NATIONAL ENERGY TECHNOLOGY LABORATORY

OIL & GAS

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Research Performance Progress Report

(Period Ending 03/31/2018)

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

Project Period (10/1/2016 to 9/30/2018)

Submitted by:
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Signature

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Office of Fossil Energy

DISCLAIMER

TABLE OF CONTENTS

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 first quarter of Year 2. A full list of milestones and Success Criteria is provided in the Appendix.

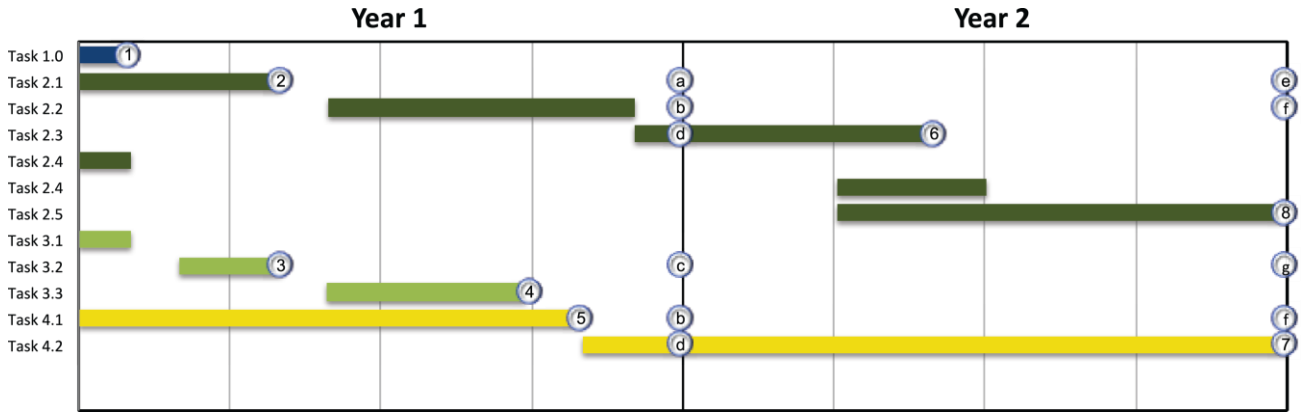

Figure 1: Project timeline, including times of activity (color bars), Milestones (numbered circles) and Success Criteria (lettered circles). A complete list of Milestones and Success Criteria are given in the Appendix.

Active Tasks this quarter included **2.3** (Microfluidic model visualization of NGHP-02 fines migration and clogging in a 2D pore network), **2.4** (NGHP-02 fines sensitivity to pore fluid chemistry), **2.5** (Compressibility and permeability dependence of NGHP-02 sediment on pore-fluid chemistry), and **4.2** (Dependence of fines migration and clogging on pore-fluid chemistry in porous media containing pure, endmember fines). A summary of accomplishments for each Task is provided below.

Task 2.3: Microfluidic model visualization of NGHP-02 fines migration and clogging in a 2D pore network

In the first quarter of Year 2, micromodel tests on two high-value targets within the NGHP-02 program were completed. This quarter, a manuscript has been prepared for submission to the *Journal of Marine and Petroleum Geology* for inclusion in their special volume covering the NGHP-02 program. Submission planned for early in Year 2, 3Q (Joint with Task 4.2).

Task 2.4: NGHP-02 fines sensitivity to pore fluid chemistry

The electrical sensitivity of an NGHP-02 specimen collected from beneath a primary gas hydrate reservoir has been measured. These measurements consume more sediment than is often available for a given specimen, but an alternative approach using the sedimentation tests as a proxy for the electrical sensitivity tests has been useful. Sedimentation tests require less sediment, and are well-suited for highlighting specimen sensitivities to gravimetric versus electrical forces, as well as indicating the specimen's electrical sensitivity. A key finding has been that even the coarse-grained reservoir specimens have clay contents that tend to dominate the sedimentation test results (Figure 2). This quarter, a manuscript detailing the sensitivity analyses of NGHP-02 sediment to date has been prepared for submission to the *Journal of Marine and Petroleum Geology* for inclusion in their special volume covering the NGHP-02 program. Submission planned for early in Year 2, 3Q.

Task 2.5: Compressibility and permeability dependence of NGHP-02

Figure 2: Sedimentation test images for a reservoir sand from NGHP-02 after more than a day of settling. (Left cylinder) Sedimentation in deionized water shows the coarse fraction has settled (dark region at the cylinder base), but the overlying water is clouded by fines that have not yet clustered and settled. (Center cylinder) Sedimentation in 2M-brine has a clear overlying liquid, indicating the brine has facilitated the clustering and settlement of fines. This is the type of behavior expected for silica-based fines.

sediment on pore-fluid chemistry

In Year 1, 4Q, pressure core testing was completed on NGHP-02 specimens from a fine-grained overburden seal, and a coarse-grained reservoir. Compressibility and permeability measurements have been made while the specimens were in various combinations of fresh and in situ water. This quarter, a set of manuscripts covering both permeability and compressibility issues have been prepared for submission to the *Journal of Marine and Petroleum Geology* for inclusion in their special volume covering the NGHP-02 program. Measurements of the dependence of these parameters on pore fluid chemistry will continue throughout Year 2.

