Bubble growth and rise in soft sediments

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ABSTRACT

The mechanics of uncemented soft sediments during bubble growth are not widely understood and no rheological model has found wide acceptance. We offer definitive evidence on the mode of bubble formation in the form of X-ray computed tomographic images and comparison with theory. Natural and injected bubbles in muddy cohesive sediments are shown to be highly eccentric oblate spheroids (disks) that grow either by fracturing the sediment or by reopening preexisting fractures. In contrast, bubbles in soft sandy sediment tend to be spherical, suggesting that sand acts fluidly or plastically in response to growth stresses. We also present bubble-rise results from gelatin, a mechanically similar but transparent medium, that suggest that initial rise is also accomplished by fracture. Given that muddy sediments are elastic and yield by fracture, it becomes much easier to explain physically related phenomena such as seafloor pockmark formation, animal burrowing, and gas buildup during methane hydrate melting.

Keywords: bubbles, mud, fracture, methane.

INTRODUCTION

Gas bubbles form in soft marine sediment as a result of in situ gas production from anoxic organic matter decomposition, i.e., methanogenesis. Under certain conditions, these bubbles can rise in such sediments as a result of their buoyancy. Gas formed catagenetically can also enter and rise through soft sediment as bubbles.

Bubble growth and movement in soft marine sediments are crucial steps in gas hydrate dynamics, including both the formation and the ''melting'' of these deposits (Bratton, 1999; Haq, 1999; Buffett, 2000). Gas bubbles interfere with acoustic seafloor imaging (Lyons et al., 1996; Anderson et al., 1998), compromise bed stability (Sills and Wheeler, 1992), and, through their rise, supply methane to seep communities (Paull et al., 1984) and to the atmosphere (Dando and Hovland, 1992; Casper et al., 2000; Smith et al., 2000; Judd, 2003), where it acts as a strong greenhouse gas. Yet without the knowledge of the mechanics of the formation and the rise of bubbles, quantitative prediction of the effects and influences of gas bubbles becomes exceedingly difficult.

The perceived pliability of soft muddy sediments to human touch and the observed fluidization, e.g., gravity flows, during some natural disturbances have suggested that such sediments can act fluidly or plastically in response to stress. Past mechanical models of bubbles in these sediments have visualized the bubbles as essentially spherical (e.g., Wheeler, 1988; Sills et al., 1991), with the implication, intentional or not, that the surrounding medium reacts fluidly or plastically to their growth and rise. Scientists and engineers have developed an impressive understanding of bubble growth in fluids, and a vast literature covers the topic (e.g., Clift et al., 1978; Lohse, 2003). However, we show here that muddy sediment does not respond mechanically either as a fluid or as a plastic solid during bubble growth,

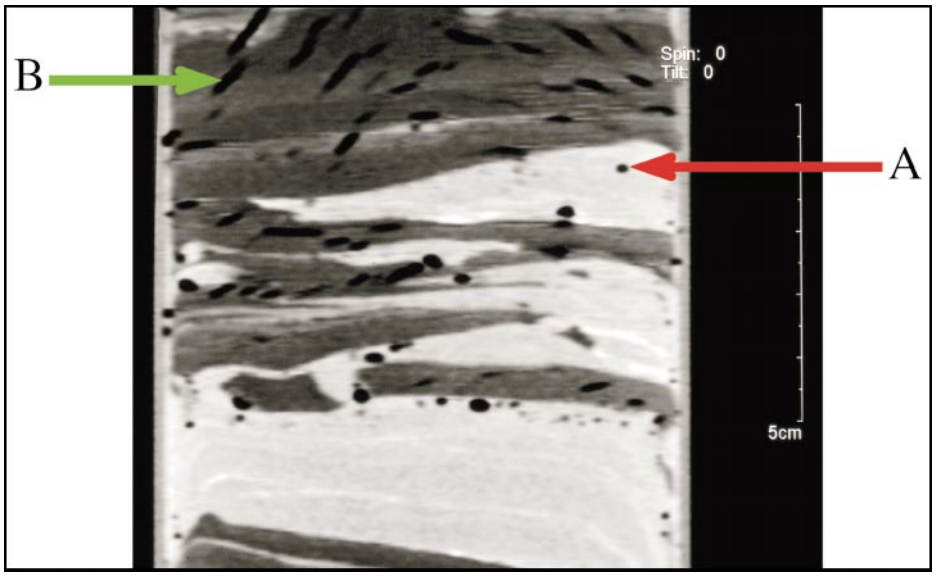

Figure 1. X-ray computed tomographic (CT) image of sediment with interbanded clay and carbonate sand layers and containing bubbles in both types of sediments (black circles and ellipses). Bubbles in sands are spherical away from mud contacts (red arrow A). Bubbles in muds are oblate spheroids (green arrow B). Dichotomy in geometry reflects differing mechanical responses of sands (plastic or fluid-like) and muds (fracturing elastic solid). Core in image is ~8 cm across and sample came from depth <1 m in this core. Some or all of these bubbles may have grown postcollection because of warming of core and resulting increased methanogenesis; this fact does not change any arguments with respect to growth mechanism.

