

Oil & Natural Gas Technology

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

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MECHANISMS LEADING TO CO-EXISTENCE OF GAS AND HYDRATE IN
OCEAN SEDIMENTS

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QUARTERLY PROGRESS REPORT
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Summary

Work during this quarter focused on the solid-fluid coupling at the grain scale to reproduce the flow and deformation behavior of unconsolidated sediments, and modeling the displacement of water by gas in such sediments.

The work on the coupled poromechanical model has focused on the development of the mathematical and computational model, and on the validation of the model for simple porous media. The emphasis has been on the ability of the model to reproduce key mechanisms of poromechanical coupling, such as: pressure diffusion within the pore fluid network, fluid pressurization upon undrained compaction, confirmation of Biot's continuum theory of consolidation, and influence of permeability on the transient effects of coupling. In doing so, we have laid the foundation for the simulation and comprehensive analysis of fracturing in a two-fluid system, of which we have some preliminary results.

The PIs participated and gave a presentation at the Project Review Meeting that took place in Golden in September. Feedback from the referees was positive. Both PIs delivered back-to-back oral presentations at the AGU Meeting in San Francisco in December. The project was also presented at MIT during the Civil and Environmental Engineering Open House.

Co-PI Juanes established collaboration with Robert Kleinberg at Schlumberger, on aspects more closely related to the second phase of the project: modeling migration of methane gas and formation of hydrate at the bed scale. We expect that the present DOE project will benefit greatly from this interaction, as it will involve real data (even if in undisclosed locations) to validate the mathematical models to be developed in the project.

Co-PI Juanes has reached an agreement with Eni to fund the research project "Energy Production from Methane Hydrates". The project is expected to develop into a multi-year, institute-wide research program at MIT.

Work is well under way to write a joint UT/MIT paper for the Offshore Technology Conference to be held in Houston, and two papers for the International Conference on Gas Hydrates that will take place in Vancouver.

Activities in This Reporting Period

Task 4.0 – Fracture Initiation and Propagation

Subtask 4.1. Initialize the model

This subtask actually comprises most of the development and validation work on the grain mechanics modeling. The first step was the generation of model sediments by settling and compaction, which reproduce the grain size distribution of granular materials of interest. It was possible to obtain good agreement with laboratory triaxial tests from Hydrate Ridge (Tan and Germaine, 2006), see Figure 1. The PFC computational model, however, only has a limited ability to reproduce the loading/unloading cycles, at least partly by the two-dimensionality of the model.

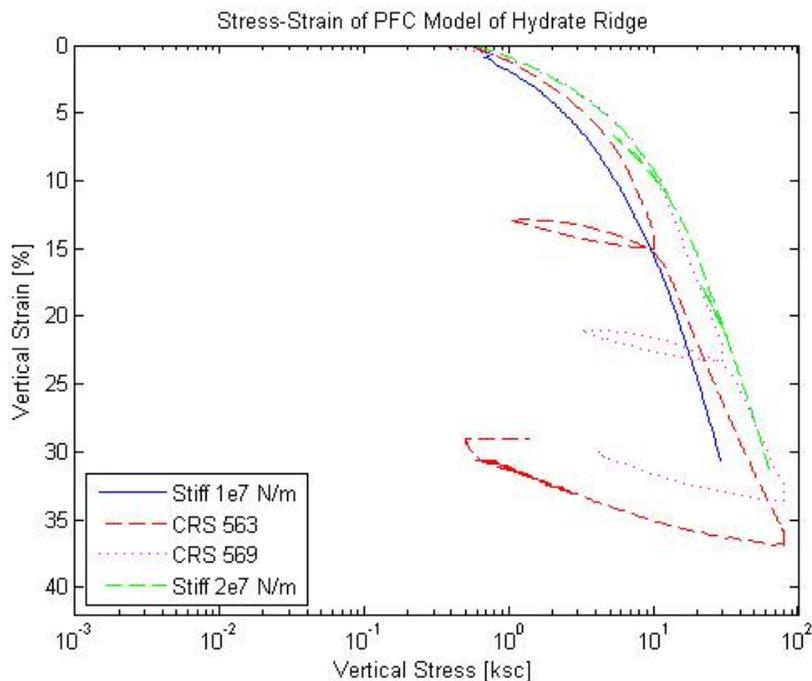


Figure 1. Stress-strain behavior of two sediment samples from Hydrate Ridge, and the stress-strain curves obtained from the simulation with the DEM model.

