NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS

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Research Performance Progress Report

(Period Ending 06/30/2017)

Impact of clays on the compressibility and permeability of sands during methane extraction from gas hydrate

Project Period (10/1/2016 to 9/30/2019)

Submitted by:
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Signature

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Office of Fossil Energy

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EXECUTIVE SUMMARY

Background: The quantity of methane potentially recoverable from gas hydrate is large enough to motivate federally-supported production tests in several countries, which in turn motivates studies of reservoir production efficiency. Evaluating long-term production well viability involves modeling permeability evolution in the reservoir sediments around the production well because processes reducing the flow of gas into the production well also reduce the long-term economic viability of the well. Fine particles, such as clays, exist nearly ubiquitously in the permafrost and marine settings that typically host gas hydrate, and fines reacting to fluid flow by migrating and clogging pore throats can reduce flow toward the production well. Many fines are sensitive to variations in pore-fluid chemistry, swelling in reaction to in situ pore brine being displaced by fresh water liberated from hydrates during dissociation. Additionally, fine particles tend to collect at gas/water interfaces created by the multiphase flow of gas and water. Thus, as methane and fresh water flow from the hydrate-dissociation front toward the production well, fine particles in the reservoir sands, interbedded fine-grained layers and seal layers can be swelled, migrated (or both), potentially clogging pathways and limiting flow to the production well.

Objective: This project seeks to provide a quantitative basis for reservoir models to account for the impact of clays and other fine-grained material ("fines") on reservoir compressibility and permeability, two key factors controlling the flow of gas and fluids toward a production well. This overall objective is addressed through a combination of site-specific and more generalized, fundamental science goals:

Site-specific measurement goals: quantify the change in compressibility and permeability due to the reaction of fines to pore-water freshening in sediment from the 2015 NGHP-02 gas hydrates research cruise offshore India.

Fundamental measurements on pure fines goal: distinguish between, and quantify, mechanisms for sediment compressibility and permeability change due to physical and chemical responses of fines to the flow of freshened pore water and gas:

- Chemical response: quantify and catalog the sensitivity of pure fines (fines with only a single component, or "endmember" fines) to pore-water chemistry.
- Physical response: quantify the link between fines migration and clogging during single and multiphase flow.

ACCOMPLISHMENTS

The overall project timeline is shown in Figure 1. This report details activities in the second quarter of Year 1. A full list of milestones and Success Criteria is provided in the Appendix.

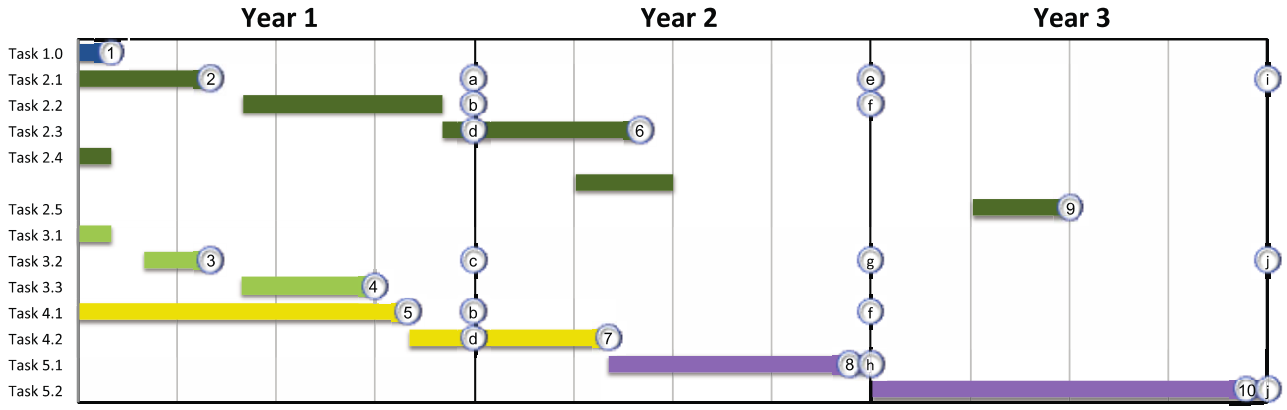

Figure 1: Project timeline, including times of activity (color bars), Milestones (numbered circles) and Success Criteria (lettered circles). A complete list of Milestones and Success Criteria are given in the Appendix.

