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Measurements of values of sediment physical properties, bubble volume, and bubble size distribution are used to predict frequency-dependent sound speed and attenuation in the fine-grained gassy sediments of Eckernförde Bay, Baltic Sea. Acoustic models [1-3] predict, at acoustic frequencies well-above resonance, that sound speed is unaffected by bubbles and scattering from bubbles dominates attenuation. At frequencies well below resonance, sound speed is much lower than bubble-free sediments and attenuation is dominated by scattering from impedance contrasts. Near-resonance sound speed varies greatly with frequency and attenuation is very high. Given the highly variable spatial and temporal distribution of bubble volume, bubble size, and bubble size distribution in Eckernförde Bay, the agreement between theoretical predictions and acoustic measurements is remarkably good.

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HIGH-FREQUENCY VOLUME SCATTERING FROM GASSY SEDIMENTS

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Measurements of values of sediment physical properties, bubble volume, and bubble size distribution are used to predict frequency-dependent sound speed and attenuation in the fine-grained gassy sediments of Eckernförde Bay, Baltic Sea. Acoustic models [1-3] predict, at acoustic frequencies well-above resonance, that sound speed is unaffected by bubbles and scattering from bubbles dominates attenuation. At frequencies well below resonance, sound speed is much lower than bubble-free sediments and attenuation is dominated by scattering from impedance contrasts. Near-resonance sound speed varies greatly with frequency and attenuation is very high. Given the highly variable spatial and temporal distribution of bubble volume, bubble size, and bubble size distribution in Eckernförde Bay, the agreement between theoretical predictions and acoustic measurements is remarkably good.

1. INTRODUCTION

Gas bubbles are ubiquitous in organic-rich, muddy sediments of coastal waters and shallow adjacent seas [4,5]. Depths and horizontal distributions of these gas-charged sediments are usually determined from seismic profiling. The presence of gas bubbles often impedes acoustic characterization of sediments below the gas horizon and terms such as acoustic masking or blanking, acoustic turbidity, bright spots, wipeouts, and pulldowns are used to characterize these gas-charged sediments. Acoustic turbidity also produces anomalously high acoustic backscattering from the seafloor [6,7] degrading the effectiveness of high-frequency sonar. Models of acoustic-bubble interactions in fine-grained sediments developed by Anderson and Hampton [1] have been corroborated by laboratory [2] and field [3,6-8] experiments. In this paper, we model the effects of bubble size and bubble distribution on sound speed and attenuation in the well-characterized sediments of Eckernförde Bay, Baltic Sea. Based on the numerous international studies over the past 50 years, Eckernförde Bay is the best-known and most studied area of gassy sediment in the world [5] thus providing the ideal setting for such comparisons.

2. ENVIRONMENTAL CHARACTERIZATION

Eckernförde Bay is the only site in the world where sufficient information is available on bubble size, bubble size distribution, and sediment physical properties to test acoustic propagation model predictions of Anderson and Hampton [1}. Bubble volume and size distribution were quantified using X-ray computed tomography (CT-scans) of sediment collected with 12-cm (inside diameter) cores that were retained at in situ temperature and pressure [8]. The bubbles resolvable in Eckernförde sediments range between 0.5 to 10 mm in equivalent radius with 0 - 2 % (mean 0.1 %) percent gas by volume. Higher gas volumes (up to 6%) were reported from the sediment found in numerous pockmarks. Considerable horizontal and vertical variability was found in methane bubble concentrations in cores collected 2-20 meters apart [8]. Sediment physical and geoacoustic properties of central Eckernförde Bay were characterized using a variety of in situ and laboratory measurement techniques and from well-established tabular values found in physical handbooks (Table 1). Descriptions of the measurement techniques are found in Wilkens and Richardson [8] and Richardson and Briggs [9].

