INFERRING BUBBLE POPULATIONS IN INTERTIDAL SEDIMENTS FROM ATTENUATION AND SCATTERING MEASUREMENTS

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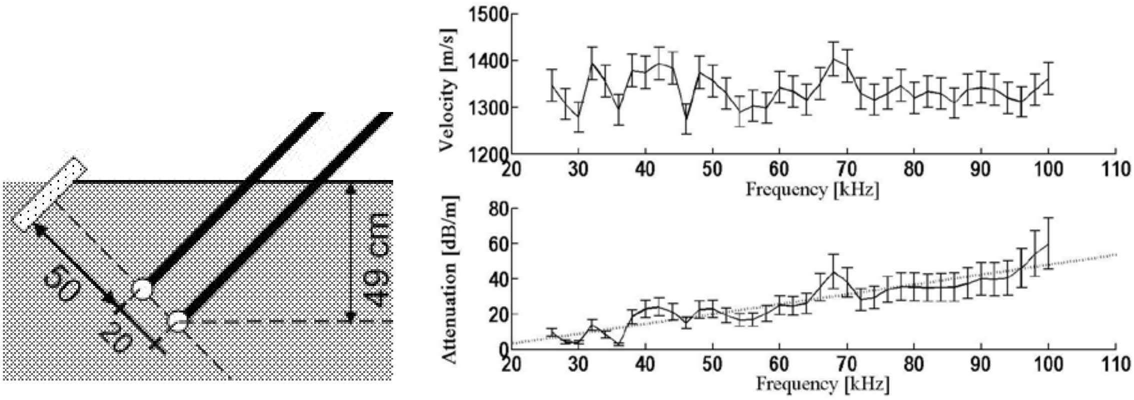
Abstract: *The presence of free gas can dramatically alter the acoustic properties of marine sediments. The effect of different shapes and sizes of gas pockets is of particular interest. Results from one acoustic transmission and two-frequency acoustic scattering experiments at intertidal gassy mud sites on the south coast of England provide evidence for the presence of both spherical and non-spherical gas voids. The characteristics of the bubble population can be estimated from new models of nonlinear bubble dynamics.*

Keywords: *gassy sediments, intertidal mud, nonlinear scattering, gas bubble dynamics*

1. INTRODUCTION

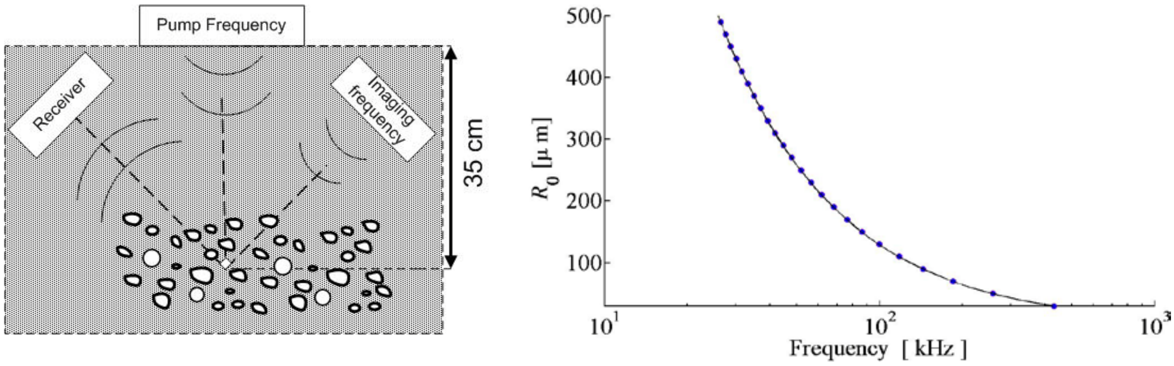
The presence of seafloor gas-bearing (gassy) sediments can impact on the activities of the offshore industry and can influence biologic cycles of marine life. In gassy sediments, both the shape and size of the gas voids are important because their influence on the sediment's bulk strength. Frequently spherical bubbles are used to model gas voids although there is evidence that gas voids in muds can form cracks or oblate spheroids [1]. In this paper, acoustic transmission and backscattering measurements are employed with theory to devise methods for quantifying scattering from the shallow sub-seabed. Field measurements were carried out in the top metre of selected intertidal sediments on the south coast of England where methane production is of biogenic origin [2].

