

The Mechanics of Bubble Growth and Rise in 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 that this information can be used to improve and test acoustic backscatter models for sediments and to better understand the ebullitive flux of methane, an important “greenhouse gas”, to the atmosphere.

OBJECTIVES

The overall objective of our work is to understand bubble growth and rise in natural marine sediments. In the first phase of our study (to mid-2003) we demonstrated that bubbles grow and rise in sediments by the mechanism of fracture. The second (current) phase has aimed to develop methods to measure the mechanical parameters that control the fracture of soft sediment; these parameters, i.e., Young’s modulus, E , the critical stress intensity factor, K_{Ic} , Poisson’s ratio, ν , etc., are not routine measurements and geo-scientists have not developed means for their in situ measurement. These parameters are needed to solve our evolving model of bubble growth.

APPROACH

1) *Mechanical Properties*. In Linear Elastic Fracture Mechanics (LEFM), the geotechnical properties that fully determine fracture strength and the size and shape of resulting cracks are the critical stress intensity factor, K_{Ic} , Young’s modulus, E , and the Poisson ratio, ν . In laboratory studies we have determined the magnitudes of K_{Ic} and E for some samples collected at our study site in Cole Harbor, Nova Scotia, and have reported these in Johnson et al. (2002). Unfortunately, our laboratory methods for determining K_{Ic} and E do not provide sufficient detail to understand the variability of these properties on desired length scales. In addition, we are concerned about the effect of sediment sampling on the physical properties that mediate bubble growth and rise. Consequently we have instituted a field program that is focused on measuring the relevant physical properties *in situ*. To do this we have developed a sediment instrument package for use in the near shore and are fitting this

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package with probes for measuring fracture strength (the critical stress intensity factor, K1C), temperature, porosity (through measuring conductivity), Young's modulus, and methane partial pressure. Where possible we are ground-truthing the field measurements with laboratory measurements on samples collected from our field sites. This ground-truthing is especially important for demonstrating the accuracy of new probe designs such as our in situ K1C and methane probes. This work is being directed by Bruce Johnson, with help from our two new PhD students, Mark Barry and Chris Algar.

2) *Bubble growth*. Because we were not able to view (visually) bubble formation in sediments during gas injection, we have been unable to confirm that LEFM is the appropriate model for bubble growth. Consequently we have formed a collaboration with researchers at NRL that allows us to use their high-resolution CT scanner. This has meant that in order to inject gas into sediments for CT scanner imaging we needed to build an automatic injector that fits the NRL CT scanner. This injector provides a highly controlled gas injection rate and at the same time measures the pressure in the bubble with micro-bar precision. Given this injector, we will take CT scans of bubbles at various stages of growth in samples of muddy sediment. These samples will be chosen to represent a broad range of properties that mediate bubble growth (E , ν , K1C). From these CT scan images we will measure bubble aspect ratio and bubble volume, and then, from the aspect ratio, the pressure/ bubble volume record and the measured physical properties of the sediment, we can determine if LEFM applies. The CT work is being directed by Bernard Boudreau, with the help of PhD students Mark Barry and Chris Algar, and the collaboration of Allen Reed and Yoko Furukawa at NRL.

WORK COMPLETED

Ground-truthing of field measurements showed that the K1C probe works well in sediments with low sand content, but with higher sand content the measurements can be as much as an order of magnitude too high. Consequently, we have re-engineered the K1C probe to provide accurate measurements in a wider range of sediment types, e.g., ranging from muddy sediments to sediment with a high sand content. We have also developed a novel methane probe. Both probes are now being tested and will be incorporated into our sediment instrument package for use in the field.

We have completed a second series of CT scan measurements and are interpreting these images in terms of model predictions.

RESULTS

1) *Mechanical Properties*. Laboratory measurements with the K1C probe showed that results for muddy sediments are consistent with K1C values determined from bubble growth. However, anomalously high results were obtained in sandy sediments. Both theory and CAT-scan images (Boudreau et al. 2005) indicate that bubbles that grow in sand tend to be spherical and do not grow by fracture. Yet measurements of K1C with the probe in sandy sediments were as much as an order of magnitude higher than measurements in muds. We have re-engineered the probe to operate in an extensional mode rather than in compression, and have obtained results for K1C that are more consistent with bubble growth behavior. For example, measurements with the extensional probe in muddy sediments have given results for K1C that range from about 2×10^{-4} to 4.5×10^{-4} MN m^{-3/2} – results that compare favorably with 2.3×10^{-4} MN m^{-3/2} to 5.5×10^{-4} MN m^{-3/2} reported for sediments from the same site and from interpretation of Eckernford Bay bubble images (Johnson et

al., 2002). Measurements in sand give results that are about an order of magnitude lower, i.e., $2.3 \times 10^{-5} \text{ MN m}^{-3/2}$.

2) *Bubble Growth in a CT.* CT images of bubbles grown in the NRL CT scanner have provided us with a broader base of information on bubble growth mechanics which in turn has led to a better understanding of the meaning of the record of bubble internal pressure. These images have also provided evidence for how growing bubbles respond when they encounter pre-existing fractures and solid objects such as shell fragments (figure 1).