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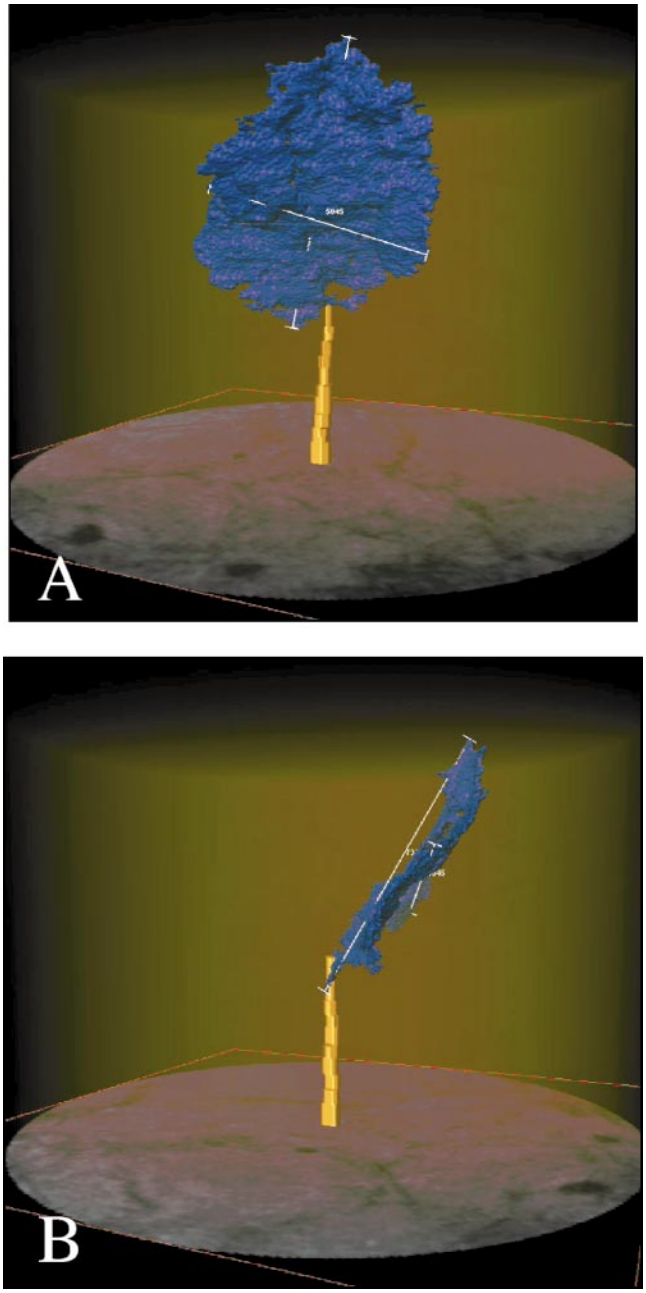

Figure 2. Three-dimensional rendition of bubble injected into mud from Cow Bay, Cole Harbour, Nova Scotia, Canada, obtained from high-resolution X-ray computed tomography. Blue false color is used to represent gas and yellow is injection capillary; sediment has been made transparent. (Copper-yellow background is ghosting of acrylic core liner.) Bubble is ~20 mm across (A) and 0.7 mm thick (B), with resulting volume of 0.3 cm³. Sample is from 25–35 cm depth interval of 10-cm-diameter core. (White lines across bubble are created during image manipulation to estimate its dimensions; white numerals are distances in internal units and not of immediate importance.)

but rather as a fracturing elastic solid. Bubbles are known to form in other solids, but surprisingly, the mechanics of the formation of bubbles in solids (e.g., bread) are not widely understood, and the literature on this topic is scant in comparison.

Johnson et al. (2002) and Gardiner et al. (2003) studied the response of fine-grained aqueous sediment to the injection of a small bubble by monitoring the internal pressure of that bubble. The resulting saw-toothed pressure record could not be explained by flow of the sediment (see Figs. 3–9 in Johnson et al., 2002), but these records are consistent with fracture of the medium. Even those records with apparently flat pressure responses are now understood to be reopening of preexisting fractures, and not fluidization.

