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THE ACOUSTIC SIGNATURE OF GAS-BEARING SEDIMENTS IN TWO COASTAL INLETS OF ATLANTIC CANADA

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The effect of free gas on the reflectivity of recently deposited muds in 2 Nova Scotian inlets is modelled using in situ measurements of acoustic velocity and the calculated effect of interstitial methane bubbles on bulk density.

Velocity profiles of the gas-bearing sediments show that a relatively small (2.5%) velocity contrast between gassy muds overlying substantially less gassy muds coincides with an acoustic reflector apparent on seismic profiles from the 2 inlets.

Reflection coefficients calculated at vertical incidence show that a sub-bottom reflector twice as reflective as the sediment-water interface is controlled primarily by a density contrast between gas-bearing muds and substantially gas-free muds rather than by any large velocity contrast.

Introduction

The Atlantic coast of Nova Scotia is indented by inlets resulting from the flooding of ice-modified valleys following deglaciation (Piper & Keen 1976). Recently deposited muds in 2 such inlets, Halifax Harbour and St. Margaret's Bay (Fig 1) have been examined to explain the way in which interstitial free gas is associated with a strong sub-bottom acoustic reflector apparent on profiler records.

Echo sounder and sparker profiles of St. Margaret's Bay muds in 50 to 70 m of water show a prominent sub-bottom acoustic reflector; Keen and Piper (1976) have stated that it is caused by free gas rather than by lithological changes within the sediment, and that it is a sufficiently strong acoustic barrier to prevent penetration by relatively low-powered, high-frequency sources. Comparable reflectors have been mapped in the same distance sub-bottom at a variety of hydrostatic pressures, ie., in water depths ranging from 24 to 30 m in Halifax Harbour (N.S. Dept. Develop. 1975) down to 70 m in Mahone Bay (Barnes 1976). Reflectors similar in appearance have been reported in numerous coastal environments, such as Chesapeake Bay (Schubel 1974), the Norwegian Channel (Van Weering et al. 1973) and coastal areas of the North Sea (Rawson 1976).

As Keen and Piper (1976) have described, the reflector is restricted to fine-grained sediments in St. Margaret's Bay and varies between 1.8 and 4.0 m below the flat-lying mud floors of 2 basins. The reflector downdips sharply either at basin margins or where a sub-bottom high (till or bedrock) nearly reaches the sediment surface. The general characteristics of the reflector in Halifax Harbour are the same (Fig 2), and it is confined to regions of ponded deposition. However, the downdipping ter-

