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Quarterly Progress Report
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Mechanisms Leading to Co-Existence of Gas and Hydrate in Ocean Sediments

Submitted by:
The University of Texas at Austin
1 University Station C0300
Austin, TX 78712-0228

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Prepared by

Steven L. Bryant
Department of Petroleum and Geosystems Engineering
The University of Texas at Austin
1 University Station C0300
Austin, TX 78712-0228
Phone: (512) 471 3250
Email: steven_bryant@mail.utexas.edu

Ruben Juanes
Department of Civil and Environmental Engineering
Massachusetts Institute of Technology
77 Massachusetts Avenue, Room 48-319
Cambridge, MA 02139
Phone: (617)253-7191
Email: juanes@mit.edu

Prepared for
U.S. Department of Energy - NETL
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26508

Summary

Work during this quarter focused on developing the methods for modeling stress-strain behavior of unconsolidated sediments and for modeling the movement of the gas/water in such sediments (Task 4 and 5). Good progress is being made on both fronts, as discussed below.

The sediments are modeled by dense random packings of spheres, and during this quarter we re-evaluated the applicability of these models to hydrate-bearing sediments. Sediments containing sand, such as the Mackenzie Delta, correspond closely to the models, exhibiting similar porosities (30% to 40%). As sand is replaced by silt, sediment porosity increases, and sediments dominated by clay may exhibit porosities greater than 70%. The physical, grain-scale basis for the range of porosity variation and for the preservation of porosity after burial is not well understood and constitutes a research question in its own right. For the purposes of this project we will continue to focus on "sand-dominated" model sediments. These permit the simplest assessment of the pore-pressure induced coupling between fracture initiation and drainage of gas into sediment. Meanwhile we will continue to evaluate physically reasonable methods for building models of silt- and clay-dominated sediments.

The development and application of Level Set Methods (LSM) for locating gas/water interfaces in granular materials is a key part of this project. An invited presentation[*] by research scientist Dr. Maša Prodanović was well received and led to an invitation to present at the fall meeting of the American Geophysical Union. We are also preparing a broader abstract on the mechanics/displacement coupling to submit to the gas hydrate session at the AGU fall meeting. A paper on the application of LSM to gas/water displacements in fractures has been accepted for presentation at the Society of Petroleum Engineers Annual Technical Conference and Exhibition (SPE ATCE) in Nov. 2007. This project's use of invasion percolation and level set methods to simulate gas/water displacement is also novel, and our proposal to present our findings at SPE ATCE has been accepted.

Background: Project Motivation

The mass of carbon held in sediments below the seafloor is a significant part of the Earth's carbon cycle. The amount currently in place may be very large; enough to implicate methane hydrates in global warming events in the geological past and to raise the prospect of a vast energy resource. However, estimates of this mass and the rate at which it can accumulate in or dissipate from sediments vary widely. One reason is the difficulty in ascertaining the form and spatial distribution of methane within the hydrate stability zone (HSZ). The goal of this project is to understand quantitatively the manner in which methane is transported within the HSZ. The research will seek validation of the

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[*] M. Prodanović and S. Bryant, "A level set method method for determining critical curvatures for drainage and imbibition", Workshop on Modeling, Analysis and Simulation of Multiscale Nonlinear Systems, Oregon State University, Corvallis, OR, June 25-29, 2007

following hypothesis: the coupling between geomechanics, the dynamics of gas/water interfaces, and phase behavior of the gas/brine/hydrate system make co-existence of free gas and hydrate inevitable in the HSZ.

If borne out, our hypothesis would provide a mechanistic basis for several observations of co-existing gas and hydrate in the HSZ. The models have implications for interpretation of seismic and borehole log data and thus for estimates of carbon held in the HSZ. It would explain observations of lateral and vertical variability in hydrate saturation, e.g. preferential occurrence in coarse grained material above and below a fine grained layer. The model would be a step toward explaining active and passive hydrate accumulations with a single set of mechanisms.

Activities in This Reporting Period

Task 3.0 – Creation of Sediment Models

We prepared and submitted a report summarizing the models developed in this task. Files containing the complete geometric and pore-space network characterization of the models were created and uploaded for eventual community access. The models are most closely related to coarse-grained hydrate bearing formations. Thus we have actively pursued compilation of data for the "sand-dominated" McKenzie Delta formation: grain-size distribution, porosity, permeability, and geomechanical characteristics. This will be incorporated into the report.

Task 4.0 – Fracture Initiation and Propagation

We have updated our DEM models to better reflect the grain size distribution observed. We have carefully reproduced laboratory conditions (confining stress, compaction rate, etc.) to simulate experimental tests of compaction for dry sediment samples, and successfully calibrated micromechanical parameters to match stress/strain curves. The results show significant improvement with respect to our preliminary results.