Methane production takes place below the sulphate reducing zone from anaerobic decomposition of organic matter (generally greater than one meter depth) [3]. Aerobic decomposition is the major reaction producing gas in the first top meter [4]. When entrained air is present this can lead to the presence of O_2, N_2 and CO_2.



(a) *(b)*

Fig. 1: (a) Schematics of the experimental geometry (all dimensions are in cm). (b) Sound speed and attenuation as measured with the set up shown in (a) where the dotted line is a linear best fit to the data points connected with a solid line and the error bars indicate intrinsic errors at these points.



(a) *(b)*

Fig. 2: (a) schematic of the experimental geometry for the scattering measurements (all dimensions are in cm). (b)Bubble size versus natural frequency where the solid line is predicted by equation 22 of ref. [14] and the dots are calculated from equation (1).

2. TRANSMISSION MEASUREMENTS

In situ transmission experiments were carried out at Calshot (50º 48', 002º 2' W) a site which had previously been characterized as poorly sorted coarse silt with porosity 62±5 % [5]. For the transmission experiments (Figure 1a) the acoustic source (which transmitted 1 ms tone-burst pulses from 26 to 100 kHz at 2 kHz steps) was buried below the sediment surface, its acoustic axis (along which 2 hydrophones were aligned) angled at 45° to the sediment surface. The transmission data were processed according to the technique described in ref. [5]. The results are shown in Figure 1b where the error bars indicate intrinsic errors [5]. According to these results the compressional sound speed (c_p) showed no dispersion (average value c_p=1340 ± 60 m/s) and the attenuation coefficient α [dB/m] follows a linear dependence with frequency f. Based on these observations, the attenuation data were fitted to the typical expression $a = Kf^{q}$, where K is the constant of proportionality and q is the exponent of frequency [6]. The best-fit values for frequencies between 26 kHz to 100 kHz are 0.56 dB/m/kHz for K and 1 for q. Comparing these results with previous data [6] and [7] for non-gassy muddy sediments suggests that gas was present. In theory, this is justified from the fact that c_p is lower than the values suggested by literature and the value of K is much greater (typically values of K for muddy sediments lay below 0.3 dB/m/kHz). However no clear resonant peaks where observed; such peaks would indicate the presence of gas in spheroidal form that is resonant in the frequency range tested.

3. SCATTERING EXPERIMENTS

Combination frequency scattering experiments were carried out within 1 metre of the transmission experiments location. The experimental set up was buried in the sediment (Figure 2a) and only volume scattering was taken into consideration. The high frequency transmitter (producing the "imaging frequency") and receiver have a common focus point where their acoustic axes intersect each other at 90°, their axes being 45° either side of the axis of the pump transmitter (which is also the axis of symmetry of the set up). Beam pattern calculations were calculated in water and then a frequency-dependent correction was applied for the different sound speed in sediment. The "imaging frequency" f_1 was kept constant at 220 kHz and the "pump frequency" f_2 varied from 30 kHz to 100 kHz in increments of 2 kHz. The acoustic sources were calibrated in water such that at the intersection point of their acoustic axis, the pressure of the pump frequency was 30 kPa and the imaging frequency 35 kPa respectively (nominal zero-to peak amplitude) within the 3 dB limit of the common volume of these devices.