Active Tasks this quarter included **Tasks 2.2** (2D microfluidic model visualization of fines migration), **3.3** (Dependence of compressibility and permeability on pore fluid chemistry in pure, endmember fines) and **4.1** (Dependence of fines migration and clogging on physical conditions in porous media containing pure, endmember fines). A summary of accomplishments for each Task is provided below.

Task 2.2: 2D Microfluidic model visualization of NGHP-02 fines

This subtask is an opportunity to compare results with 2D micromodeling between LSU (Task 4), and the USGS (Task 2.2). Observations will be made on endmember fines as a function of fines concentration and pore fluid chemistry to examine fines migration and permeability shutdown (clogging). Accomplishments in this initial quarter of activity include:

- Acquiring a microscope/camera system at the USGS.
- Development of a transparent apparatus for visualizing sediment particle interactions in response to alterations of pore-fluid chemistry

(vertical flow). This development is in support of upcoming 2D micromodel tests (horizontal flow) to be conducted once LSU micromodels are available at the USGS, and may help link observations from the settlement experiments (Task 3.2) to the micromodel studies (Tasks 2.2 and 4.1).

Task 3.3: Dependence of compressibility and permeability on pore-fluid chemistry in pure, endmember fines

Compressibility and permeability are two critical parameters for describing the ease with which fluid can flow through a formation over the production life of a reservoir. As the reservoir is subjected to increased effective stresses during the pressure draw down required to destabilize the hydrate in situ, reservoir sediment porosity (and hence, permeability) will be lost as the sediment compresses. The relationship between applied stress and the extent of compression is given by the compressibility, which was the focus of laboratory activities in this quarter. Accomplishments include:

- Oedometer-style compression tests have been run at LSU and the USGS on fines for a variety of pore fluids. This quarter builds on last quarter's efforts to understand the dependence of compressibility on pore-water salinity by including the effects of a low-permittivity, non-polar fluid (kerosene). Kerosene is considered here as an end-member fluid that 1) provides insight into the behavior of fines in hydrocarbon reservoirs or in the presence of some Non-Aqueous Phase Liquid (NAPL) contaminants, and 2) provides a contrast to earlier tests in water and brine, where interparticle interactions are moderated by the behavior of fluid between the particles. Non-polar fluids, such as kerosene, do not form the particle-surrounding fluid layers that water molecules form, and hence allow particles to come closer together than is possible when bound water layers surround each particle. Interparticle interactions determined by the unbalanced charge distributions on each particle can be observed.
- Compression tests for fines immersed in kerosene show two behaviors that can be understood in terms of the sedimentation test results

from Task 3.2: Fines in kerosene show uniform sedimentation, meaning suspended particles cluster together regardless of size, fall under the force of gravity and form a loose sediment fabric (relatively high void ratio) in which grain contacts can have large and small grains. This is in contrast to fines in deionized water, for which segregated sedimentation can cause fine particles to collect in pores, away from the contacts between larger grains. When intergranular contacts are formed by particles with a range of grain sizes, the overall sediment compressibility is higher than an equivalent sediment in which the fine-grained particles are located in the pore space, away from the grain contacts between larger particles.

- A conference paper for the Ninth International Conference on Gas Hydrates (held June 25-30, 2017) was submitted, and a poster presentation lead by Jang was given at the conference. These products focused on the behavior of fines as a function of pore fluid salinity.

Task 4.1: Dependence of fines migration and clogging on physical conditions in porous media containing pure, endmember fines

Fines existing in coarse-grained material can migrate in pore-fluid flow, collect at pore-throats and clog flow pathways, reducing the overall permeability required for efficient methane extraction from hydrate-bearing sands. In this task, endmember fines are assessed in terms of their mechanical capacity to migrate and clog pores of various sizes relative to the grain size of the fines themselves. Accomplishments this quarter include:

- LSU micromodel tests have been run for all endmember fines in water and brine. For each fine-type and fluid, tests are run on micromodels with pore throat widths of 10, 20, 40, 60, and 100 μm, plus a micromodel containing a random distribution of those pore-throat widths. For each combination, increasing concentrations of fines are used to establish a matrix describing the particle type, particle concentration, geometry, and chemistry combinations that

result in apparent pore-throat clogging. Generally speaking, clogging occurs more easily (in larger pore throats) for fines in water relative to fines in brine.

