Gas Bubble Growth in Muddy Sediments

Bruce D.Johnson
Department of Oceanography
Dalhousie University
Halifax, Nova Scotia B3H 4J1, Canada
phone: (902) 494-2089 fax: (902) 494-3877 e-mail: bjohnson@is.dal.ca

Bernard P. Boudreau
School of Ocean and Earth Sciences
University of Southampton
European Way, Southampton SO14 3ZH, UK
phone: (011)+44-2380-596-544 fax: (011)+44-2380-593-052 e-mail: bpb@soc.soton.ac.uk

Award Number: N00014-99-1-0063

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 and better understand the ebullitive flux of methane, an important "greenhouse gas", to the atmosphere.

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, and the dynamic response of sediments to bubble growth. The modelling research (Bernard Boudreau and Bruce Gardiner), guided by the laboratory results, is developing appropriate model(s) for observed bubble growth.

WORK COMPLETED

During the second year, significant advances have been made in theory and experimental observations.

RESULTS

A. Theory/Modelling. With regard to theory, we now have a plausible theory for the overall control on the rate of bubble growth. Specifically, observation of bubbles in freshwater estuarine and coastal marine sediments indicates that bubbles below 10 cm depth grow on seasonal time scales (primarily

Report Documentation Page			*Form Approved* *OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **SEP 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**
4. TITLE AND SUBTITLE **Gas Bubble Growth in Muddy Sediments**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Oceanography,Dalhousie University,,Halifax, Nova Scotia B3H 4J1, Canada, , ,**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

May-October). We have developed a diffusion-reaction model that describes the dynamics of methane formation, its diffusion through porewaters, its incorporation into a bubble, and the consequent growth of the bubble. The model produces an explicit equation for the radius of a growing bubble, R(t), with time using mean parameter values and under the assumption that the growth is ultimately controlled by diffusion of the gas from the sources:

$$R(t) = \left[\frac{ND}{2c_g}\left(\frac{SR_1^2}{3D} + (c_1-c_0) \right) t + R_0^2 \right]^{1/2} \qquad (1)$$

where N is the porosity, D is the tortuosity-corrected diffusivity, c_g is the concentration of gas in the bubble, S is the local rate of methanogenesis, R_1 is the separation distance between bubbles ($R_1 \gg R$), c_1 is the ambient concentration of CH_4, c_o is the porewater methane concentration at R, t is time, and R_o is the initial radius of the bubble, if not zero. The effects of the diagenetic source S and the level of super-saturation (c_1-c_o), thus, appear as separate contributing terms, and this formula can then be applied even in those cases where apparently $c_1 = c_o$. The latter point constitutes a significant new contribution to the theory of bubble growth.

We applied our model to three sediments where bubbles have been previously studied, i.e. Cape Lookout Bight (USA), White Oak River (USA) and Eckernförde Bay (Germany), see figure 1. In all three cases, using the site-specific time-averaged parameter values, the model predicts seasonal growth rates, consistent with the observations. Furthermore, the source term dominates the rate of growth at the first of these two sites, while diffusion from the ambient supersaturation dominates at the German location. Real bubbles may follow a more complicated growth history than predicted by the above equation because of the mechanical properties of sediments (see below); nevertheless, the overall growth times should be concordant with ultimate diffusion control from the diagenetic methane source.

The model was expanded to account for the effects of "rectified diffusion", the pumping of gas into a bubble by pressure oscillations, e.g. from waves and tides. This effect appears to be negligible due to the low frequency of these types of oscillations.

The theoretical work in year three will center on including the mechanical behaviour of sediments, which affects the shape of the growth history curve, as in figure 1.

