Preliminary mapping of void fractions and sound speeds in gassy marine sediments from subbottom profiles

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Abstract: Bubbles of gas (usually methane) in marine sediments affect the load-bearing properties of the seabed and act as a natural reservoir of "greenhouse" gas. This paper describes a simple method which can be applied to historical and future subbottom profiles to infer bubble void fractions and map the vertical and horizontal distributions of gassy sediments, and the associated sound speed perturbations, even with single-frequency insonification. It operates by identifying horizontal features in the geology and interpreting any perceived change of depth in these as a bubble-mediated change in sound speed.

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1. Introduction

The bubbles that occur at many seabed locations[1] can impact upon the structural integrity and load-bearing capabilities of the sediment[2,3] and can be indicative of a range of biological, chemical, or geophysical processes[4] (such as global methane budgets). In acoustical terms,[5] such bubbles can degrade the operation of a subbottom profiler (Fig. 1) or be inverted to estimate the bubble population. Bubble radii distributions from 10 μm to 20 mm, and void fractions as great as 9%, have been inferred from the inversion of either compressional wave data,[6–10] acoustic backscatter,[11–13] or two-frequency techniques.[14–16] While such inversions can be based on models of bubbles in water, a model incorporating geotechnical properties of the host sediment surrounding the bubbles (both before and after it is altered by the presence of bubbles) would be preferable.[17]

Table 1 shows that, in addition to the scattering studies,[11–16] there have been many investigations of sound speeds and attenuations of compressional waves in gassy sands and muds, but only one[8] of these has even attempted to estimate void fractions (VFs) remotely (sensitive to VF > 2%). This report outlines a very basic method by which subbottom profiles may be rapidly analyzed to estimate the effect of bubbles on the sound speed in the sediment, and hence map the void fractions, sensitive to VF = 0.002% or better. Furthermore, this method could in principle be applied to single-frequency data. This approach will not replace, but will instead complement, the large-scale field trials which deploy specialist equipment to monitor gas bubbles in sediment. It provides a method either to exploit archived subbottom profiles, or to survey a large area rapidly with commercial equipment from a small vessel.

This paper illustrates the method on a single historical subbottom profile. Supplementary data are not available for this trace, and it is fully recognized that lack of supplementary data on this figure means that the validity of key assumptions (any significant occurrence of severely aspherical bubbles,[18,19] or bubbles whose resonant frequency is not much less than the

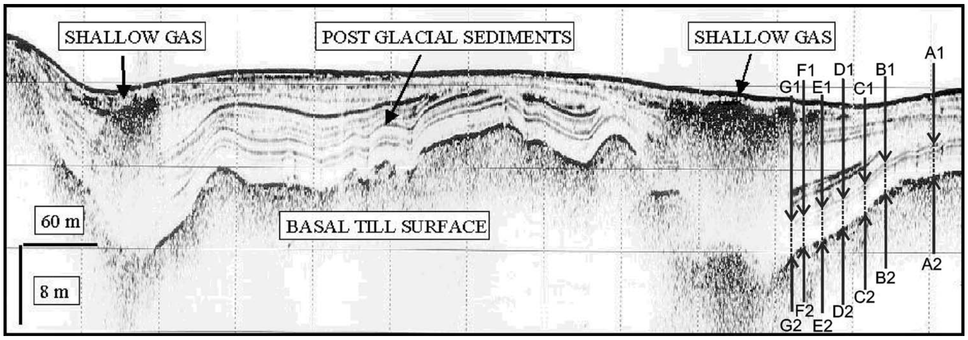

Fig. 1. A chirp subbottom profile from Strangford Lough, Northern Ireland, which displays sediment layers and gas "blanking" (where shallow gas prevents the profiler from obtaining information from beneath the gas). The three interfaces used in this paper to determine sound speed and void fraction are the seabed (upper dark line), the interface denoted by A1 to G1, and the interface denoted by A2 to G2. The chirp signal was a 2–8 kHz linear sweep of 32 ms duration, and the water depth was estimated to be 15.5 m. Reproduced from Ref. 20 and annotated by T. G. Leighton with permission of the National Oceanography Centre, Southampton (J. S. Lenham, J. K. Dix, and J. Bull).

insonifying frequency; the horizontal nature of the sediment layering) cannot be tested without revisiting the site with modern equipment: one purpose of this paper is to show what preliminary estimations can be made from historical data without resorting to such a visit.