- Two flow types are tested in each run: 1) an initial injection of water + sediment that saturates the 2D-micromodel and establish an initial distribution of fines, and 2) a reverse flow of CO2 gas to simulate production of a gas phase that passes through a water-saturated zone before reaching the production well. Observations confirm the dramatic increase in clogging that occurs as the production gas/water interface moves through a water-saturated, fine-bearing region.

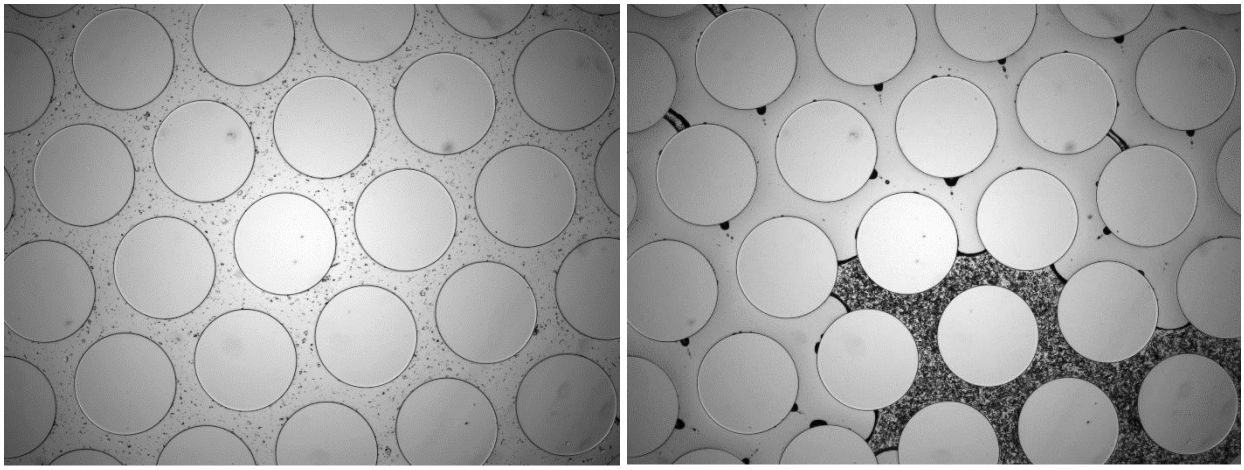

Figure 3: 2D micromodel images for the Mica/brine system. Pore throat width (distance between circular "particles," is 100µm. (**Left**) Mica suspended in brine is injected into the micromodel, saturating the micromodel and distributing mica clusters (black flecks in the pore space). Note the lack of obvious pore-throat clogs. (**Right**) subsequent flushing with CO_2 gas shows the importance of the gas/water interface in collecting and concentrating fines to create likely zones of clogging. Darkened pore area at the lower right is water with a high concentration of mica, while the remaining pore space is CO_2 gas with some localized concentrations of mica (small dark regions adjacent to circular "particles").

PRODUCTS

Jang, J., Waite, W.F., Jung, J., Pore-fluid sensitivity of clays and its impacts on gas production from hydrate-bearing sediments [Abstract]. Accepted for the 9th International Conference on Gas Hydrates, June 25-30, 2017, Denver, Colorado.

Jang, J., Cao, S., Waite, W.F., Jung, J., Impact of pore-water freshening on clays and the compressibility of hydrate-bearing reservoirs during production. Conference paper submitted for the 9th International Conference on Gas Hydrates, June 25-30, 2017, Denver, Colorado.

APPENDIX: PROJECT TIMELINE & MILESTONE TRACKING

Figure A1 is the complete Project timeline. Milestones and Success Criteria are listed thereafter, with updates given for elements in the current reporting period.