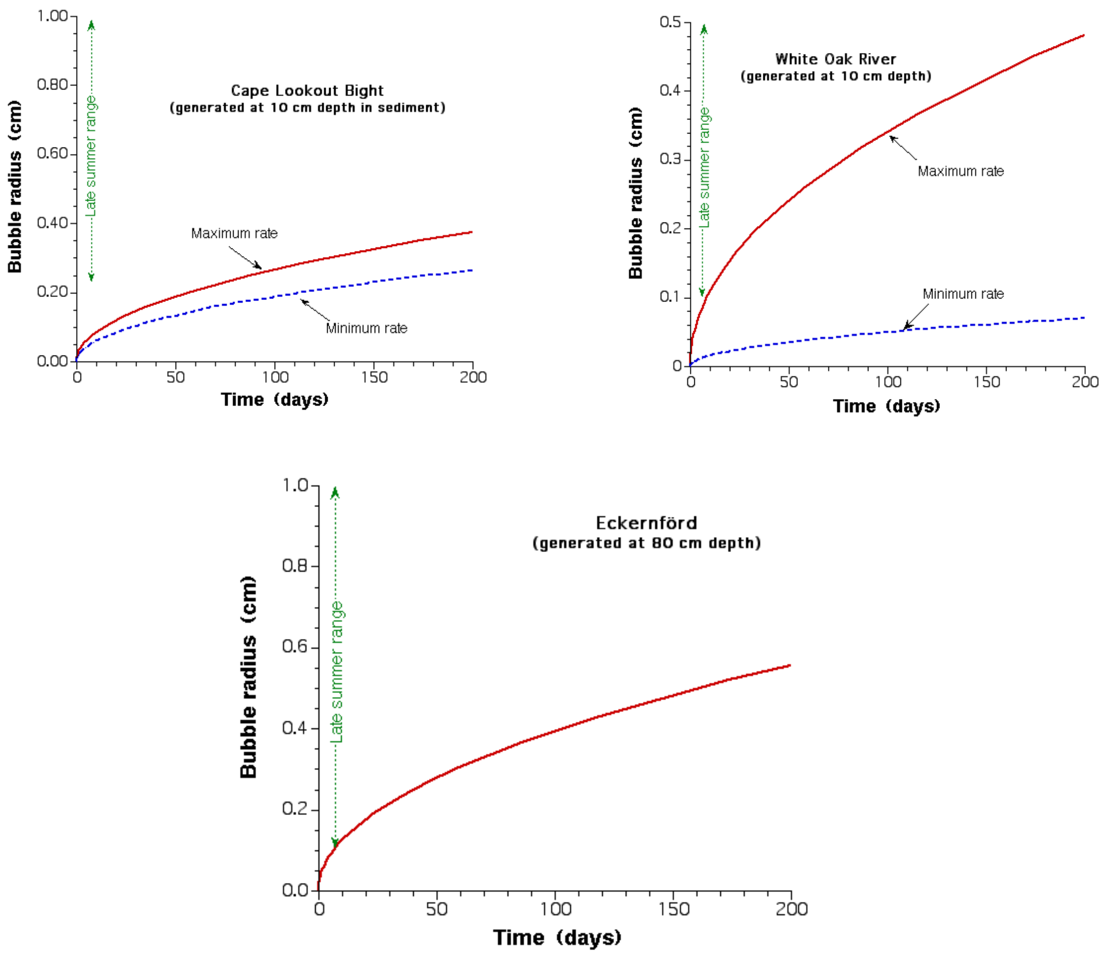

Figure 1: Growth histories of bubbles in sediments from Cape Lookout Bight, NC, USA (top left), White Oak River, NC, USA (top right), and Eckernförd, Germany (bottom). Observed sizes of bubble at the end of the summer/fall growth period at each site is also indicated. The theory, eq (1) above, provides a reasonable explanation for the observed bubble sizes, except perhaps the largest sizes; however, the larger bubbles are probably the result of coalescence of smaller bubbles or intense local methanegenesis not fully accounted for by the mean value of S used here.