The difficulty in documenting this novel growth process in sediments has been in problems of visualization of an optically opaque medium, leaving us to rely on pressure records. Earlier X-ray photographs and X-ray computed tomographic (CT) investigations (e.g., Lyons et al., 1996; Anderson et al., 1998) suggested that sedimentary bubbles were often nonspherical; however, they did not offer a growth mechanism, although they did observe that the eccentricity of these bubbles increased with their volume. We present new high-resolution CT images that are diagnostic of the governing mechanics.

CT IMAGING AND RESULTS

Figure 1 displays a scan of a laminated subtidal sediment core from Bridgwater Bay, North Somerset, UK. The image was obtained with a medium-resolution (medical) Siemens Somatom Plus4 Volume Zoom multislice spiral scanner. The section is ~8 cm across and displays interfingered layers of carbonate-rich fine sand (light gray) and mud (dark gray layers). Additional black bodies in both sand and mud are gas bubbles that have grown as a result of natural internal methane production, i.e., methanogenesis. Note that the bubbles in the sand, and far from the mud contacts, are round, i.e., spherical in three dimensions. The bubbles in sand near mud contacts remain rounded on the area exposed to the sand and otherwise follow the mud contact, indicating that the mud cannot be displaced (fluidly) by such bubbles. Conversely, the bubbles in the mud are elliptic in section, i.e., oblate spheroids in three dimensions. The mechanical responses of mud and sand to bubble-growth stresses are fundamentally different. We argue that the mud acts as an elastic solid that fractures. (The alternative explanation of strongly anisotropic viscosity of a surrounding fluid is not supported by constancy in the shape of the oblate bubbles regardless of their orientation and the extreme eccentricity of the bubbles.) The sand appears to be displaced spherically and thus to behave like a fluid or an elastic-plastic solid in response to the stress created by the bubble. Both behaviors may be contrasted with gas cluster bubbles that are restricted to existing pore space in a porous medium that is either cemented or rigidly constrained (e.g., Li and Yortsos, 1995).

Because these medical-based CT images are, unfortunately, not of sufficient resolution, and because we do not know the mechanical properties of the Bridgwater Bay sediment, we cannot use theory to verify that the bubbles in Figure 1 are consistent with fracture. A second set of images, Figure 2, was obtained with a high-resolution (to $\leq$10 μm) HD-500 CT scanner at the Naval Research Laboratory, Stennis Space Center. The images are of a bubble injected into a soft muddy sediment, with known mechanical parameters, from Cole Harbour, Nova Scotia, Canada (see Johnson et al., 2002). The injection was accomplished with a portable version of a previously described instrument (see Johnson et al., 2002). The narrow injection capillary is visible as the apparently segmented gold rod. This injected bubble is 22 mm at its widest and 17 mm at its narrowest in plan view (Fig. 2A), and 0.7 mm thick at its center (Fig. 2B). The volume from summing gas voxels is ~0.3 cm^3. This shape is well approximated by an oblate spheroid, and the observed deviations are expected, given the heterogeneity of the surrounding medium. A few holes and gaps exist in the bubble image and represent areas that contain no gas because the sediment has

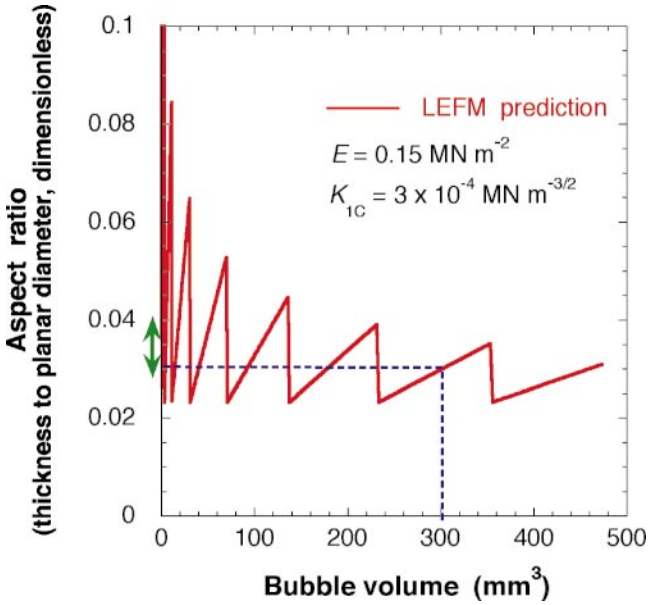

Figure 3. Linear elastic fracture mechanics (LEFM) predicted aspect ratio, i.e., thickness to planar diameter (red solid line) of oblate spheroidal bubble as function of its volume in sediment with Young's modulus, *E*, and critical stress intensity factor, K_{1C}, typical of Cole Harbour, Nova Scotia, Canada. Precipitous decreases in aspect ratio are result of fracture events, which cause bubble to increase in planar radius but decrease in thickness. Linear increases between fractures are due to purely elastic increase in bubble thickness, with constant planar radius, as internal pressure increases with gas accumulation. Gas must build up in bubble to critical pressure (see equation 1) before fracture event can occur. Blue (dashed) line indicates predicted aspect ratio for 0.3 cm³ bubble. Green double arrow (adjacent to y-axis) indicates range of aspect ratios for bubble in Figure 2; agreement is excellent.