Water depth	24 meters
Sediment depth	2 meters
Sediment temperature	4.8-8° C at surface; 5.8-6.7° C at 180 cm
Pore water salinity	20 ppt at surface;14-18 ppt at depth
Bubble radius (r_o)	0.3 - 10.0 x 10^{-3} m
Bubble volume	0-8% (mean 0.1%)
Ratio of specific heats of gas (γ)	1.31 at 15° C
Thermal conductivity of methane gas (C_g)	3.11 x 10^{-2} J s^{-1} °C^{-1}
Specific heat at constant pressure (s_p)	2.19 J kg^{-1} °C^{-1}
Methane gas density at 1 atm (ρ_g)	7.17 x 10^{-1} kg m^{-3}
Hydrostatic ambient pressure (P_o)	1.013 x 10^2 kPa at 1 atm
Fractional porosity (η)	0.85
Seawater density (ρ_w)	1.013 x 10^3 kg m^{-3}
Sediment density (ρ_s)	1.25 x 10^3 kg m^{-3}
Sediment grain density (ρ_m)	2.59 x 10^3 kg m^{-3}
Shear modulus of sediment (G)	2.8125 x 10^2 kPa at 2 mbsf
Imaginary shear modulus (G')	0.153 x 10^2 kPa at 0.35 mbsf
Bulk modulus of grains (K_m)	3.6 x 10^7 kPa
Bulk modulus of pore water (K_w)	2.14 x 10^6 kPa
Mean grain size (ϕ)	9.0 – 11.0 (mean 9.9 ϕ)
Permeability	3 x 10^{-6} cm sec-1
Sound speed	1428 m s^{-1}
Shear wave speed	15 m s^{-1}
Sound speed attenuation	4.11 dB m^{-1}
Shear wave attenuation (@ 70 Hz)	13.5 dB m^{-1}

Table 1. Measured, calculated, and tabular handbook values of sediment physical properties that were used as inputs to predict sound speed and attenuation in the gassy sediments of Eckernförde Bay, Baltic Sea. Values of sediment physical properties are for gas-free sediments.

3. ACOUSTIC MODEL – MEASUREMENT COMPARISIONS

Bubble size distributions based on CT-scans and values of sediment physical properties presented in Table 1 were used to predict sound speed and attenuation in the gassy sediments of Eckernförde Bay, based on the modified versions of the acoustic propagation models in gassy sediments [1,3,6,8]. These models assume bubbles are large relative to particle size and the structure of the sediment frame interacts with the bubbles and changes bubble resonance, compressibility, absorption, and scattering. The low sediment permeability, in the modelled sediments, restricts pore fluid motion and allows the use of the visco-elastic propagation models used in this paper to approximate sediment propagation predicted by more complex poro-elastic models [10]. Sound speed and attenuation were first calculated assuming single bubble sizes for gas fractional volumes ranging 0.0001 and 0.01 (Fig. 1). The higher sediment rigidity lowered bubble resonance compared to the same bubble in water in a predicable manner. The sound speed and attenuation predictions were in general agreement with results of acoustic measurements presented by Wilkens and Richardson [8].

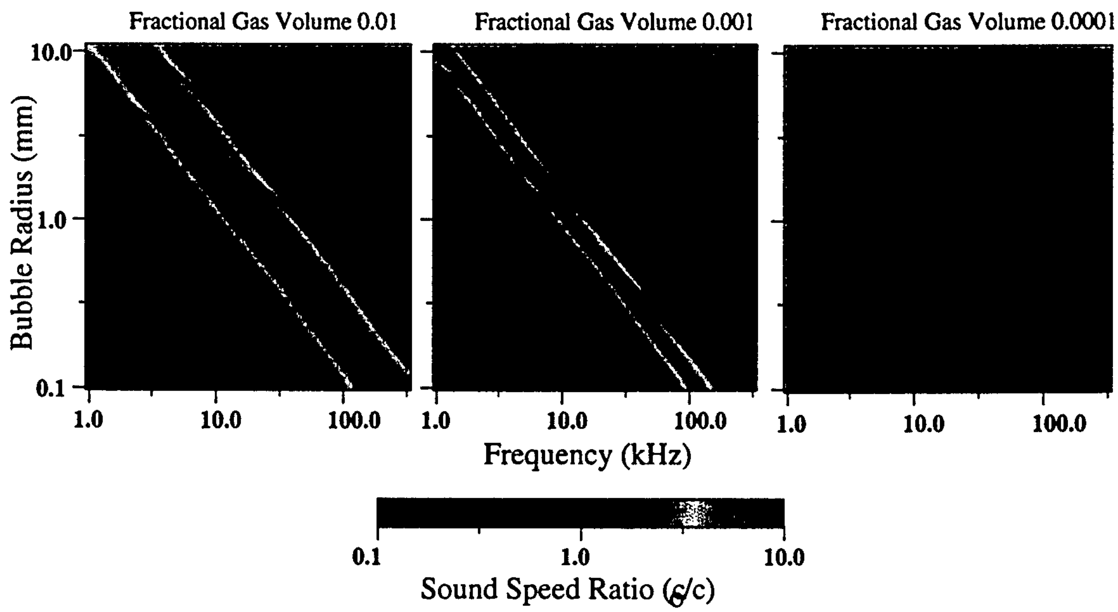

Fig. 1: Sound speed ratio and attenuation (dB m^{-1}) of sediments from Eckernförde Bay as a function of bubble size and acoustic frequency for bubble concentrations of 1%, 0.1% and 0.01%. Calculations are based on references [1,3] and inputs from Table 1.