2. Method and results

Figure 1 shows a chirp subbottom profile containing gassy sediment.[20] Bubbles cause two "blanking" zones, at which the majority of the sound is scattered (and multiply reflects), and in which no information can be determined on the sediment layering. However, before the geological layering features on either side of the gas pockets become obscured, they appear to dip to greater depths as they approach the "blanking" zones. If a given pair of interfaces in this region was to maintain a constant separation, any apparent changes in separation observed in the subbottom profile can be directly attributed to a change in sound speed in the medium between them.[33,40]

This analysis can be applied to the estimate c_{s-1}, the vertically averaged sound speed between the seabed and interface 1 in Fig. 1 (labeled A1–G1). In a similar way, it can be used to estimate c_{1-2}, the vertically averaged sound speed between interfaces 1 and 2 (labeled A2–G2). The two key assumptions, namely that upper and lower interfaces lie parallel to one another, and that no bubbles exist in the sediment at the location chosen for the calibration (at A), would ideally be justified by the observation of the two layers appearing horizontal over a more extended region than is visible in Fig. 1: no such data were available with this historical record. Recognizing this limitation, the estimated sound speeds perturbations are calculated simply from the ratio of the apparent separation to the assumed separation in Fig. 1 and are plotted in Fig. 2(a).

Retaining the principle that this is an example of using the simplest assumptions to gain a preliminary estimation from this historical data, of the many options[21] for estimating the bubble population from Fig. 2(a) this paper will use Wood's equation[22] for an effective two-fluid medium for illustrative purposes. It is understood that the dynamical response of the bubble population will be influenced by the range of bubble sizes present, and that the bubbles may indeed depart significantly from sphericity. However, assuming that the bubbles are small enough to satisfy the quasistatic conditions inherent in Wood's equation,[21,22] and that the bubbly sediment can be treated as an effective fluid medium, then the effective compressibility is therefore $(1-\beta)(\rho_s c_s^2)^{-1}+\beta(\kappa p_0)^{-1}$, where β is the void fraction of bubbles, ρ_s and c_s are the equilibrium density and sound speed of the bubble-free saturated sediment, p_0 is the static pressure at the position of the bubble, and κ is the polytropic index[17,21] of the gas within the bubbles

Table 1. Compilation of measured compressional wave properties of gassy sediments, including frequency f (kHz), experimental technique, sediment type, compressional wave velocity c_{eff} (m s^{-1}), ratio of velocity in gassy sediment to that in saturated sediment c_{eff}/c_s, attenuation coefficient α (dB m^{-1}), attenuation coefficient of equivalent saturated sediment α_s (dB m^{-1}), void fraction, and the source reference. The symbol ⋯ indicates that no available information is available and the attenuation coefficient of the equivalent sediment was predicted using Hamilton.[31] Note that some simplification and interpretation has been required to condense these data onto a single Table, and that data from sediment containing both free gas and gas hydrate have been omitted from this compilation, owing to the complex four-phase nature of these sediments.[32]