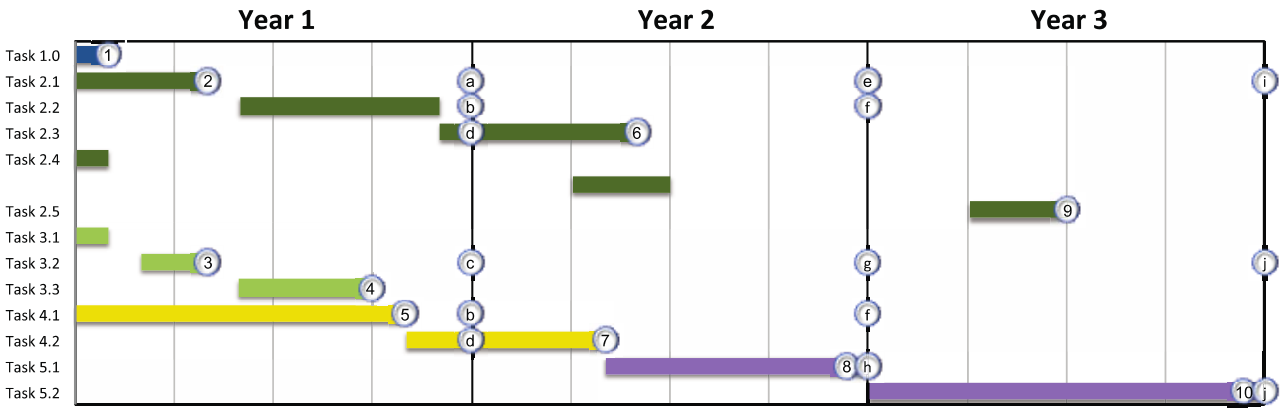

Figure A1: Project timeline, including times of activity (color bars), Milestones (numbered circles) and Success Criteria (lettered circles). A complete list of Milestones and Success Criteria are given below.

Milestones (listed according to the numbers given in Figure A1)

Budget Period 1

1. Task 1, Project Management (LSU/USGS). This task will be completed October 31, 2016 and verified through DOE acceptance of the project SOPO, annual budget forecasts and Project Management Plan.

   Status: Completed. SOPO and PMP accepted by DOE. Kickoff meeting presentation complete.

2. Task 2, Site-specific pore fluid sensitivity study (USGS). This data acquisition component of Task 2 will be completed January 31, 2017 and verified through comparison of NGHP-02 data obtained with available shipboard data from the NGHP-02 cruise offshore India.

   Status: Initial phase of milestone completed. NGHP data has been collected on shipboard depressurized core material, but project will take the opportunity to collect additional data as pressure core material becomes available. Data will be integrated into a set of NGHP-02 special science volume papers currently with a February 2018 submission deadline.

3. Task 3, Endmember fines – electrical sensitivity index (USGS). This data acquisition component of Task 3 will be completed January 31, 2017. Results will be verified

through duplicate measurements of targeted specimens using LSU equipment, literature comparison where available.

Status: Completed. Data from this milestone have been incorporated into a conference paper and poster presented at the Ninth International Conference on Gas Hydrates (June 25-June 30, 2017 in Denver, CO).

4. Task 3, Endmember fines – dependence of compressibility and permeability on pore fluid chemistry (LSU). This data acquisition component of Task 3 will be completed June 30, 2017. Results will be verified through duplicate measurements of targeted specimens using USGS equipment.

   Status: Completed. Data from this task is partly included in the conference paper and poster presented at the Ninth International Conference on Gas Hydrates (June 25-June 30, 2017 in Denver, CO). Remaining data are being incorporated into a manuscript for peer-reviewed journal publication.

5. Task 4, 2D micromodel studies – mechanical contribution of endmember fines to clogging (LSU). This data acquisition component of Task 4 will be completed July 31, 2017. Results will be verified through duplicate measurements of targeted specimens using USGS equipment.

Budget Period 2

6. Task 2, 2D micromodel studies – mechanical contribution of NGHP-02 fines to clogging (USGS). This data acquisition component of Task 2 will be completed March 1, 2018. Results will be verified through linkages between imaged clogs and measured evolution of pressure and flow parameters.
7. Task 4, 2D micromodel studies – clogging dependence of endmember fines on pore fluid chemistry (LSU). This data acquisition component of Task 4 will be completed January 31, 2018. Results will be verified through duplicate measurements of targeted specimens using USGS equipment.
8. Task 5, 3D visualization of clogging and clog fracturing – dependence on endmember fines (LSU). This data acquisition component of Task 5 will be completed September 30, 2018. Results will be verified through linkages between imaged clogs and measured evolution of pressure and flow parameters.

Budget Period 3

9. Task 2, Site-specific dependence of compressibility and permeability on pore fluid chemistry (USGS). This data acquisition component of Task 2 will be completed March 31, 2019. Results will be verified for brines and freshened pore water by comparisons with pressure core data obtained elsewhere in the NGHP-02 project.
10. Task 5, 3D visualization of clogging and clog fracturing – dependence on pore water chemistry (LSU). This data acquisition component of Task 5 will be completed

September 30, 2019. Results will be verified through linkages between imaged clogs and measured evolution of pressure and flow parameters.