Sound speed and attenuation were then predicted as a function of bubble size and acoustic frequency for typical bubble concentrations found in Eckernförde Bay sediments (Figures 2 and 3). At acoustic frequencies well above resonance (>30 kHz), bubbles resonance rarely affects sound speed and scattering from bubbles dominates attenuation. At frequencies well below resonance (< 1 kHz) "compressibility effects" dominate, sound speed is much lower (250 m s^{-1}), and attenuation is controlled by scattering from impedance contrasts. Near resonance sound speed varies greatly with frequency and attenuation is very high. Analysis of in situ and remote acoustic propagation and scattering data over a frequency range of 5-400 kHz, support these model predictions [3, 4], especially well above and well below the bubble resonance frequency. Analysis of the dispersion of measured sound speeds established the upper limit of methane bubble resonance at 20-25 kHz. These data, combined with bubble sizes determined from CT scans yielded estimates of effective bubble sizes between 0.3 and 8.0 mm. The lower limit of effective bubble size was smaller than the resolution of the CT-scanning technique. Values of sound speed predicted using the entire spectrum of bubble sizes (Figs. 2 and 3) were lower than predicted values based on a single bubble size (Fig. 1). These predictions are in concordance with sound speeds (1100 - 1200 m s^{-1}) reported for 5-15 kHz by Wilkens and Richardson [3] and suggest that the proportional distribution of bubbles must be considered when predicting acoustic behaviour of gassy sediment.

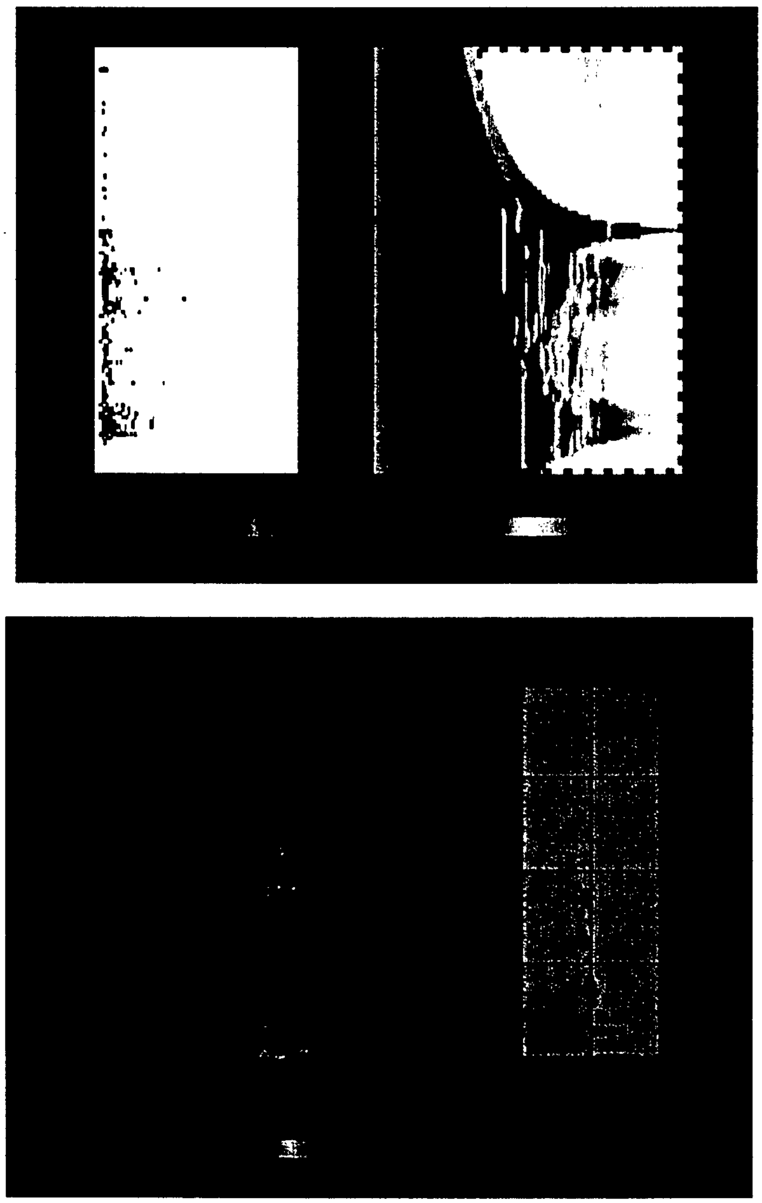

Fig. 2: Sound speed ratio and attenuation calculated for measured bubble size distribution at site P2 (see reference [8]) and sediment properties presented in Table 1.