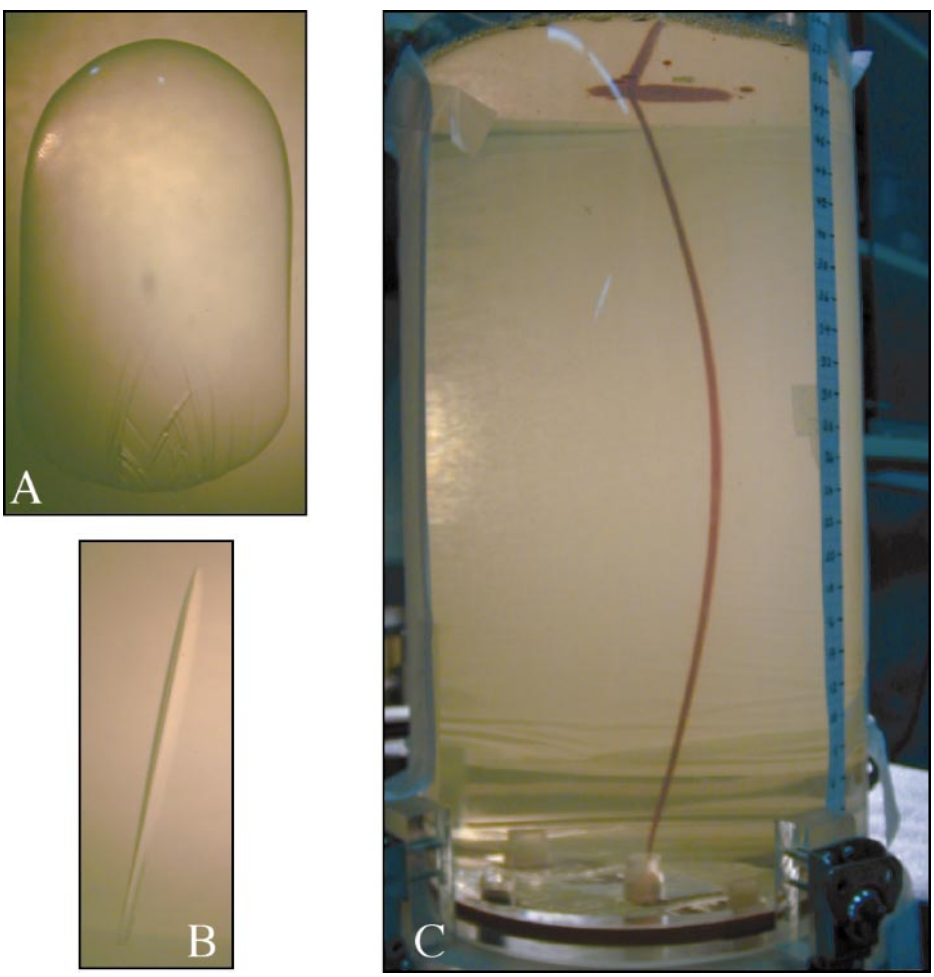

Figure 4. A and B: Plan and cross section of bubble rising in double-strength gelatin. Bubble is 6.62 cm in length, 3.8 cm wide, and ~0.1 cm thick. C: Rise path of this bubble as visualized by pouring red ink at surface where bubble escaped from gelatin. Injection port is at base of this trail. Column is 35 cm high, and bubble took ~3 min to rise from base to surface.

not been displaced by the fracture as a result of local mechanical heterogeneities in the sediment medium.