f (kHz)	Site	Sediment type	c_{eff} (m/s)	c_{eff}/c_s	α (dB/m)	α_s (dB/m)	VF (%)	Reference no.
⋯	Remote	Gravel to mud	1210–1650	0.65–0.93	⋯	⋯	⋯	33
⋯	*In situ*	Mud	110–304	0.06–0.22	⋯	⋯	<1	6
0–11	*In situ*	Mud	320–1500	0.21–1.02	<230	<1.3	<6	7
<0.4	Remote	Sand/silt	1250	0.70			<2	8
<1	Remote	Mud	250–1280	0.17–0.86	⋯	⋯	⋯	34
<1	Remote	Mud	550–1100	0.38–0.75	⋯	⋯	⋯	35
<12	Remote	⋯	800	0.55	⋯	⋯	⋯	36
<20	Remote	⋯	>1050	0.60			⋯	37
0.13–1	*In situ*	Clay	800	0.55	1.4/kHz	<0.1/kHz	0.065	9
0.2–3.2	Remote	Mud and sand	45–122	⋯	⋯	⋯	⋯	38
0.1–2	Lab	Mud/Kaolinite	114–326	0.07–0.21	⋯	⋯	0.1–0.4	39
3.5	Remote	Sand to mud	⋯	0.77			⋯	40
0.6–1.2	Remote	⋯	75–170	⋯	114	⋯	⋯	41
1–30	*In situ*	Mud	⋯	⋯	2–2433	<4	⋯	42
3–20	*In situ*	Mud	852–1526	0.56–1.03	⋯	⋯	⋯	43
3–100	Lab	Silty clay	1280	0.88	⋯	⋯	<20	44
3.5	Remote	Sand to sandy mud	1610–1660	0.89–0.92	⋯	⋯	⋯	45
5–20	*In situ*	Silty clay	1000–1430	0.70–1.00			0–2	10
7.5	*In situ*	Sand to mud	700–1200	0.47–0.81	⋯	⋯	⋯	46
10–100	Lab	Sand and soil	⋯	⋯	2500–7100	<80	⋯	47
10–1000	Lab	Mud	200–500	0.13–0.34	600–4000	<120	0.4–19.8	48
38	*In situ*	Silty clay	⋯	⋯	40–50	<5	0–2	10
40	*In situ*	Mud	⋯	⋯	13	<5	⋯	Cited by 49
40	Lab	Sand	305–1706	0.18–1.00	⋯	⋯	⋯	50
40–80	*In situ*	Mud	⋯	⋯	25–90	<10	⋯	Cited by 49
50	Lab	Glass beads	280–1750	>0.16	⋯	⋯	0.1–100	51
50	Lab	Sand	250–1700	>0.15	⋯	⋯	0.1–100	51
110	*In situ*	Soil	1220–1270	0.84–0.87	105–470	⋯	⋯	52
200	Lab	Sand	1218–2090	0.58–1.00	⋯	⋯	0–100 controlled	53 and 54
300–700	Lab	Mud	1400–1700	0.95–1.15	<700	<84	<6	7
400	Lab	Mud	1522–1523	1.00	⋯	⋯	0.1–0.4	39
400	Lab	Silty clay	1430	1.00	>500	<48	0–2	10
400	Lab	⋯	736–1372	0.50–0.94	⋯	⋯	⋯	55
400	Lab	Mud	1200–1300	0.80–0.87	⋯	⋯	⋯	56
500	Lab	Sand to mud	1900–1460	0.62–1.00	⋯	⋯	⋯	57
500–1000	Lab	Sand and silt	<1000	<0.56	⋯	⋯	⋯	58
700	Lab	Sand	1264–2515	⋯	⋯	⋯	0–100 controlled	59
1000	Lab	Sand to mud	1300	0.88	⋯	⋯	⋯	46