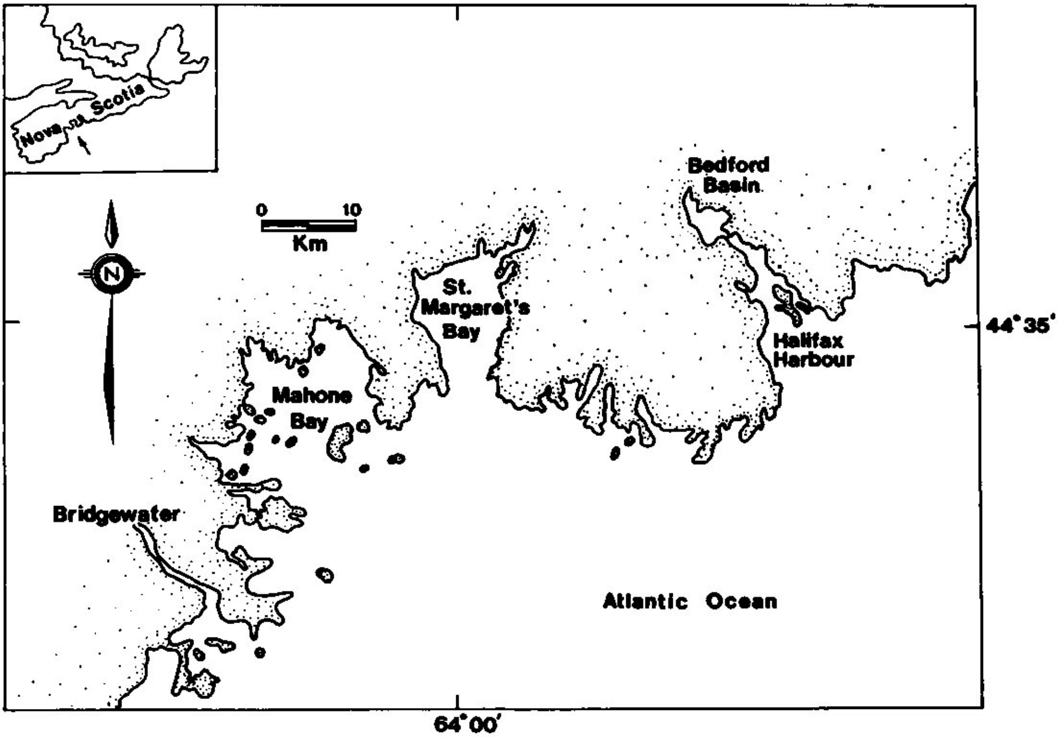

Fig 1. Location of the study areas on the Atlantic coast of Nova Scotia.

mination of the reflector in Halifax Harbour is not always associated with topography, sub-bottom or otherwise (Fig 2).

The appearance of the reflector depends on the type of acoustic source used. It shows up as an impenetrable acoustic mask on 3.5 kHz transducer systems (Fig 2a). The signature on sparker records (Fig 2b) is more akin to the "acoustically turbid zones" of Schubel (1974), although use of a sufficiently powerful source of lower frequency can penetrate the reflector (Piper & Keen 1976).

From the analysis of a 10 m piston core, Keen and Piper (1976) have shown that methane is associated with the reflector, generating large expansion voids at 1 to 2 m sub-bottom in the core when it is brought to the surface. In anoxic marine sediments, carbon dioxide is microbially reduced to methane below a horizon dominated by sulfate-reducing bacteria (Claypool & Kaplan 1974).A microbial origin for methane is probable when evidence from the St. Margaret's Bay sediments is considered; data of Keen and Piper (1976) show a downward decrease of organic carbon in cores to about one-half the surface value at the depth of the reflector (about 2 m), and the methane found in the St. Margaret's Bay sediments is not associated with its higher homologs (Rashid & Vilks, in press), indicating that the gas has not leaked from petroleum accumulations. Rashid and Vilks (in press) also measured markedly less sulfate in cores of gassy sediment compared with cores collected from gas-free environments, indicating a microbial succession leading to methane production.

We report here, from sound velocity profiles determined in situ, how interstitial methane bubbles in the fine-grained sediments of Halifax Harbour and St. Margaret's Bay act to produce a sub-bottom acoustic reflector.