The most significant step is the development of a coupled fluid-solid interaction model at the pore scale. The conceptual view of this coupled model is shown in Figure 2. The model developed is a fully-coupled model with two-way coupling:

1. The pore fluid pressure exerts forces on solid grains, contributing to the deformation of the medium.
2. Grain rearrangements cause changes in volume of individual pores which, in turn, yield pore-pressure changes.

Moreover, the hydraulic properties of the medium will change as a result of deformation. Notably, this is reflected in the dependence of the pore-to-pore conductance on the distance between grains.

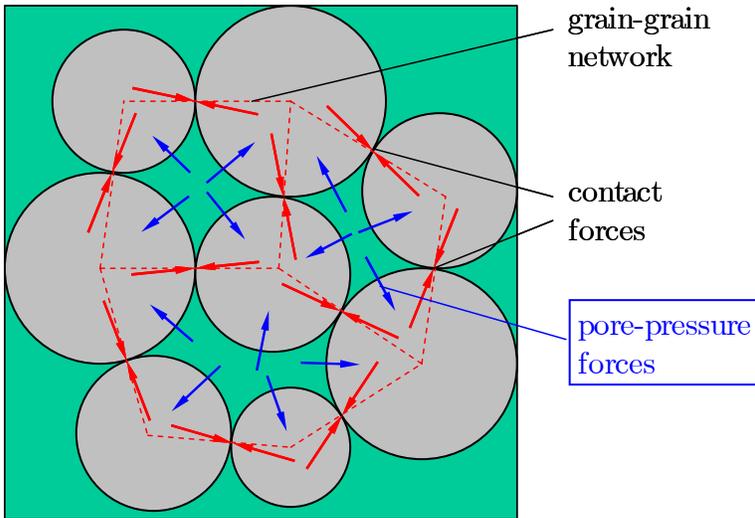


Figure 2. Conceptual picture of the fluid-solid interaction model at the pore scale.

One can write the microscopic equations governing the fluid pressure at each individual pore. In our model, this equation takes the form

$$\delta p = \frac{K_f}{V_p} \left(-\delta V_p - \sum_j q_j \delta t \right)$$

The main feature of our model is the term $-\delta V_p$, which accounts for the change in volume of each pore. This term has been neglected in all previous investigations of pore-scale poromechanical models but is essential, for example, to reproduce pressurization of the fluid upon fast compaction.

Computationally, the model then consists of two overlapping and interacting networks: the grain network and the fluid network. A particular instance is shown in Figure 3.

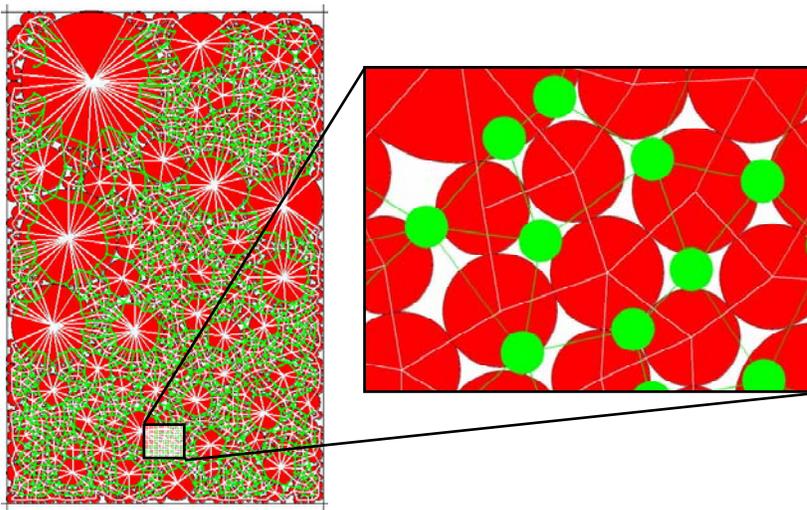


Figure 3. Representation (and zoom-in) of the grain and fluid networks.

We have spent a great effort in the validation of the coupled fluid-micromechanical model. This is a necessary step to build confidence that all the important mechanisms that play a role in methane gas migration (in particular, those related to fracturing of Subtasks 4.2 and 4.3 below) are properly captured.

