

Gas Bubble Growth in Muddy Sediments

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LONG-TERM GOALS

Our long term goal is a quantitative, mechanistic and predictive understanding of the dynamics of bubbles and bubble populations in marine sediments. We believe this information can be used to improve and test acoustic backscatter models for sediments.

OBJECTIVES

The immediate objective is a working model for the growth of a single, isolated bubble in a marine sediment, validated with bubble growth data obtained in laboratory studies and with in situ data.

APPROACH

We have a strategy of coordinated laboratory and modelling research to achieve our objective. The laboratory work (directed by Bruce Johnson and assisted by Bruce Gardiner and Regine Maass) aims to determine the size that bubbles can attain in sediments, internal variables like pressure, dynamic parameters like apparent viscosity and compressibility at bubble scales. This work will determine the most appropriate model for growth (i.e. non-Newtonian viscous vs. plastic (Bingham) vs. elastic vs. visco-elastic). The modelling research (Bernard Boudreau and Bruce Gardiner), guided by the laboratory results, will develop the appropriate model(s). After this model(s) is identified (and there may be more than one), the model(s) will be applied to natural situations to obtain rates of growth.

WORK COMPLETED

Developing an appropriate model for bubbly sediments requires an understanding of the magnitude and range of variability of physical and rheological properties of natural sediments and how these properties influence bubble growth and transport. In the laboratory we have worked to develop methods to measure sediment properties and to study bubble dynamics. Results of these studies will guide model development, and in turn, output from these models will be used to steer further experimental design. A description of some of the methods and results follows below.

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On the modelling front, we have a working model of a sediment as a Newtonian/Power-Law fluid, surrounding a growing bubble; some results are discussed below. We have also initiated the development of an elastic model, though that remains quite primitive at this time, as we don't wish to allow the modelling to get far ahead of the laboratory work, so that effort is not misdirected.

RESULTS

Sediment properties: To study the rheological and physical properties that influence bubble growth and transport in sediments, we have injected gas through a fine capillary (0.5 mm diameter) into samples of natural sediment (taken from 1 meter depth; Cow Bay, N.S.) - see Fig. 1. To avoid problems with sediment and interstitial water entering the capillary, the tip of the capillary has been fitted with a disc of microporous Teflon. During bubble injection, pressure within the capillary is monitored using a pressure sensor of high accuracy and micro-bar precision (Fig. 2). In each experiment, gas is injected in small incremental volumes at a preset time interval. Between experiments these intervals are varied in order to study the time dependence of the rheological behavior of the sediment samples. During each experiment, the size of the bubble being formed is determined in two ways: first, from knowing the gas pressure and how much gas has been injected, and second, from the pressure change with each increment of gas added. This second method is necessary for longer experiments, i.e., hours to days, where diffusion of gas into or out of the bubble makes the first method unreliable.

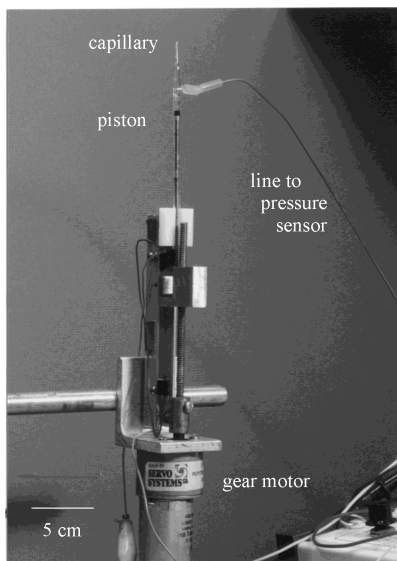


Fig. 1 Gas Injection Apparatus.

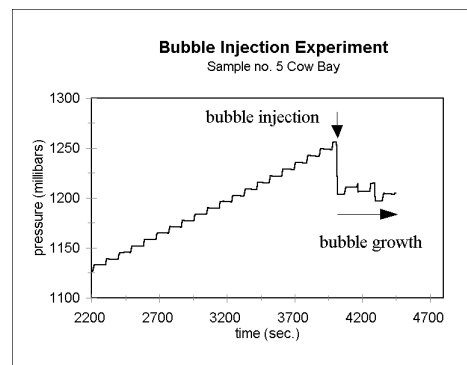


Fig. 2. Pressure vs time for bubble injection in a sample of natural sediment from Cow Bay, Nova Scotia.

Typical results from the injection experiments show that pressure in the capillary increases until a threshold, T_1 , is reached, at which time gas begins to form a cavity in the sediment. Beyond this threshold, gas pressure rapidly falls until it reaches a lower limit. With further gas injection into the bubble, the pressure cycles between this lower limit and another threshold that is always below pressure, T_1 . Our initial interpretation is that the injection threshold, T_1 , represents the point at which Laplace pressure for the capillary is exceeded, and thus provides information on surface tension. The cycle of pressures during bubble growth is then thought to be due to rheological properties of the sediment. We are now developing conceptual and mathematical models based on these results.

Bubble Shape: In order to model results of bubble injection in our laboratory studies and bubble growth and transport in natural sediments, we have studied bubble injection in various mediums that allow observation of bubble growth and rise. These mediums include gelatin, and particle - interstitial fluid pairs that have matching refractive indexes.