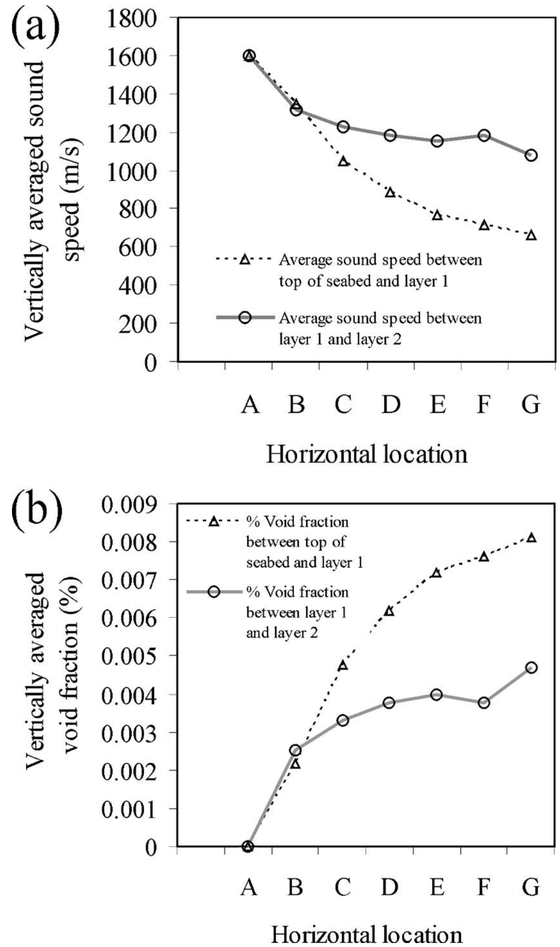

Fig. 2. (a) The vertically averaged sound speeds between the seabed and interface 1, and between interface 1 and 2; (b) the vertically averaged void fractions between the seabed and interface 1, and between interface 1 and 2.

(equal to the ratio of the specific heats of the gas, divided by the polytropic coefficient[7,10,12]), which is assumed to be 1.3 for nearly adiabatic pulsations of biogenic sedimentary gas.[9] The void fraction being small, $\beta \ll 1$, means that the bubbly sediment can be treated as an effective fluid medium of density ρ_{eff}, where $\rho_{\mathrm{eff}}^{-1} \approx \rho_{\mathrm{s}}^{-1}$, since if $\rho_{\mathrm{eff}} = \rho_{\mathrm{s}}(1+\Delta\rho/\rho_{\mathrm{s}})$, then $\rho_{\mathrm{eff}}^{-1} \approx \rho_{\mathrm{s}}^{-1}(1 - \Delta\rho/\rho_{\mathrm{s}} + \cdots) \Rightarrow \Delta\rho/\rho_{\mathrm{eff}} \approx \Delta\rho/\rho_{\mathrm{s}} - (\Delta\rho/\rho_{\mathrm{s}})^2 + \cdots$ if $\Delta\rho/\rho_{\mathrm{s}} \ll 1$. Equating the above effective compressibility with $(\rho_{\mathrm{eff}} c_{\mathrm{eff}}^2)^{-1} \approx (\rho_{\mathrm{s}} c_{\mathrm{eff}}^2)^{-1}$ (where c_{eff} is the effective sound speed of the gassy sediment, noting that dissipation is neglected in this definition[21]), implies $\beta = (c_{\mathrm{s}}^2/c_{\mathrm{eff}}^2 - 1)[\rho_{\mathrm{s}} c_{\mathrm{s}}^2/(\kappa p_0) - 1]^{-1}$. Assuming $\kappa p_0 \ll \rho_{\mathrm{s}} c_{\mathrm{s}}^2$ and $|c_{\mathrm{s}}^2/c_{\mathrm{eff}}^2 - 1| \ll 1$, this reduces to

$$\beta \approx \frac{2\kappa p_0}{c_{\mathrm{s}}^2 \rho_{\mathrm{s}}}\left(1 - \frac{c_{\mathrm{eff}}}{c_{\mathrm{s}}}\right). \tag{1}$$

A detailed form of this basic derivation may be found in Ref. 23, and more sophisticated versions may be used if the above assumptions are violated.[17,21] Application of Eq. (1) to the data in Fig. 2(a) allows estimation of the vertically averaged void fraction between the top of the seabed and layer 1 ($\beta_{\mathrm{s}-1}$), and the vertically averaged void fraction between layer 1 and layer 2 (β_{1-2}). At the time the measurements of Fig. 1 were taken, techniques for measuring the density and sound speed in the sediment were not as advanced as they are today. These values are therefore predicted for the silts and clays typical of this section of Strangford Lough through the use of empirical regressions,[24] resulting in a bubble-free sound speed of 1600 $\mathrm{m\ s^{-1}}$ and a bubble-free density of 2300 $\mathrm{kg\ m^{-3}}$. Nowadays it is commonplace to examine cores from regions of saturated sediment to determine density from gamma ray attenuation and compressional wave velocity from ultrasonic propagation at 500 kHz (which for these saturated sediments is assumed to provide a sound speed relevant to the frequencies used in this paper).[25]