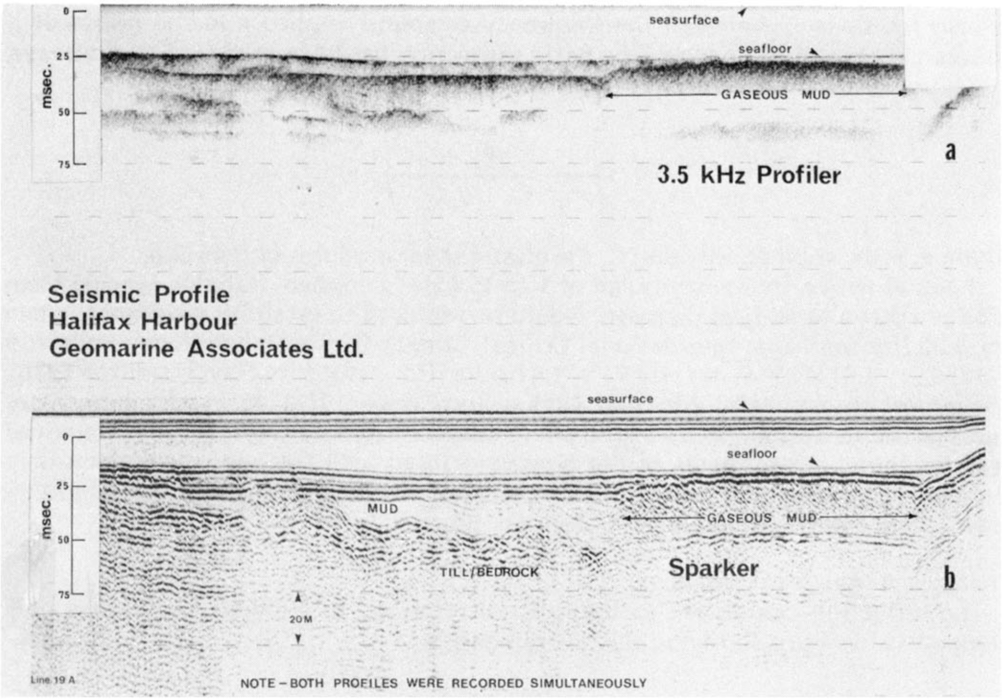

Fig 2. Simultaneous 3.5 KHz transducer (2a) and lower frequency sparker (2b) profiles showing the reflector as an acoustic mask in Halifax Harbour (courtesy of Geomarine Associates, Halifax). The two-way travel time is shown in milliseconds and the vertical scale in meters is based on the speed of sound in seawater. The sub-bottom reflectance cannot be quantitatively compared to that of the sea floor on these profiles.

Controls of Reflectivity

Two factors must be considered to describe the reflectivity of gas-bearing sediments. Most commonly examined is the redirection of sound (much of it back to a surface receiver) due to the scattering effect of resonating bubbles. In addition, the effect of interstitial free gas on sound velocity and acoustic impedance determines the reflection coefficients at interfaces between gas-bearing and gas-free sediments.

Bubble Resonance

Minnaert's (1933) equation for the resonant frequency of bubbles in water subject to an underwater sound source is:

$$fr = \frac{1}{2\pi r_o}\left(\frac{3\gamma P_o}{\varrho_w}\right)^{1/2}$$

where fr is the fundamental pulsation in Hz; r, the bubble radius;γ, the ratio of the specific heat of the gas at constant volume to the specific heat at constant pressure; P_o, the hydrostatic pressure; and ϱ_w, the water density. Explicit in the equation is the inverse relationship between the frequency of sound applied and the radius of a bubble capable of resonating. The basic expression has been modified by Andreeva (1964) to include the elastic properties of a solid so that:

$$fr = \frac{1}{2\pi r_o}\left(\frac{3\gamma P_o + 4G}{\varrho_s}\right)^{1/2}$$

where ϱ_s is the solid density and G, the elastic shear modulus of the solid.

If sound with a frequency range of 1 to 15 kHz is applied, bubbles ranging from 7583 μm down to 506 μm diameter would be required to establish resonance, when $\gamma = 1.30$ (for methane; International Critical Tables), $G = 10^6$ dynes/cm^2 (Anderson 1974) $\varrho_o = 1.01 \times 10^6$ dynes and $\varrho_s = 1.42$ g/cm^3 (for a wet silty clay; Hamilton 1976). The largest interstitial bubbles that Kepkay and Cooke (1978) observed in laboratory muds of the same grain size were 60 μm diameter. It is clear then that the interstitial bubbles found in sediments of the type associated with the acoustic reflectors in Halifax Harbour and St. Margaret's Bay will not resonate and scatter the sound incident from even high frequency transducer sources.

Changing Acoustic Impedance

The reflection coefficient as the ratio of reflected to incident amplitudes of a plane wavefront at a flat-lying elastic boundary is:

$$r = \frac{\varrho_2 v_2 - \varrho_1 v_1}{\varrho_2 v_2 + \varrho_1 v_1}$$

for the case of vertical incidence. The products of the bulk densities and sound velocities, $\varrho_i v_i$ [i = 1, 2], are the acoustic impedances above and below the boundary.

It is generally assumed in the case of gassy sediments that low sound velocity is the dominant control of their acoustic impedance. Wood's (1931) emulsion theory predicts this velocity behavior because of the effect of only small numbers of evenly dispersed bubbles on the bulk modulus of the system (Anderson 1974). However, Domenico (1976) and Kepkay and Cooke (1978) have shown in the laboratory that this is not the case in natural sediments containing less than 20% by volume of free gas because interstitial bubbles do not behave as an emulsion. Therefore, to define the reflectivity of the gas-bearing sediments in Halifax Harbour and St. Margaret's Bay, the in situ measurement of acoustic velocities was carried out and the effect of free gas on wet sediment density was determined.