The validation of the model included:

- Isochoric pressurization tests that must reproduce wall loading (Figure 4).
- Multistep inflow/outflow test that must capture pressure transients, as well as pore volume changes and pore-to-pore flow (Figure 5).
- Uniaxial pressurization tests that must reproduce the pressure diffusion across the fluid network (Figure 6).
- Drained consolidation tests that must predict the macroscopic diffusive behavior of the pressure transient, as well as stress-strain curves governed by the effective stress (Figure 7). This type of simulation allows one to obtain the macroscopic elastic and poroelastic parameters corresponding to the grain-scale model.

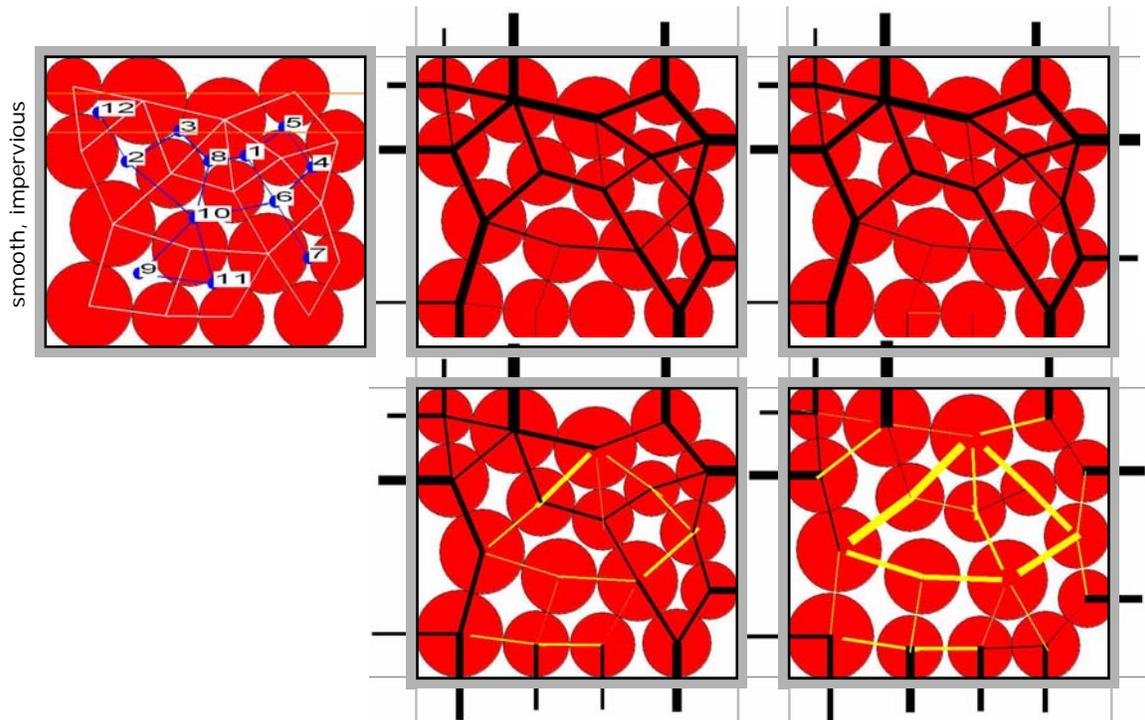


Figure 4. Wall loading during an isochoric pressurization test.