The final parameter required for the calculation is the pressure p_0. This was computed for the central portion of each layer using $p_0 = p_A + \rho_w g h_w + \rho_s g h/2$, where p_A is the atmospheric pressure on the survey date (103 kPa), g is the acceleration due to gravity, ρ_w is the density of water (1000 $\mathrm{kg\ m^{-3}}$), h_w is the depth of the water (15.5 m), and h is the depth of the sediment layer below the seabed (5.1 m for layer 1, and 7.4 m for layer 2). This resulted in an average hydrostatic pressure of 312.5 kPa for layer 1 and 338.5 kPa for layer 2.

Figure 2 summarizes the sound speeds and void fractions calculated for each of the coordinates A to G. The assumptions in the sediment parameters introduce an unknown uncertainty.

3. Discussion and conclusion

This report outlines a simple scheme for assessing the sound speed perturbation induced by bubbles in the seabed, and for estimating the void fraction and extent of the bubble layers (including changes both in the horizontal and vertical). Although in the present work this technique has only been applied to two sediment layers (three interfaces), the technique can be extended to include more interfaces and even three-dimensional profiles.[26] Contrast enhancement[27] of the geological layers compared to the bubble scatterers will extend the technique to higher void fractions, closer to the center of the gas pocket.

The approach provides a quick first-order technique, but the simplicity of its use is offset by limitations. The conditions may violate key assumptions (quasi-static dynamics of noninteracting spherical bubbles), and inhomogeneities may contradict the assumed averaging. Nevertheless, the ease with which first-order environmental data can be gained at little extra effort using existing technology, and through examination of historical records of subbottom profiles, offers the possibility of making rapid progress. This is significant given

(i) quantitative sound speeds and void fractions can be estimated from subbottom profiles which were previously used qualitatively to assess the location of gassy sediments;
(ii) the method shows that the extent of the gas, as indicated by the void fractions shown in Fig. 2(b), is much greater than the extent of the shadows in Fig. 1; which one might otherwise consider to represent the location and extent of the gas pocket;
(iii) the method can be implemented without the complex equipment often required to assess gassy sediments (e.g., difference frequency sonars, CT scanners, etc.);[10,28–30]; and
(iv) the method is remote and highly sensitive (compare with Table 1).

This method is not presented as an alternative to the more sophisticated methods under development, or as competition for the innovative and large-scale field trials specifically designed to measure *in situ* bubble populations in sediments. Instead it is envisaged to be a complementary technique which would allow the rapid low-cost assessment of a gassy area using current commercial apparatus, and the new analysis of historical data. Geological expertise will be required in each case to assess the likelihood that the interfaces selected are parallel, and that the perceived dipping is solely due to sound speed perturbations[33,37,40] (though, because gassy sediments are dispersive, this can be tested remotely by taking additional profiles of the same location at higher frequencies and seeing whether the apparent separations remain constant). In the model used here, the material parameters of the sediment enter only through the sound speed and density of saturated sediment, and there is therefore no reflection of the complexity of propagation that can occur in such materials. While this simplification could be overcome through the substitution of improved models for sound speed into this scheme[17] (and while the assumption of quasi-static dynamics can be replaced using a more sophisticated inversion routine), the importance of this report lies in expressing such a simple scheme for obtaining the void fraction and extent (in the vertical and horizontal) of bubble populations in marine sediment. It can also be applied to tissue, and to domestic products and pharmaceuticals into which deliberate target layers could be placed.

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