B. Experimental Work. In order to study the nature of bubble growth in sediments, we have injected bubbles through a fine glass capillary into sediment samples, and have followed stress and strain during bubble growth through monitoring bubble internal pressure. Shape information has been obtained through x-ray images and from performing the experiments in surrogate materials such as gelatin. X-ray images of sediment samples in which gas has been injected show that bubbles are not spherical in shape. Instead the horizontal cross-section of the gas inclusions formed at the capillary tip are in the shape of a crack. This result is consistent with other observations (e.g., results of x-ray tomography, Eckernförde Bay, Germany) in which many of the bubbles in natural sediments were found to be coin or disk-shaped with the long axis oriented vertically. Gas injected into gelatin, results in formation of disk shaped bubbles at higher gelatin concentrations (2X) (figure 2) and a shape approaching spherical at low concentrations (1/2X).

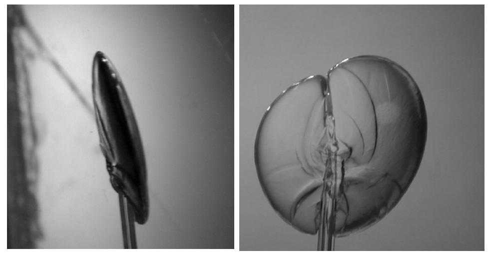

Figure 2: Disk-shaped (2 cm high) bubble formed at the tip of a capillary in 2X gelatin (left: side view; right: front view)

Gas injection into sediment samples shows two types of stress-strain behavior: pressure rise, to the point of bubble injection, followed by bubble growth as pressure cycles through regular rises and falls in a sawtooth pattern (figure 3); pressure rise to the point of bubble injection followed by a smooth, gradual decline as the bubble grows. These appear to be two end members, as combinations of these two types of behavior are common. Bubble growth in the surrogate (gelatin) samples shows the same types of stress-strain behavior, with that as in figure 3 observed for the 2X concentrations and the smooth response in the less concentrated samples.

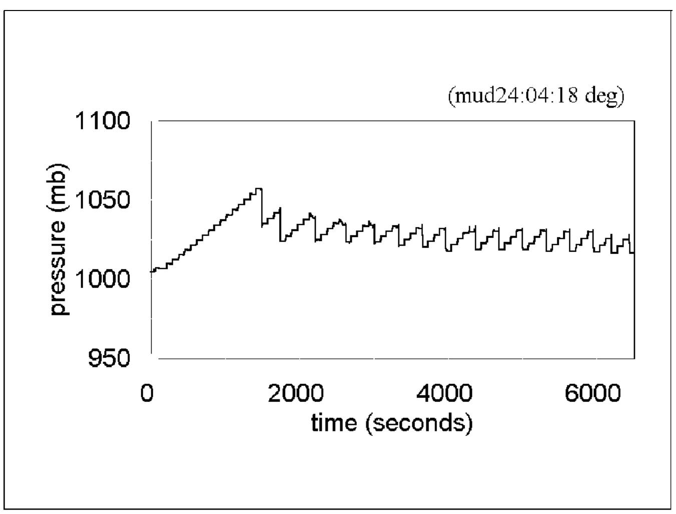

Figure 3: Pressure record for injection of gas through a fine capillary into a sediment sample from Cow Bay, N.S. at 18 EC

The results shown in figure 3 can be understood in terms of linear elastic fracture mechanics (LEFM). From LEFM, (Sneddon, 1946; Irwin, 1962; Green and Sneddon, 1950) we have derived an equation that relates critical pressures, P_c for bubble growth (the peaks in figure 3), to bubble volume at fracture, V_c , and properties of the sediment or surrogate medium. This relationship is

$$P_c = [K_{1c}^{6/5}\, B^{4/5}\, (1/12)^{1/6}] / (E^{1/5}\, V_c^{\ 1/5}) \qquad (2)$$