Success Criteria (listed according to the letters given in Figure A1)

End of Budget Period 1

a. Subtasks 2.1, 2.4: NGHP-02 fines properties (Offshore India). Index property measurements and liquid limit tests should have begun on NGHP-02 conventional core sediment. Additional index property and liquid limit tests can be run on NGHP-02 material as the material becomes available from pressure cores that were previously dedicated for USGS study during NGHP-02.

   Status: Initial phase of criteria completed. NGHP data has been collected on shipboard depressurized core material, but project will take the opportunity to collect additional data as pressure core material becomes available. Data will be integrated into a set of NGHP-02 special science volume papers currently with a February 2018 submission deadline.

b. Subtasks 2.2 and 4.1 (linked): 2D microfluid models – clogging via physical processes. Measurements of clogging by endmember fines should have been run separately by both participants. Results should be quantified in terms of clogging potential due to mechanical activity (fines migration) and geometry (pore throat size relative to grain size of the fines). Results should demonstrate similar behavior within the subset of LSU and USGS tests that are paired for interlaboratory verification purposes.

c. Task 3: Endmember fines assessment of pore fluid chemistry impact on compressibility and permeability. All data for a manuscript detailing the implications of the electrical sensitivity (pore fluid sensitivity) of fines on compressibility and permeability should be in hand, and a conference abstract prepared.

   Status: Criteria complete. Conference paper and poster have been presented on this material at the Ninth International Conference on Gas Hydrates (June 25-June 30, 2017 in Denver, CO).

d. Subtasks 2.3 and 4.2 (linked): 2D microfluid models – clogging dependence on pore fluid chemistry. 2D micromodel experiments should have been started by both participants to assess the dependence of clogging by fines in relation to fluid chemistry. Initial comparisons between participants should guide subsequent efforts and dictate any additional tests that may need to be run.

End of Budget Period 2

e. Subtasks 2.1, 2.4: NGHP-02 fines properties (Offshore India). Index property measurements and liquid limit tests should continue on NGHP-02 pressure core sediment as the material becomes available from pressure cores that were previously dedicated for USGS study during NGHP-02. The publication moratorium should have expired in time to allow a conference abstract submission covering the NGHP-02 fines study to date.

f. Subtasks 2.2, 2.3 and Task 4: 2D Micromodel studies of clogging by endmember fines. All data for a manuscript detailing the implications of mechanical and chemical controls on clogging by endmember fines should be in hand. A joint manuscript should be submitted for peer reviewed journal publication, though the review process will likely be ongoing at the end of Budget Period 2.
g. Task 3: Endmember fines assessment of pore fluid chemistry impact on compressibility and permeability. Based on feedback from presenting this material at a conference, a peer-reviewed journal manuscript should have been written and submitted during this budget period, though the review process will likely be ongoing at the end of Budget Period 2.
h. Subtask 5.1: 3D micromodel imagery of the role of endmember fines in clogging, clog fracturing, and relative permeability. This Subtask is a 3D extension of the Subtasks 2.2 and 4.1 2D micromodel tests. By the end of Budget Period 2, comparisons between 2D and 3D observations of fines clogging based on mechanical and geometric factors should be providing insight into how the 2D micromodel results scale up to 3D, and these insights should be captured in a submitted conference abstract.

End of Budget Period 3

i. Subtasks 2.1, 2.4: NGHP-02 fines properties (Offshore India). Index property measurements and liquid limit tests should be complete on NGHP-02 pressure core sediment as the material. Based on feedback from presenting this material at a conference, a peer-reviewed journal manuscript should have been written and submitted during this budget period, though the review process for an NGHP-02 special volume may be ongoing even by the end of Budget Period 3.
j. Tasks 3 and 5: Interaction of fines with pore water – effect of pore water chemistry on index properties and flow behavior of endmember fines. Tying the macroscopic property insights from Task 3 with the 3D pore-scale behaviors observed in Task 5 provides the scientific content for the capstone publication in this project. Based on reviewer feedback from Task 3 and conference feedback from Subtask 5.1, a manuscript covering the interaction between fines and pore water and the subsequent impact on index and flow properties will be submitted.

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