3.1. Theoretical considerations

The sediment is assumed to be the only source of nonlinearity. This assumption is based on previous work [8] which suggests that the nonlinearity associated with bubble-free sediment is greater than twice that of the nonlinearity of bubble-free water (which is much smaller than the nonlinearity of water containing spherical pulsating bubbles) [8]". If two frequencies f_1 and f_2 are projected at a population of bubbles containing a wide distribution of bubble sizes, a spectra of various frequencies can be detected (f_1, f_2, $2f_1$, $2f_2$, $|f_1 \pm f_2|$, $|f_1 \pm 2f_2|$ etc.). Commonly, interpretation of these scattered spectra relies on an assumed one-to-one mapping between a spectral component and a bubble size. This may be a valid assumption by suitable choice of f_1 and f_2. For example if $f_1 \approx f_2$ *and* there are no bubbles resonant at f_1 *or* f_2 then the only sources of spectral energy at difference frequency ($f_1 - f_2 = f_{1-2}$) are the bubbles resonant at that frequency, i.e. f_{1-2}. One problem with this approach is finding suitable frequency ranges for sediments. *Leighton et al* [9] developed a scheme whereby the contributions of all bubbles in the population to each spectral component are considered in the inversion that estimates the bubble population from the scattering. This is more rigorous than application of the above assumptions, but also is particularly important in gassy sediment, where the high attenuation makes it difficult to exploit a frequency which can be guaranteed to be much higher than the resonances of any bubbles present. In order to interpret such spectra, a new bubble model was required. The bubble radius time response R and natural frequency f_0 were estimated from the nonlinear bubble models build on earlier models for sediment [10,11] and biological tissue [12]. The model incorporates shear effects from first principals, and can cope with amplitude-dependent effects, and two-frequency insonification, which cannot be captured by a linear model, for example of Anderson and Hampton [13, 14]. In the small-amplitude linear limit the model of [11] predicts a pulsation resonance frequency predicts the linear resonance frequency:

$$f_0 = \left(2\pi R_0\right)^{-1} \sqrt{\left(3\kappa p_{\mathrm{b0}} + 4G_{\mathrm{s}}\right)/\rho_s} \tag{1}$$

of a bubble with equilibrium radius R_0 assuming adiabatic pulsations, where κ (=1.3) is the polytropic index of the bubble gas (assuming CO_2), p_{b0} (=104 kPa) is the bubble ambient pressure for the set up shown in Figure 2a and the parameters ρ_s and G_{s} are the density and the shear modulus of the *gas-free* sediment having values 1640 kgr m^{-3}and 2.6 MPa respectively. The thermal effects are of minor importance in sediment of the type discussed here. This is demonstrated in Figure 2b where equation (1) is compared with equation 22 of ref. [14]. For these simulations the gas was assumed to be atmospheric air at 10 ºC and the compressional wave speed (in the bubble host medium i.e. gas-free sediment) equal to 1430 m/s. As expected there is good agreement of the two equations as G_{s} is the dominant term.

The spatial distribution of any bubbles present is assumed to be random and hence the measured scattering is interpreted as incoherent and the concept of scattering cross section is invoked. The nonlinear differential extinction cross section of the individual bubbles (σ_s) was computed numerically from the nonlinear bubble model using the input parameters mentioned in the previous paragraph and definition of extinction cross section [15]: $\sigma_s = R_0^2 \left|P_{\mathrm{b}}\right|^2 \big/ \left|P_{\mathrm{i}}\right|^2$, where $\left|P_{\mathrm{i}}\right|$ and $\left|P_{\mathrm{b}}\right|$ are the amplitude pressure spectral components of the incident and scattered field respectively at the frequency of interest (f_{1-2}), where in (2) the scattered field is evaluated at the bubble wall ($r = R_0$):

$$P_b = \rho_{\mathrm{s}}\left(2R\dot{R}^2 + R^2\ddot{R}\right)/r\,\big|r = R_0 \text{, where dots represent time derivatives.} \tag{2}$$

The received pressure spectral component at f_{1-2} from a number N of identical bubbles depends on the radial distance, R_{m}, of the centre of the receiver face to the centre of the sensing volume at difference frequency :

$$\left|P_{\mathrm{r}}\right|^2 = \int_V N\sigma_{\mathrm{rs-}} \left|P_{\mathrm{b}}\right|^2 R_{\mathrm{m}}^{-2} dV\left(\Omega_{-}\right) \text{, where } \sigma_{\mathrm{rs-}} \text{ is the receiving cross section.} \tag{3}$$

(i.e. $\sigma_{\mathrm{rs-}}$ is the σ_s corresponding to the sensing solid angle), an expression which can easily be extended to a continuum of bubble sizes.