in which K_{1c} is critical stress intensity factor and E is Young's Modulus. K_{1c} is a material property and the determinant of bubble growth behavior. According to equation 1, plotting log P_c against log V_c should give a straight line with a slope of -1/5 and an intercept of log ($1.65\ K_{1c}^{6/5} / E^{1/5}$). From this intercept, K_{1c} can be determined and used to model bubble growth. Note that E must also be known, however, as it only appears to the 1/5 power, bulk values can be used with little error. Figure 4 shows the log-log plot of the critical pressures at fracture, P_c, (the peaks in the pressure record of figure 3) against bubble volume at fracture, V_c. Note that the slope is nearly -1/5. Bubble volume during gas injection is determined in two ways: first, if PV is conserved, bubble volume can be inferred knowing the pressure and the dead volume of the system; second, the gas injection is made in well defined discrete volume increments, and thus, each dP/dV and the dead volume can be used to determine the instantaneous bubble volume. The first method is not sensitive to changes in the total number of moles of gas, but the second makes no assumptions about the number of moles in the system and consequently, processes such as mass transfer and gas leaks do not introduce error.

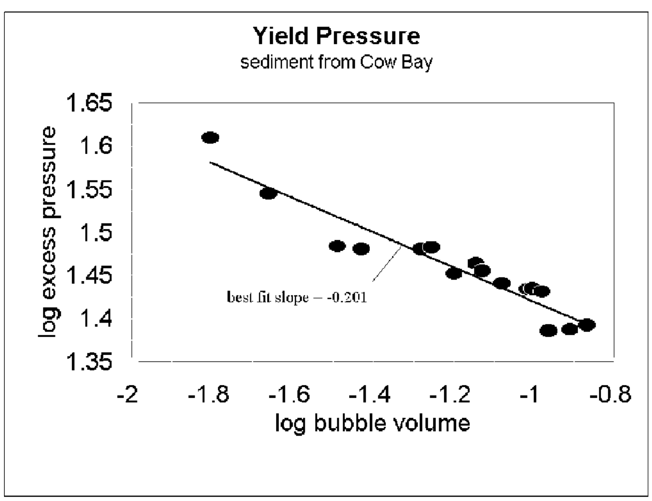

Figure 4: Plot of log P_c against log V_c for Cow Bay sediment sample: No. 24:04:18 showing a slope of approximately -1/5

Also from LEFM, the troughs in the pressure record of figure 3 can be understood in terms of crack arrest. The pressure rises to P_c, and then falls below this critical pressure because of the kinetic energy contribution to crack growth.

Having solved the problem of growth of a spherical bubble by diffusion from a distributed methane source, we have turned to solving the problem of growth of a non-spherical bubble. In particular, the Laplace equation is solved for the case of a distributed source in the oblate spheroidal coordinate system. This model is appropriate for treating bubble growth through fracture as has been observed in the laboratory experiments, and our goal now is to determine if the model can reproduce injection results such as those in figure 3.

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 in the future.

REFERENCES:

Abegg, F., A. Anderson, L. Buzi, A.P. Lyons and T.H. Orsi 1994. Free methane concentration and bubble characteristics in Eckernförd Bay, Germany in: Forschungsanstalt der Bundeswehr für Wasserschall- und Geophysik (FWG); T.F. Wever, Editor., 84-89.

Boudreau, B.P., B.S. Gardiner and B.D. Johnson. Rate of Growth of isolated bubbles in sediments with a distributed source of methane; Limnol. Oceanogr., in press.

Green, A.E. and I.N. Sneddon 1950. The stress distribution in the neighborhood of a flat elliptical crack in an elastic solid. Proc. Cambridge Philosophical Soc., 46, 159-164.

Irwin, G.R. 1962. The crack extension force for part-through crack in a plate. Trans. ASME. J. Appl. Mech., 651-654.

Sneddon, I.N. 1946. The distribution of stress in the neighbourhood of a crack in an elastic solid. Proc. Roy. Soc. London A, 187, 229-260.