Velocity Probe

Design and Operation

The probe is based on Schubel's (1974) method of monitoring the pulse driving a transmitter on one leg and the acoustic signal picked up by a receiver on the other. In our design, the delay time between transmission and reception of compressional waves was recorded employing the delay facility of an oscilloscope connected to the single-cylinder, piezo-electric elements of hydrophones free to slide in the legs. The probe and time delay system is described in more detail by Kepkay (1977). The received signal was filtered passing 3 to 100 kHz, so that the acoustic wavelengths used were all greater than 1 cm in seawater and the frequency range encompassed those employed in high resolution profiler systems.

The acoustic velocity profiles of the gas-bearing sediments in Halifax Harbour and St. Margaret's Bay were determined along with the velocity profile of a gas-free mud in Bedford Basin. The travel time of sound in seawater was determined at each site before the probe was allowed to free-fall into the sediment. The salinity and temperature of the seawater at each site were obtained (Jordan 1972; El Din et al. 1970) and used to calculate the sound velocity from Wilson's (1960) equation. Thus, with the acoustic velocity and travel time in seawater, the correct travel path between transmitter and receiver could be calculated at each site. This distance was then used rather than the separation of the probe legs to compute acoustic velocities from travel times measured in the sediments. Probe penetration was recorded to within 5 cm by mud adherence to scales on the legs and delay times were recorded at a series of sub-bottom depths by reeling in or letting out the hydrophones together.