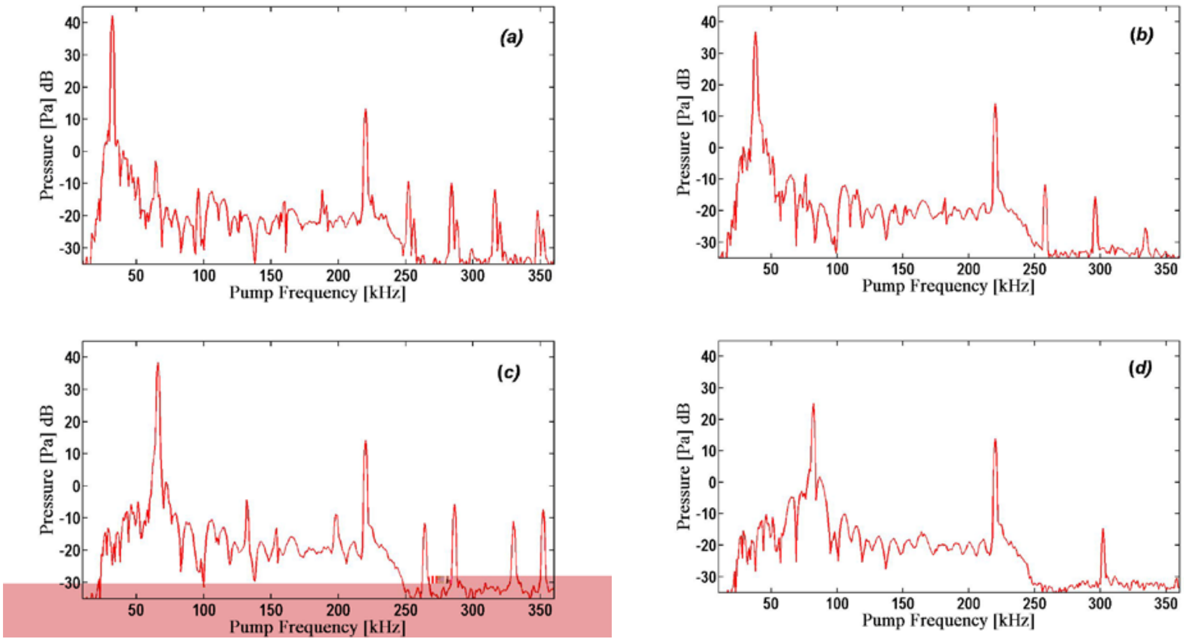


Fig.3. Pressure spectral component $|P_r|$ in dB (with a common dB reference) as measured by the receiver. The imaging frequency is kept constant at 220 kHz. The figures show measurements with pump frequency at (a) 32 kHz, (b) 38 kHz, (c) 66 kHz and (d) 82 kHz.

4. RESULTS & DISCUSSION

Figure 3 shows example spectra obtained when two frequencies are projected into the sediment. Generally such data are ambiguous: for example, scattering at the difference frequency f_{1-2} is studied, and this can arise from bubbles being resonant at the primary frequencies (f_1 and f_2) and those resonant at f_{1-2}. However for the site in question the transmission results showed no resonances at the frequency range of 26-100 kHz. Therefore it is proposed that occlusions corresponding to these bubble sizes i.e. from 130 to 500 micron do not exist in spherical form. The consequence of this working hypothesis would be that the scattering at f_{1-2} is generated from bubbles resonant at f_{1-2} i.e. bubbles smaller than 130 micron. As shown in Figures 3a-c resonances at the difference frequency (f_{1-2} =188 kHz, 182 kHz and 154 kHz respectively) are clearly observed which correspond to resonant sizes from 60 to 70 microns. However this is not the case for the Figure 3d (f_{1-2} =132 kHz) which corresponds to approximately 100 microns (see Figure 2b). In conclusion these preliminary results reveal the existence of spherical voids in muddy sediments with radius smaller than 70 microns (larger gas pockets probably forming aspherical gas pockets e.g. cracks [16]). In later work these preliminary experimental data will be inverted to estimate bubble size distributions.