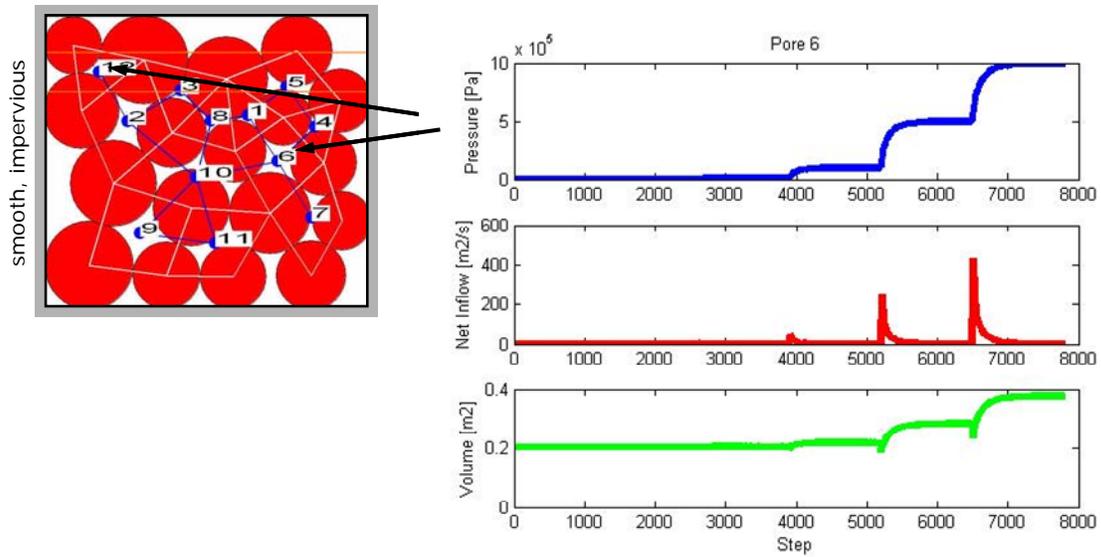


Figure 5. Pressure evolution, pore-to-pore flow, and pore volume at individual pores in a multistep pressurization test.

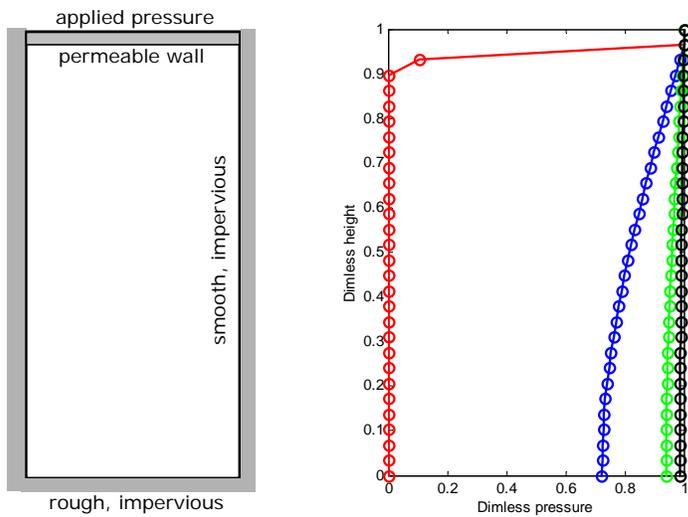


Figure 6. Width-averaged evolution of the pressure in a one-dimensional pressurization test.

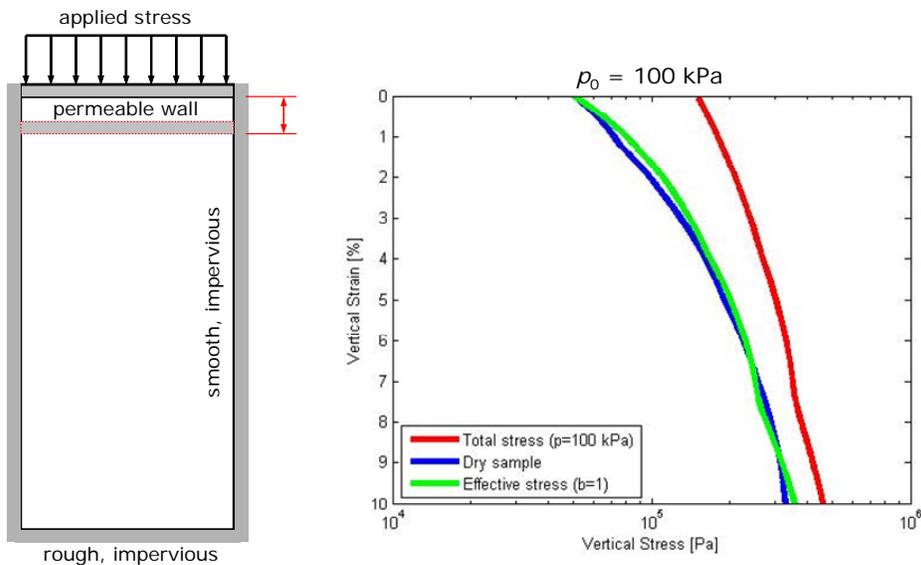


Figure 7. Stress-strain curves (total stress and effective stress) for a one-dimensional consolidation test.

Subtask 4.2. “Fracturing” with a single-fluid system

The developments briefly described above now permit investigating the poromechanical behavior of model sediments under a variety of scenarios. Of particular interest is the influence of bonding between grains, and the dependence of the mechanical deformation on the strength of those bonds. We may abuse language and say that a medium that is fully saturated with one fluid “fractures” when bonds between grains break.