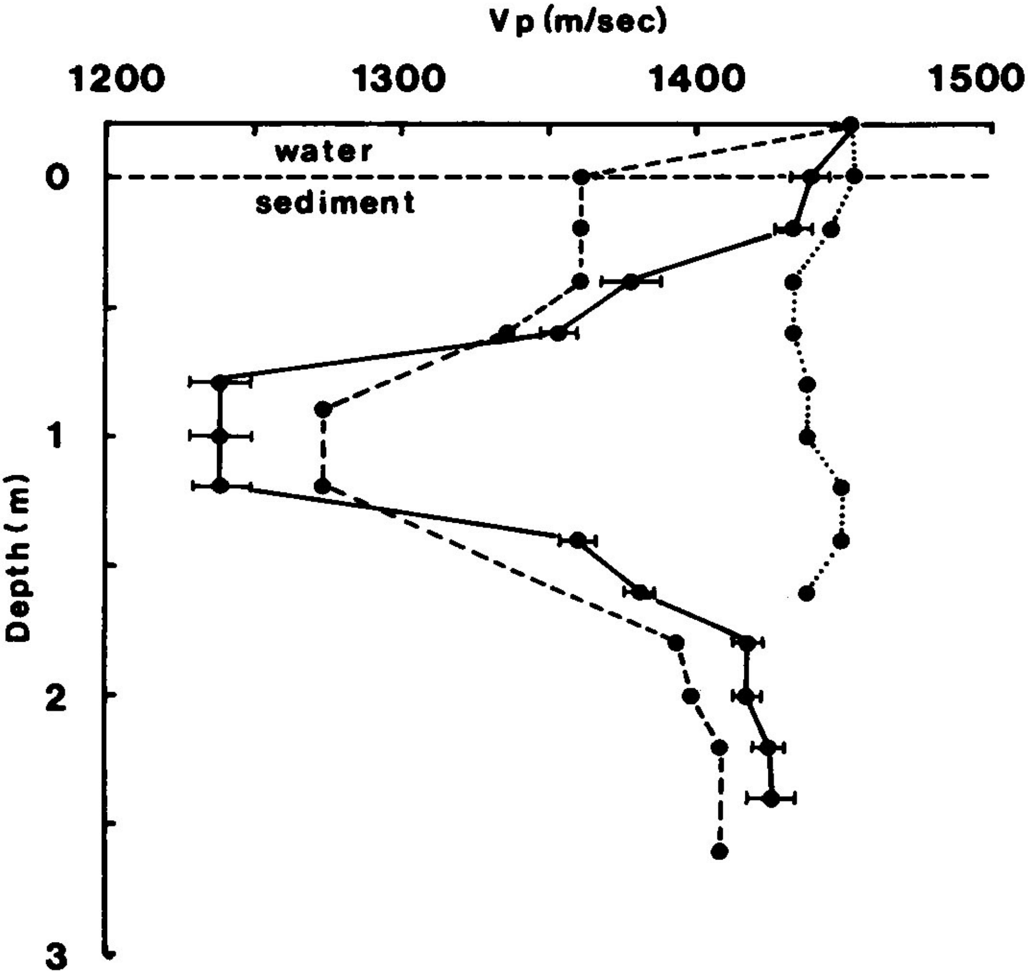

Fig. 3 Velocity(V_p) profiles through gas horizons in Halifax Harbour (•—•) and St. Margaret's Bay (•–•) muds. Profiles at a gas-free control site in Bedford Basin (•...•) are shown for comparison, and the velocity of sound in seawater is shown as a reference. Mean sediment velocities were calculated from 5 profiles taken at the same site in Halifax Harbour, and the error bars delineate 2 times the standard deviation.

Discussion of Results

Figure 3 shows compressional velocity profiles from sites in Halifax Harbour and St. Margaret's Bay where the reflector was recorded at 1.85 m sub-bottom on profiler records, and from the control area in Bedford Basin. The general vertical pattern of velocities measured in the 2 gas-bearing sediments is the same for reflectors at the same depth sub-bottom and significantly different from the sequences measured at the control site.

The acoustic reflector at an apparent sub-bottom depth of 1.85 m on profiler records of the gas-bearing sediments (corrected to 1.73 m using the measured sediment velocities) is coincident with a downward transition to a higher acoustic velocity. This relationship, which is also implicit in Schubel's (1974) measurements of signal loss in the gassy sediments of Chesapeake Bay, must form the basis for any model of the reflector in both areas.

Bulk Density Determinations

Wet sediment densities were calculated from the weight fractions of silty clay and water in diver-collected cores from Halifax Harbour so that decreasing water content with increasing burial was taken into account.

The weight fractions of pore water and dry sediment were converted to volume fractions using the density of Halifax Harbour bottom water (1.03 g/cm^3) and that of silty clay (2.70 g/cm^3) from Hamilton's (1976) synthesis of world marine sediment data. The bulk densities of gas-free sediment were then calculated by dividing total weight by total volume fractions. The estimated gas volumes associated with specific velocities in the Halifax Harbour profile were obtained from the laboratory data of Kepkay and Cooke (1978) and converted to weight fractions using the density of methane at 0°C and 2 m sub-bottom in Halifax Harbour (0.02 g/cm^3, assuming ideal gas behavior). The weight and volume fractions of gas were then incorporated in the calculation of the bulk densities of gassy sediment, assuming that gas replaces water.

Models of Gas-Zone Reflectivity

Calculation of Reflection Coefficients

To determine reflection coefficients from equation 3, interfaces must be defined between distinct layers of different acoustic impedance. Therefore, stepped profiles (Fig 4) were drawn through the velocity and bulk density data from Halifax Harbour, so that six imaginary interfaces were defined between the sediment surface and 2 m sub-bottom.

Kepkay and Cooke (1978) have shown in the laboratory that a significant volume of gas can accumulate with no apparent velocity decrease. This requires the derivation of at least 2 distinct models of acoustic impedance (models A and B in Fig 4) in addition to a model assuming no gas (model C). The 2 models differ only in the upper 0.2 m which can have a bulk density equivalent of 3.2% gas by volume (model A) or 13.8% gas by volume (model B).

Discussion of Reflectivity Models

As Figure 4 shows, model B (high gas content in the upper 0.2 m) satisfies 2 qualitative observations from transducer and sparker records. First, the most reflective interface (with a calculated reflection coefficient of 0.10) is 1.8 m sub-bottom. Second, low reflectivity (with a calculated reflection coefficient of 0.05) is evident at the sediment-water interface. Both models A and B, using gassy sediment den-