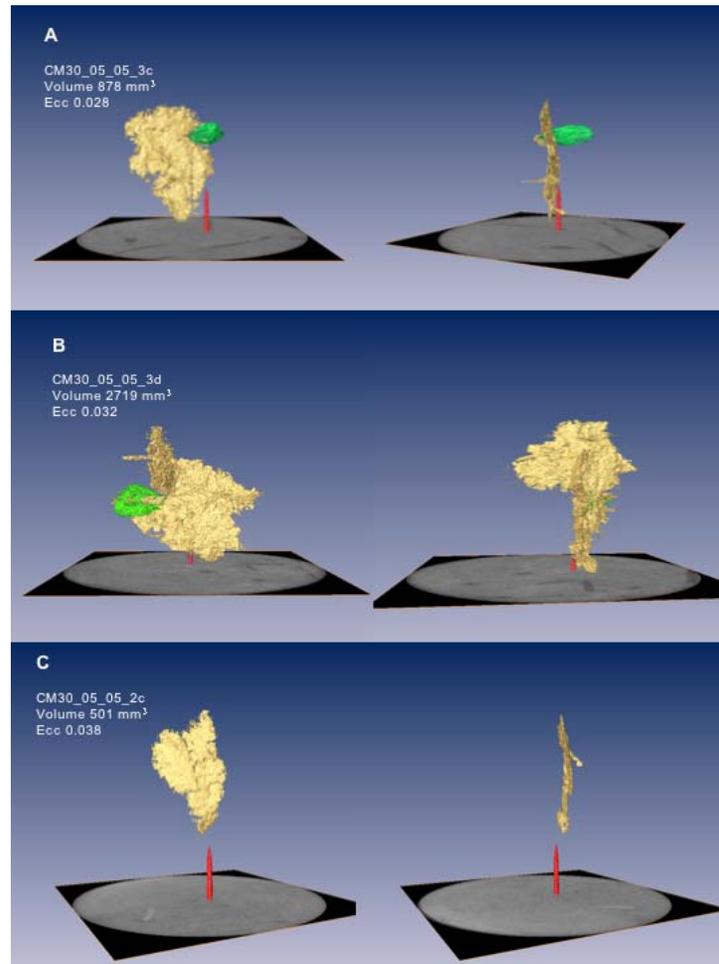


Figure 1: 3D reconstructions of CT-scans of gas bubbles injected into sediments. Gold color represents gas, Red is the capillary tip and green represents shells or higher density regions. Bubble volumes and aspect ratios are a: 878 mm³ and 0.028, respectively, b: 2,719 mm³ and 0.032 and c: 501 mm³ and 0.038. [Three sets of images are shown (a-c). Each set shows a front view and a side view. In all three sets the front view shows an irregular shaped gas inclusion and a side view in which the bubble is much thinner. Images a and b show bubbles that have grown around shell fragments and c shows a bubble that has grown without any solid obstruction.]

Interpretation of CT scan results has shown that bubble aspect ratios follow LEFM predictions. In LEFM theory bubble aspect ratio is determined by the sediment physical properties K_{1c} , E , and ν . Measurement of these properties for a sediment sample for which CT scans were used to image a growing bubble indicates that the bubble aspect ratios follow predictions of LEFM (figure 2).

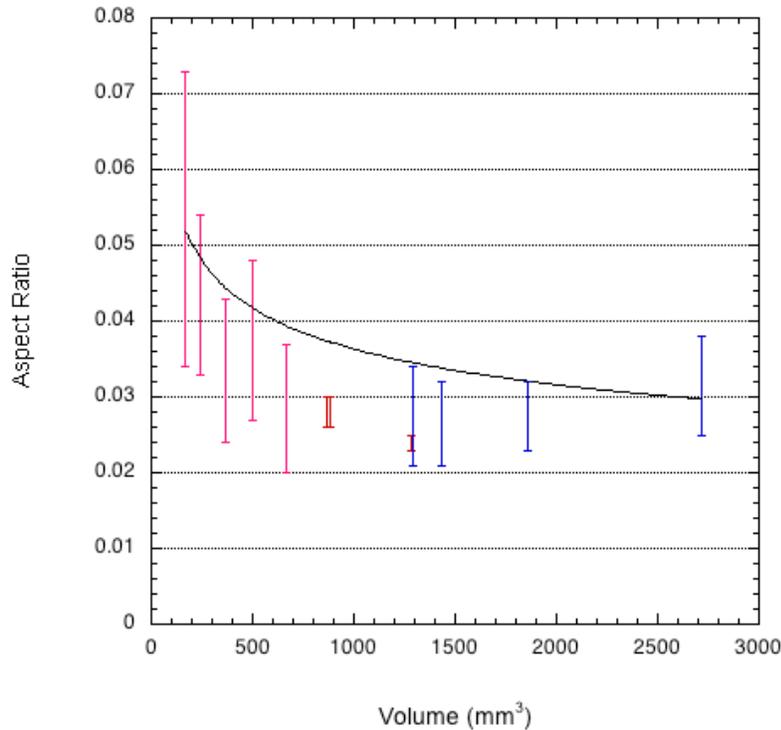


Figure 2: CT scan measurements of bubble aspect ratios during bubble growth compared to predictions based on LEFM. Red and blue lines represent error bars for measurements on two different bubbles. Solid line is predicted aspect ratio from LEFM. [The results of CT scan measurements are well described by the curve of predicted aspect ratios.]

IMPACT/APPLICATIONS

Our results may prove to me highly significant to acoustic seafloor imaging and estimates of seafloor stability.

RELATED PROJECTS

In collaboration with Peter Jumars (Univ. Maine), and his PhD student Kelley Dorgan, we have been applying the results of our bubble-mechanics work to the problem of the burrowing of infauna. This related project is groundbreaking in that it has identified a new and efficient mode of movement for burrowing organisms; one that takes far less energy that has been supposed in the past.

PUBLICATIONS

We have 1 published paper in this reporting period:

Boudreau B.P.L Algar C., Johnson B.D., Croudace, I., Reed, A., Furukawa, Y., Kelley M.D., Jumars, P.A., Grader, A.S., Gardiner, B.S. (2005) Bubble growth and rise in soft sediments. *Geology* 33(6) 517-520.