The model now allows one to investigate under which conditions the material will “fracture” (the fluid pressure is sufficiently high that bonds will break under tension). By resolving the dynamics of the flow and the texture (layering) of the sediment, we can also investigate whether failure will be isotropic or in a preferential direction. While these issues have been investigated at length for dry media, their characterization for fluid-saturated media is still an open issue.

We illustrate the importance of bond strength with an isochoric pressurization test (see Figure 4). The fluid pressure is ramped up in stages. In Figure 8 we show the evolution of the associated increase in wall stress as a function of fluid pressure, for a consolidated rock that supports tension between grains (“tension”), and a granular material that does not (“no tension”). The difference is apparent, and it reflects the micromechanical mechanism of bond failure which, in turn, may greatly affect the hydraulic properties of the medium.

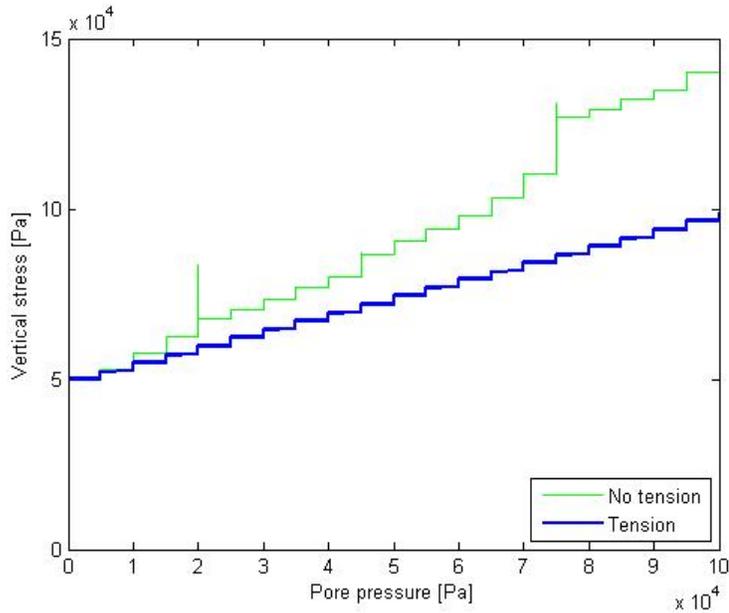


Figure 8. Wall stress in an isochoric pressurization test for a consolidated material (“tension”) and a granular material (“no tension”).

Subtask 4.3. Hydraulic fracturing with an elastic membrane representation of a two-fluid system

Preferential fracturing of the sediment invariably requires differences in pressure between neighboring pores. While this is typically not a favored scenario in single-fluid systems, it is natural in two-fluid systems because the two fluids do not mix and have different pressures (Figure 9). A simple and elegant formulation of the key hydraulic property (the conductance between pore bodies) has recently allowed us to consider such processes. A thorough analysis of this mechanism, and an evaluation of when it should be expected to be dominant, will be reported next Quarter.