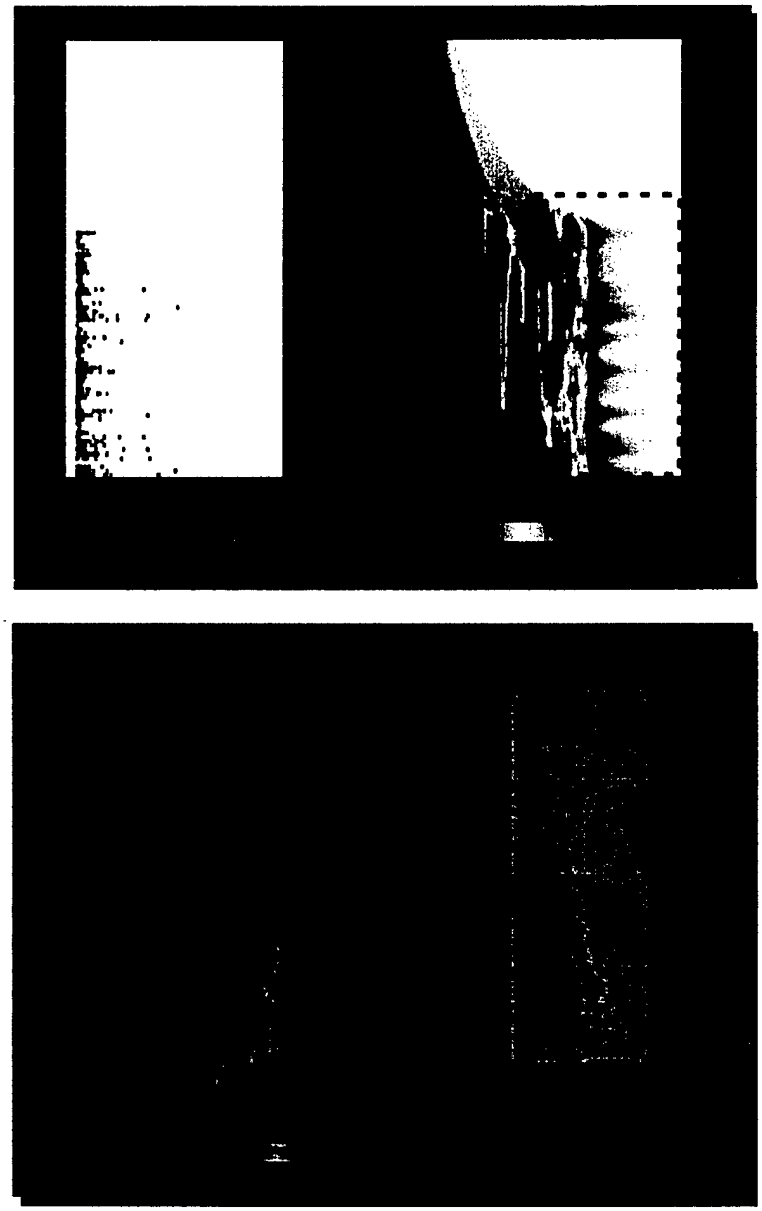

Fig. 3: Sound speed ratio and attenuation calculated for measured bubble size distribution at site P6 (see reference [8]) and sediment properties presented in Table 1.

Also evident is the great spatial variability in sediment sound speed and attenuation especially near bubble resonance at sites P2 and P3, which were only 20 m apart (see Figs. 2 and 3). This predicted spatial variability, both down core and between cores, is in concordance with the high variability in normal incident acoustic profiles made in Eckernförde Bay, where the depth and intensity of acoustic scattering varied widely on all spatial (cm to km) and temporal scale (seconds to years) scales. The high spatial variability in bubble distribution, sound speed, attenuation, and scattering makes deterministic validation of scattering and propagation models proposed for gassy sediments difficult.

4. FUTURE STUDIES

Additional joint German/US experiments are planned for Eckernförde Bay during the spring- summer of 2001. In situ measurements of sound speed and attenuation in the upper 2-m of sediment will be made using wide-bandwidth transducers (5-200 kHz). In addition, normal incident acoustic scattering will be measured using a broadband (15-200 kHz), constant beam width (12°) transducer mounted above the sea floor. These data, combined with extensive characterization of bubble distribution and seafloor physical properties will provide validation of the visco-elastic propagation models used for gassy sediments.

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