DISCUSSION

The aspect ratio of the bubble in Figure 2 is between 1:24 and 1:32. Johnson et al. (2002) proposed that bubble growth in soft sediments can be described by linear elastic fracture mechanics (LEFM). The LEFM-based model makes three specific predictions about bubbles in solids: (1) they must be oblate spheroids, (2) the bubble's shape and size are functions only of the mechanical properties of the medium, i.e., Young's modulus, *E*, which measures the elasticity of the medium, and the critical stress intensity factor, K_{1C}, which measures the strength of the material at failure, and (3) bubble aspect ratio (thickness to planar diameter) must increase with its volume. This latter prediction is illustrated by the solid red (saw-toothed) line in Figure 3, for a sediment with measured values for E and K_{1C} of 0.15 MN m^{-2} and 3×10^{-4} MN m$^{-3/2}$, respectively. The fracture events, i.e., the falls in Figure 3, occur when the internal pressure of the bubble equals or exceeds a critical value over ambient, P_c:

$$P_c = \left(\frac{\pi^4 K_{1C}^6}{24EV}\right)^{1/5}, \qquad (1)$$

where V is the bubble volume.

The LEFM-based model in Figure 3 predicts that a bubble with a volume of 0.3 cm^3 should have an aspect ratio of 1:32: the observed ratio is between 1:24 and 1:32. Given the suspected uncertainties in the parameter values of the model, predicted and observed aspect ratios are in remarkable agreement. Thus, our images not only indisputably document the finding that bubbles in mud are oblate spheroids, but also that their shapes are quantitatively predicted by an LEFM model.

We also believe that fracture of the soft surrounding sediment plays a central role in initial bubble rise through sediments, i.e., the creation of a bubble tube or path, a suggestion made independently by van Kessel and van Kestern (2002). Because of the present difficulty in visualizing rising bubbles in sediments, even with a CT scanner, we base this belief on the behavior of bubbles in gelatin. Gelatin is another soft solid in which bubbles grow by fracture (Johnson et al., 2002). In addition, when large enough to possess critical buoyancy, bubbles in gelatin will rise by propagating a fracture. The typical shape and path of a rising bubble in gelatin are displayed in Figure 4. Although gelatin is more elastic than muddy sediment because of its smaller Young's modulus (Menand and Tait, 2001; Johnson et al., 2002), i.e., $E = 0.0015 - 0.01$

MN m^{-2}, its critical intensity factor, $K_{1C} = 0.5 - 2.2 \times 10^{-4}$ MN $m^{-3/2}$, is close to that of our Cole Harbour sediment. Thus, the results with gelatin are applicable to muddy sediments. We expect that natural bubbles that reach critical size can initiate rise by fracture. Once formed, a bubble-rise path offers a lowered-resistance conduit for the movement of other bubbles because, we believe, these long cracks anneal slowly.

Given this mechanism, it is possible to create models that predict rates of bubble rise as a result of methanogenesis and hydrate melting, and even to model the unstable gas accumulations that result in seafloor pockmark formation (e.g., Kelley et al., 1994). Specifically, rise by fracture offers possibilities for trapping gas and sudden violent release. We have measured the fracture strength, K_{1c}, of sediments (e.g., Johnson et al., 2002) and found that this parameter need not simply decrease toward the sediment-water interface. Layers with markedly larger K_{1c}, i.e., greater strength, can overlay layers with much lower values. There can be planes where K_{1c} is unusually low compared with adjacent sediment, perhaps because of large preexisting lateral fractures or erosional surfaces. Rising bubbles then encounter depth zones where (sub) lateral fracturing is far easier than vertical crack propagation. We argue that under these conditions, the bubbles can change direction and move along the low K_{1c} surface; however, because gravity is no longer driving the rise, the vertical fracturing will cease, and the bubble stall at this surface. Other bubbles will either encounter the same barrier or follow the rise path of the first bubble and accumulate along the low K_{1c} surface. The result is an accumulation of gas, which can build to a new critical pressure that is capable of catastrophically fracturing the overlying sediment; a seafloor pockmark is then formed.

Our findings have wider implications. Many past studies of faunal locomotion in sediments have assumed that these organisms ''eat'' their way through sediment, which is an energy-intensive mode of locomotion. However, we believe that many animals are more likely to move by propagating a fracture in a muddy sediment (Dorgan et al., 2005). This mode of locomotion means that these organisms can expend far less energy to move through sediments. These results have the potential to alter significantly our understanding of life in sediments.

CONCLUSIONS

We have presented CT images of bubbles in natural sediments and shown that bubbles are highly eccentric oblate spheroids (disks) in soft muddy sediments. Bubbles in sandy sediments are essentially spherical away from mud contacts. These different morphologies strongly imply that muddy sediment responds as a fracturing elastic solid to bubble growth, whereas sands appear to act plastically or as a fluid in response to bubble-growth stresses. We have compared the thickness-to-length ratio of bubbles injected into a mud with the ratio predicted by a linear elastic fracture model and have found extremely good agreement between observation and theory. Our results strongly support an elastic-fracture model of bubble dynamics in soft muddy sediments.

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