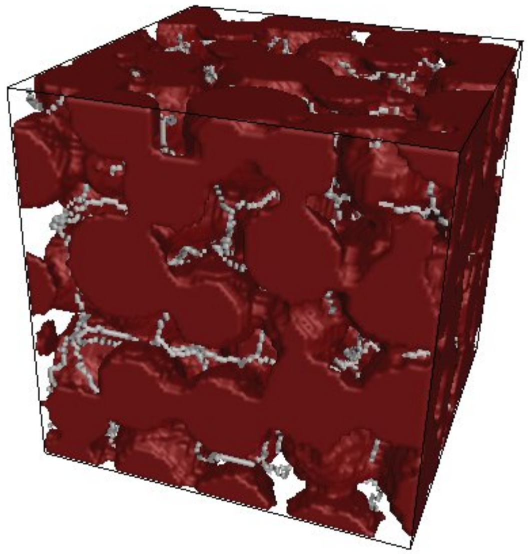
Our next step is under way: introducing the effect of fluid in the sediment models. PFC includes a logical capability to do this, but we are evaluating whether this is sufficiently accurate physically and robust computationally. The immediate objective is to be able to reproduce compaction tests for a variety of pore pressure conditions. It is also a necessary step for including the effect of multiple fluids.

Task 5.0 – Compute Grain-Scale Gas/Water Geometry

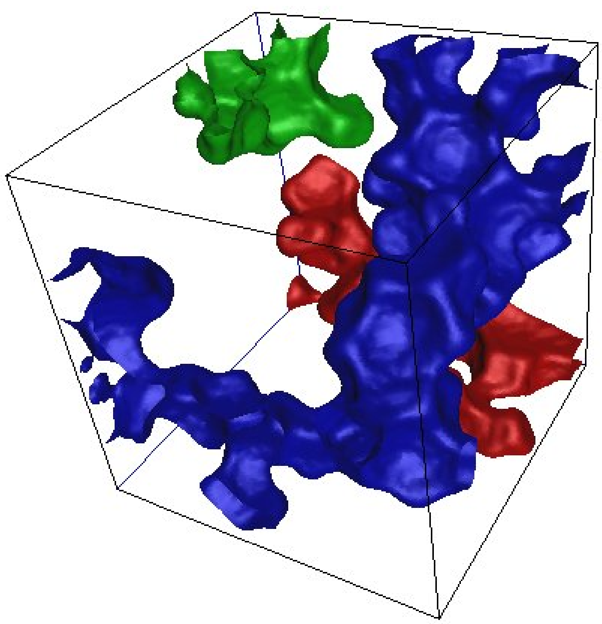
The model sediments created in Task 3 are periodic. Thus the grain-scale gas-water displacement simulations can be carried out without imposing any artificial boundaries on the pore space. In other words, the pore space is infinite-acting, especially with regarding to the trapping or isolation of fluid phases during displacement. This is an important advance in the state-of-the-art in this type of modeling. We are now developing the next necessary concept, namely an algorithm to identify finite vs. periodic clusters of fluid-filled pores. Finite clusters are trapped and cannot be displaced, while periodic clusters can undergo displacement.

We have continued developing the so-called Progressive Quasi-Static (PQS) algorithm for determining gas/water interface locations in pore space using the level set method. The main application of the PQS is to identify critical curvatures for pore-level events during drainage and imbibition in the model sediments. We plan to use network invasion percolation to upscale the level-set computation of capillarity-controlled interfaces. Recently we have managed to compute directly the interface location in tens of pores simultaneously. Figure 1b shows an example of such a computation in the pore space of an actual sand pack (not a model sediment), shown in Figure 1a. This is an exciting advance; we will be able to verify the invasion percolation upscaling in this way, and ultimately (given sufficient time and computing power) it may be feasible to compute directly the gas-water interface in macroscopic volumes of sediment (tens of thousands of pores).

Figure 1. **(a)** CT image (courtesy Clint Willson of LSU) of a packing of AccuSand. Grain surface shown as red; pore-space network as identified by medial axis algorithm shown as gray voxels.



(b) Location of gas-water interface at the endpoint of drainage (large capillary pressure) into the sample of (a). The three colors indicate separate clusters of nonwetting phase.



National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

One West Third Street, Suite 1400
Tulsa, OK 74103-3519

1450 Queen Avenue SW
Albany, OR 97321-2198

2175 University Ave. South
Suite 201
Fairbanks, AK 99709

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