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REFERENCES

[1] **A. I. Best, M.D. Tuffin, J.K. Dix and J. M. Bull,** Tidal height and frequency dependance of acoustic velocity and attenuatiomn in shallow gassy marine sediments. *J. Geophys. Res*., **109,** B08101 , 2004

[2] **A. G. Judd** and **M. Hovland**, The evidence of shallow gas in marine sediments, *Continental Shelf Research*, **12**(10), pp. 1081-1095, 1992.

[3] **G. E. Claypool** and **I. R. Kaplan,** The origin and distribution of methane in marine sediments, In *Natural Gases in Marine Sediments*, Editor: I. R. Kaplan. New York Plenum, pp. 99–139, 1974.

[4] **C. Martens** and **R. A. Berner**, Methane production in the interstitial waters of sulfate-depleted marine sediments, *Science,* **185**, pp. 1167-1169, 1974.

[5] **G. B. N. Robb, A. I. Best, J. K. Dix, J. M. Bull, T. G. Leighton** and **P. R. White**, The frequency dependence of compressional wave velocity and attenuation coefficient of intertidal marine sediments, *J. Acoust. Soc. Am.*, **120**(5), pp. 2526-2537, 2006.

[6] **E. L. Hamilton**, Compressional-wave attenuation in marine sediments, *Geophysics*, **37**(4), pp. 620-646, 1972.

[7] **F. A. Bowles**, Observations on attenuation and shear-wave velocity in fine-grained marine sediments, *J. Acoust. Soc. Am.*, **101**(6), pp. 3385-3397, 1997.

[8] **J. M. Hovem**, The nonlinearity parameter of saturated marine sediments. *J. Acoust. Soc. Am*. **66**(5), pp. 1463-1467, 1979.

[9] **T. G. Leighton, A. Mantouka, P. R. White** and **Z. Klusek**, Towards field measurements of populations of methane gas bubbles in marine sediment: An inversion method required for interpreting two-frequency insonification data from sediment containing gas bubbles. *Hydroacoustics*, **11**, 203-224, 2008.

[10] **T. G. Leighton,** Theory for acoustic propagation in marine sediment containing gas bubbles which may pulsate in a non-stationary nonlinear manner, *Geophysical Research Letters*, **34**, L17607, 2007.

[11] **A. Mantouka** and **T. G. Leighton**, Theory for the dynamics of acoustically-excited gas bubbles in porous media (with specific application to marine sediment), *ISVR Tech. Rep. 324*, University of Southampton, 2008.

[12] **X. Yang** and **C. C. Church**, A model for the dynamics of gas bubbles in soft tissue, *J. Acoust. Soc. Am*., **118**(6), pp 3595-3606, 2005.

[13] **A. L. Anderson** and **L. D. Hampton**, Acoustics of gas-bearing sediments I. Background, *J. Acoust. Soc. Am*., **67**(6), pp. 1865-1889, 1980.

[14] **A. L. Anderson** and **L. D. Hampton**, Acoustics of gas-bearing sediments II.Measurements and models *J. Acoust. Soc. Am*., **67**, 1890-1903, 1980.

[15] **H. Medwin** and **C. S. Clay,** *Fundamentals of Acoustical Oceanography*, Academic Press, 1998.

[16] **A. P. Lyons, M. E. Duncan, A. L. Anderson** and **J. A. Hawkins,** Predictions of the acoustic scattering response of free-methane bubbles in muddy sediments, *J Acoust Soc Am.,* **99** (1), pp 163-171, 1996.