Bubble injection in gelatin shows a pressure - volume behavior similar to that observed for sediment, i.e., a pressure threshold for injection to begin, followed by cycling of pressure between upper and lower limits as the bubble grows. The shapes of bubbles that are formed in gelatin vary from spherical in dilute gelatin to disc shaped (with principal axis oriented vertically) in stiff gelatin. These results are especially interesting in that bubbles ranging from spherical to "coin-shaped" with vertical principal axes were described for natural sediment samples from Eckernfjorde Bay.

Bubble injection in systems of particle - fluid pairs with matching refractive index again shows the initial threshold as the bubble is being injected, and then the cycling of pressure as the bubble grows. Two types of behavior have been observed. When the particles are coarse (sand-like) bubble growth occurs as the gas cavity deforms to pass through pores in the particle bed. The pressure rises as the local radius of curvature of the bubble decreases to fit through the pores (Laplace pressure) and then the pressure decreases as the bubble flows to fill interstitial spaces between particles. In contrast, gas injection into fine particles produces near-spherical bubbles that rise as through a single phase.

To determine the shapes of bubbles that form in beds of sand and in our samples of natural sediments, we have employed two types of experiments. In one type of experiment, sand is mixed with water that is supersaturated with gas. The bubbly mixture is rapidly frozen in liquid nitrogen (about 2 minutes) and then sectioned using a band saw, and/ or ablated using an abrasive disc. Results show that the bubble cavities are typically near-spherical in shape.

While this freezing technique appears to work well for sand, it does not work for muddier sediments such as our Cow Bay samples. For these samples we have injected a polymer that has been ballasted with small iron particles to match the density contrast of bubbles in these sediments, and thus, provide a gravitational force (down rather than up) that is comparable to that for bubbles. Of course, unlike bubble injection, which is done through the bottom of samples, the polymer is injected into the sediment from the top. Once the polymer has been injected and has set, the sediment is washed away, and the morphology of the inclusion determined. When this experiment is done with our samples of natural sediment, the shape of the inclusion has typically been spherical or quasi-spherical.

Results from our experiments indicate that bubble shape can vary from spherical, which is most often observed, to disc-like or even sinuous, depending on the nature of the sediments. These results along with measurements of sediment physical and rheological properties from our injection experiments are now being used to develop realistic models for bubble growth and transport in natural sediments.

Modelling Results: The radius, R , of a growing bubble in a Newtonian/Power-Law sediment is governed by a mechanical equation coupled to a mass-transfer constraint. The mechanical equation has the form:

$$R\ddot{R} + \frac{3(\dot{R})^2}{2} + 4\mu_a (2\sqrt{3})^{n-1} |\dot{R}/R|^{n-1} (\dot{R}/R) = \frac{1}{\rho_f} \left\{ P_B - P_A - \frac{2\sigma}{R} \right\} \quad (1)$$

where μ_a is an apparent viscosity, n is the power ($n=1$ for Newtonian), ρ_f is the density of the bulk sediment, P_B is the internal pressure in the bubble, P_A is the ambient pressure and s is the surface tension of the bubble. With Henry's law, P_B can be related to the dissolved concentration of the gas, C_o , in the porewater in contact with the bubble, i.e. $C_o = K_g P_B$. The coupled mass-transport constraint states that the bubble growth (volume change with time) must be fed by gas diffusion,

$$\frac{d}{dt}(\rho_g R^3) = 3R^2 D \left. \frac{\partial C}{\partial r} \right|_{r=R} \quad (2)$$

where ρ_g is the density of the gas and D is the effective molecular diffusion coefficient in the porewater

The gas-bubble literature considers the solution to these two equations, assuming the gas is simply extracted from a surrounding fluid of infinite extent; there results from that model the famed square-root of time growth rate, i.e. $R \sim \sqrt{t}$. This case is not relevant to sediments; they have a source, S , of gas via methanogenesis at every point around the bubble. We have resolved the equation for a fluid with an internal source, S , and found that

$$\left. \frac{\partial C}{\partial r} \right|_{r=R} = \frac{SR}{3D} + \frac{1}{R} \left[C_1 - C_o - \frac{SR^2}{6D} \right] \quad (3)$$

where C_1 is the gas concentration an arbitrary far distance, R_1 , from the bubble ($R_1 \gg R$). From (3) it is fairly easy to show that $R \sim e^{at}$ ($a = S/\rho_g$), i.e. exponential growth, which is a far faster than has been suggested previously. We expect this finding will not be changed if an elastic model proves to be appropriate. In addition we now possess a full numerical solution to these equations when P_B is provided by injecting gas into the sediment, as is done in the laboratory experiments. Early indications (Fig. 2) are that sediments initially act like a Bingham plastic, i.e. yield/flow only when a certain critical normal stress is achieved, which can be reproduced by modifying the Newtonian model or approximated with a Power-Law fluid model.

IMPACT/APPLICATIONS

Bubbles seriously compromise acoustic sensing of sediments, e.g. locating naval mines. Gas ebullition of methane is a major release mechanism to the atmosphere for this greenhouse gas. Thus, understanding bubble formation (and latter movement) constitutes an important practical and scientific problem. Our findings provide information that could help remove/filter bubble-produced acoustic signals and place limits of the flux of methane to the atmosphere.

RELATED PROJECTS

We are not formally cooperating with any particular ONR funded project, but we hope to integrate our study with work being done in the Bubble-Acoustics DRI.