rise.

Indications of shallow gas occurrence in the seafloor can be derived from geochemical analyses in the water column and on sediment cores. Even small amounts of free gas may significantly alter the geoacoustic properties of the seafloor, giving rise to highly enhanced acoustic scattering compared to the surrounding sediment/pore water mixture (Anderson and Hampton, 1980; Lyons et al., 1996). Thus, vessel-operated hydroacoustic subbottom profilers were established as a standard tool for remote sensing of shallow gas (Fleischer et al., 2001).

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Today a wide range of multibeam echosounder (MBES) mapping systems is available covering frequencies between 12 kHz and 700 kHz. High frequencies offer high resolution at the cost of higher attenuation and low seafloor penetration. In contrast, low frequency multibeam sounders have lower resolution but allow greater operating ranges and potentially deeper seafloor penetration. Recent developments in hardware and processing have significantly improved MBES data and today additional seafloor information can be derived from backscatter analyses and statistical approaches (Brown et al., 2011; Simons and Snellen, 2009; Preston, 2009). Those studies mainly examine high frequency data (~100 kHz) for seafloor classification based on the relation between seafloor roughness and backscattering strength. Fonseca et al. (2002) demonstrated the potential of MBES for shallow gas sensing, however, their 95 kHz signals only allowed for a decimeter penetration into the seafloor.

Early studies performed with the sidescan sonar GLORIA (Mitchell, 1993) demonstrated the potential of low frequency approaches at low grazing angles for sediment investigations. Data in the focus of this study were gathered with a low frequency multibeam echosounder (see description below). Our approach was to make use of an enhanced seafloor penetration of a few meters with this low frequency MBES to promote increased subbottom volume scattering and thus mapping of shallow gas over large areas.

2. Methods

Data were acquired on the German R/V Maria S. Merian (Cruise 16/1) in August 2010. A Kongsberg EM120 (12 kHz, hull-mounted), an EM1002 (95 kHz, moonpool), and an ATLAS PARASOUND DS3 (PS, 4 kHz, hull-mounted) system were connected to a Seapath DGPS positioning and motion reference unit. Keel sound velocity and vertical sound velocity profile data were derived from online thermosalinographic and CTD cast measurements. Both MBES used a $2^\circ \times 2^\circ$ TX/RX aperture forming 191 and 111 beams, and covered a 140° and 150° swath, respectively. The pulse length was set shortest (2 ms, 0.2 ms) to achieve a maximum range resolution. Depth below seafloor estimates were performed by multiplication of the subbottom travel time (s) with the value of the deepest sound velocity measurement sampled close to the seabed ($v = 1459\ \mathrm{m\ s^{-1}}$). Corrections accounting for seawater attenuation and geometrical spreading were applied by the recording software SIS. Then average backscattering strength (BS) values were computed by the system for data around the detected depth-time sample in each beam. The recorded soundings were cleaned and gridded using the *MB System* software package. Backscatter data were extracted by *MB System* (raw) and *QPS-IVS Geocoder 7.3* (corrected). The MBES systems were calibrated for roll, pitch, yaw, and latency, but not for absolute echo level voltage measurements. Accordingly all BS data must be regarded as relative values with an accuracy specified by the manufacturer to ±1 dB. The data in this paper were acquired at shallow water depth; thus near-field effects add as an extra uncertainty.

3. Field site & survey

The study area is located in the Bornholm Basin – a 90 m deep sedimentary basin in the western part of the Baltic Sea (Fig. 1). The basin reflects deeper structures and has been influenced by tectonics during the Cenozoic and Mesozoic. Recently, sediments have been deposited in the late Pleistocene during and after deglaciation. The uppermost layer of several meters thickness consists of organic rich silt (Holocene mud) deposited after the Littorina transgression (Fig. 2a, upper layer). Morphology and thickness variation of the muddy unit are strongly controlled by postglacial basin development and bottom current pathways. Within this layer widespread occurrences of shallow gas were observed (Hinz et al., 1971; Laier and Jensen, 2007, Fig. 2a left part). Recent measurements of water column methane concentrations close to the seabed (Schmale et al., 2010) further indicated the presence of significant shallow methane sources in the seabed of this area.

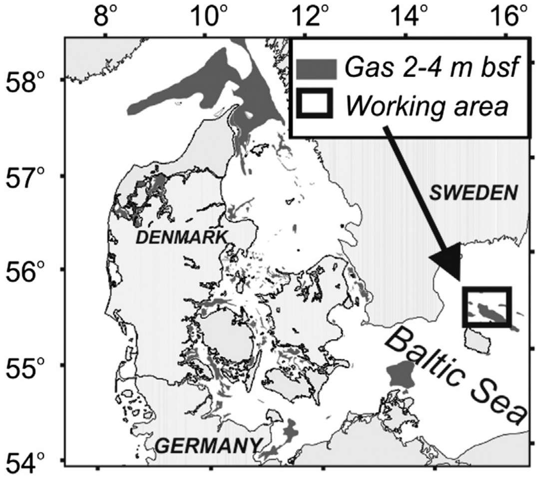

Figure 1. Shallow gas distribution map modified after Laier and Jensen (2007). The working area plots within an area hosting shallow gas between 2 and 4 m bsf.

Six survey lines of approximately 2 nautical miles length were run in the northern part of the Bornholm Basin at 4 knots recording EM120 and PS data in parallel; two survey lines were repeated with the EM1002 MBES. Finally, Rumohr Lot (RL) cores were taken at each of five stations along the transect line and respective CH_4 concentrations were measured onboard.

4. Results and discussion

4.1. Evidence of shallow gas from seismic and geochemical profiling

PS records and Rumohr Lot core data disclosed two regimes, A and B, where Holocene mud appeared with and without free methane gas. To the left in Figure 2a a scattering reflector is interpreted as the upper gas front within the Holocene mud between 1 m and 5 m below seafloor (bsf). Below this depth methane gas bubbles efficiently absorbed the acoustic energy and thus ‘blanked’ any information from the underlying sedimentary strata. In the middle of the profile (Fig. 2a) a transition zone T between A and B is characterized by the down-dipping shallow gas front from 2 m to 5 m bsf. To the right the blanking effect is absent revealing the 12 m thick layer of acoustically transparent Holocene mud followed by well-layered deposits of earlier Baltic Sea stages (Ancylus to late Pleistocene). Five core samples along the recorded PS profile (positions see Fig. 2a) support the findings from the seismic records, i.e. the measured methane concentration gradients in 1 m long RL cores are high in A and low in B. Sampling procedures for dissolved methane in pore waters were optimized to minimize gas loss even when concentrations exceed solubility at 1 atm (Fig. 2b) by drilling into the core liner and immediate sampling. Loss of gas from the base of the core is evident at the gas-rich core c31 (Fig. 2b). From core c31 the free gas depth is estimated to be around 0.9 m bsf from Figure 2b by assuming a linear gradient between the sulfate–methane transition zone and the level where gas saturation and consequently free gas occurrence is reached. The horizon of shallow gas occurrence is gradually appearing at greater sediment depth for cores c103, c102, and c101. No free gas is expected at core site c32.