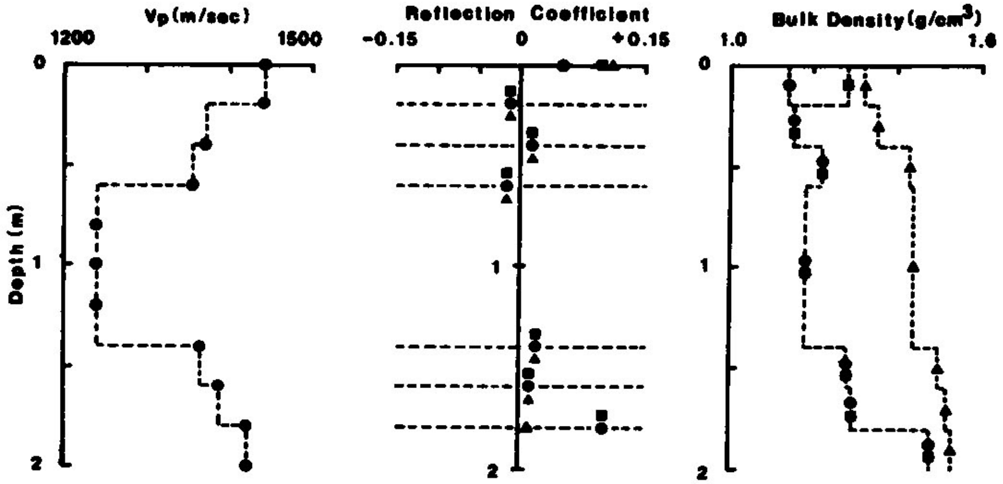

Fig 4. Reflection coefficients calculated at 6 sub-bottom interfaces generated by a step profile of acoustic velocity through Halifax Harbour data and 3 bulk density profiles. Models A (■) and B (●) use gassy sediment densities and only differ in the free gas content of the upper 0.2 m of sediment. The densities of Model C (▲) are calculated assuming no free gas, so that only velocity contrasts are involved in the control of reflectivity.

sities, show that it is possible to develop a reflective interface at 1.8 m sub-bottom between a less dense zone of gas-rich sediment overlying a denser, almost gas free sediment. Model C, without free gas, shows high reflectivity (0.10) at the sediment-water interface and low reflectivity (0.02) at the 1.8 m interface. This emphasizes the importance of the gas-control of bulk density in producing a reflector at this depth, and shows that an acoustic velocity contrast alone is not sufficient to produce the reflector recorded.

The reason for a relatively low bulk density yet no velocity reduction in the upper 0.2 m may be that bubble populations are unevenly distributed, as described by Kepkay and Cooke (1978). More even distributions may exist below, unable to migrate through undisturbed sediment (Kepkay & Cooke, unpubl. data) and it is not difficult to imagine bioturbation or the disturbance of sediment by currents contributing to an uneven bubble distribution in the top 0.2 m.

The conclusion that a downward decrease in gas concentration controls sub-bottom reflectivity is in apparent conflict with Rashid and Vilks' (in press) data, which show an increasing methane content with increasing depth in a 9 m piston core from the St. Margaret's Bay muds. However, the absence of dissolved gas data from sub-bottom horizons equivalent to where velocity increases to a relatively high value at 1.8 m could mean that this conflict is indeed apparent. Their data allow the existence of a low-gas zone over a sub-bottom depth interval of 1.8 to 2.4 m that, in turn, may be underlain by other gas bodies. Schubel (1974) has already suggested that gas-bearing sediments in Chesapeake Bay with similar acoustic signatures could be vertically interlayered with virtually gas-free zones less than 1 m thick.

Although the reflectivity models show that a reflector at 1.8 m can be twice as reflective as the sediment-water interface (model B), the absolute value of the reflection coefficient is low (i.e., the maximum possible reflected amplitude is 10% of the incident). However, these values are within the ranges measured for marine sediments by Akal (1974), and agree with the qualitative impression of reflectance conveyed by the seismic profiles in Figure 2.

Although our modelling of reflectivity at vertical incidence is overly simplistic, it demonstrates that acoustic velocity contrasts need not be the major control of reflectivity at an interface between gas-bearing and gas-free sediments. More complex models that do not assume vertical incidence may be required, and it must be stressed that the density control of reflectivity in gassy muds described in this work cannot be applied to all gas-bearing sediments. At present, the factors controlling the implied free gas distributions are being examined, and it is clear that future work in these highly accessible nearshore areas should include the examination of the physical controls of bubble populations in situ for a correct understanding of the acoustics of gas-bearing sediments.

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