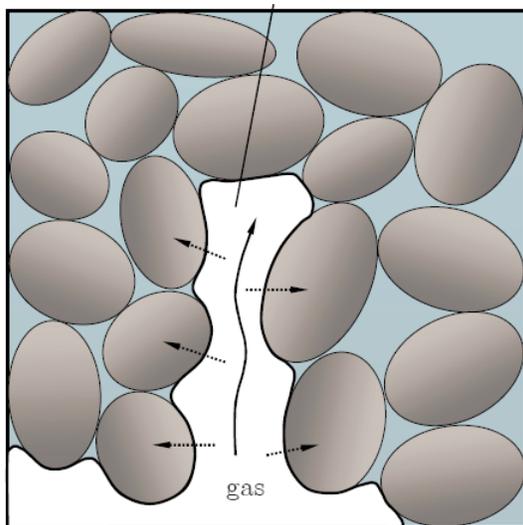
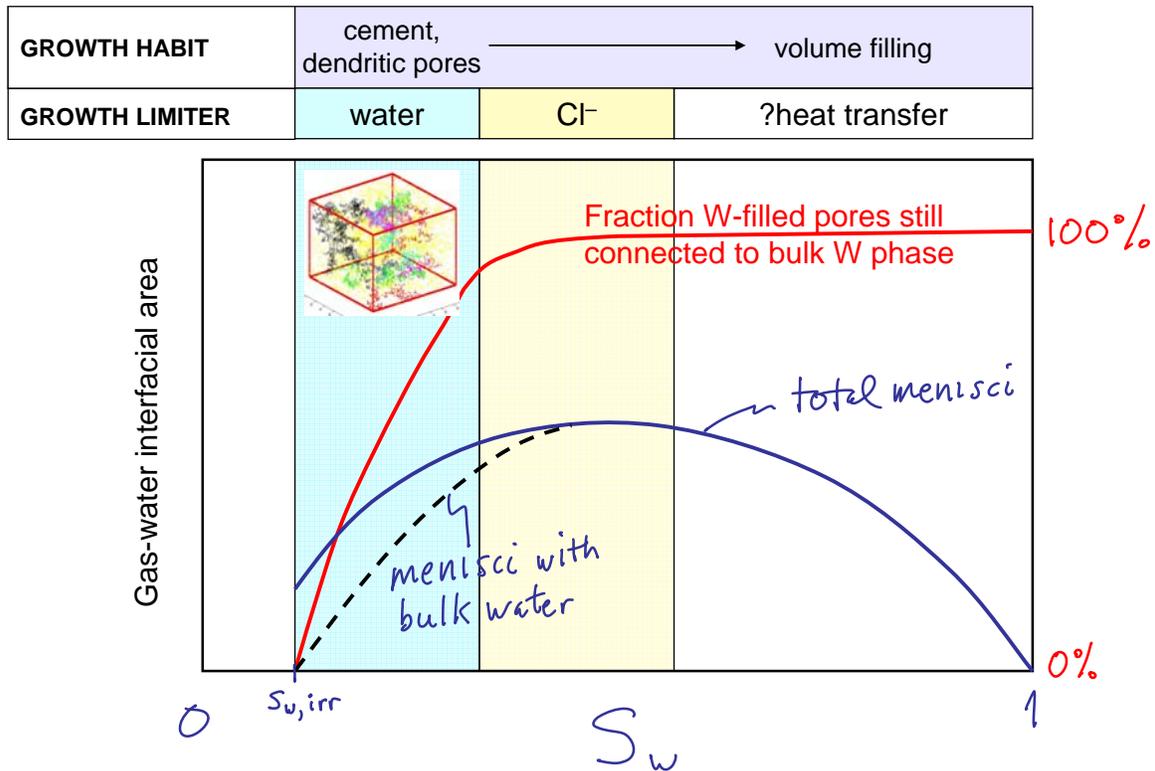


Figure 9. Fracturing of a sediment in a two-fluid system.

Task 5.0 – Compute Grain-Scale Gas/Water Geometry

The growth of hydrate at the gas/water interface will depend on how much water and gas are available locally and on how much the chlorinity builds up in the available water. The value of $S_{w,irr}$ and the spatial configuration of that water will thus affect the predicted growth habit. We previously reported on our innovation of “infinite-acting networks”, a method for simulating drainage that eliminates the boundary effects inherent in traditional grain-scale or network models. The simulations invoke a natural and physically robust criterion for trapping the wetting phase: if the wetting phase in a pore is part of a percolating cluster of wetting phase within the network, then it can be displaced. Otherwise, it is trapped. We are analyzing these simulations to determine the fraction of the wetting phase that is disconnected as drainage proceeds. A qualitative depiction of the results to date is shown below; an interpretation of the likely implications for hydrate growth follows.



As sketched above, nearly all the water is part of the percolating cluster (red curve) during the early stages of drainage. The total area of gas/water interfaces (blue curve) increases steadily during this period. Because both phases (gas and water) are well connected, we expect that hydrate growth would not be limited by availability of CH₄ nor of H₂O. Some other process such as the dissipation of the heat of fusion of the hydrate is likely to be limiting.

As drainage proceeds through an intermediate range of saturations, the water phase remains well connected (red curve). However, the percolating cluster is becoming increasingly ramified (dendritic), so that the pathway from a typical pore to the backbone of the cluster is becoming longer and more tortuous. The diffusive transport of excess Cl⁻

(remains in the water phase as water molecules enter the hydrate phase) is slower along such paths. Thus the continued growth of hydrate is likely to be limited by the buildup of chlorinity in this region.

As drainage proceeds to smaller water saturations, there is a rapid decline in the fraction of wetting phase that is still connected to the percolating cluster (red curve). The total gas/water interfacial area begins to decrease (blue curve), and the number of gas/water menisci associated with the percolating cluster of water phase decreases even faster (broken black line). Thus when invading gas has drained a sediment well, we anticipate that hydrate growth at gas/water interfaces will be limited by water availability.

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