Task 4.2: Dependence of fines migration and clogging on pore-fluid chemistry in porous media containing pure, endmember fines

In addition to the mechanical drivers for pore-throat clogging by fines, there are chemical stimuli as well. Fine-grained particles are generally smaller than the pore throats they end up clogging, so many of the clogging behaviors studied in this task are caused when clusters or clumps of fine-grained particles form, growing large enough to span the pore throats. As shown in Task 3.2, clustering depends on the combination of the type of fine and the pore fluid, and cannot be predicted if only the fine type or only the pore fluid is known. A suite of micromodel clogging tests have been run for pure, endmember fines: kaolinite, montmorillonite (or bentonite), mica, diatoms, calcium carbonate and silica silt. From these tests, critical clogging concentration "maps" have been generated for each fine type. As shown in Figure 3, for bentonite, clogging occurs more readily in brine than in fresh water. This is due to positive ions in the brine allowing the negatively-charged bentonite particles approach each other closely enough to form clusters that can grow large enough to clog pore throats. For kaolin, however, clogging occurs more readily in deionized water because kaolin clusters are more bulky in deionized water than in brine. When evaluating the clogging potential of naturally-occurring gas hydrate reservoirs, it is therefore necessary to establish the type of fines present in the system in order to predict whether the

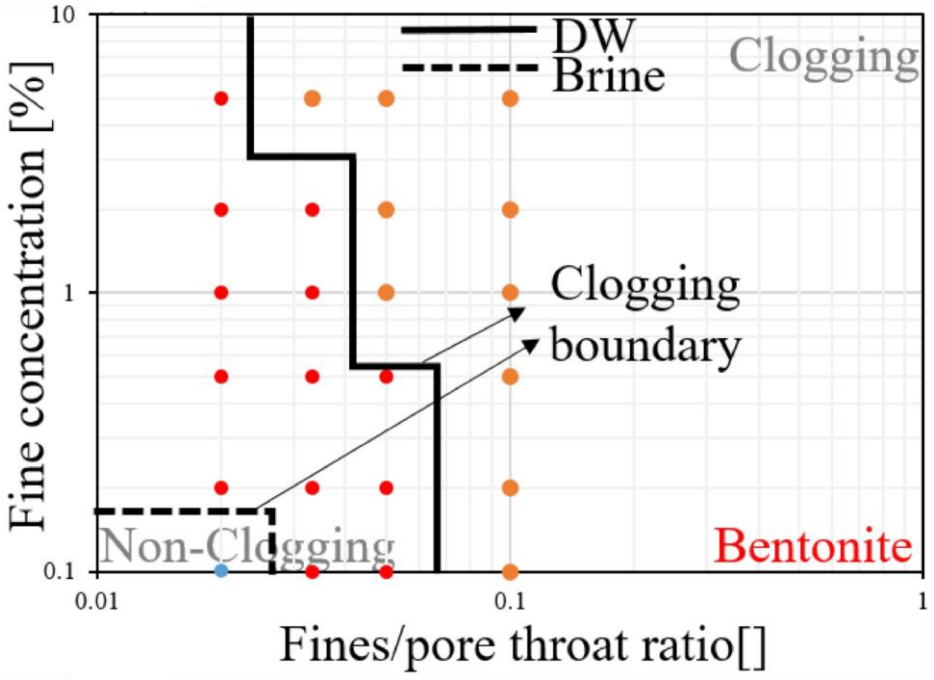

Figure 3: Critical clogging concentration map for bentonite in deionized water (DW) and 2M-brine as a function of the ratio of the mean sediment grain size (d_{50}) to the pore throat size. Low ratios mean each pore throat is many particles across, and thus more difficult to clog. The boundaries (solid and dotted lines, represent transitions between conditions with and without pore-throat clogging. Lower left part of the figure represents non-clogging conditions with the blue point while the orange points in the upper right part of each figure represents clogging conditions for bentonite in either fluid. Red points between these two extremes represent conditions for which clogging occurs for only 2M-brine. For bentonite, clustering is hindered by deionized water, so clogging will not occur until the concentration of bentonite particles is fairly high. For kaolin, however, clogging occurs more readily in deionized water because kaolin forms much bulkier clusters in deionized water than in brine.

clogging potential will increase or decrease when the pore water is freshened during gas hydrate dissociation. This quarter, a 2D-micromodel-based manuscript detailing the analyses of the pure endmember fines, as well as specimens of NGHP-02 sediment, has been prepared for submission to the *Journal of Marine and Petroleum Geology* for inclusion in their special volume covering the NGHP-02 program. Submission planned for early in Year 2, 3Q (Joint with Task 2.3).

PRODUCTS

Cao, S.C., Jang, J., Waite, W.F., Jafari, M., Jung, J., A 2D micromodel study of fines migration and clogging behavior in porous media: Implications of fines on methane extraction from hydrate-bearing sediments [Abstract]. Talk presented at the 2017 Fall American Geophysical Union Conference, New Orleans, LA, December 11-15, 2017.

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

APPENDIX: PROJECT TIMELINE & MILESTONE TRACKING

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

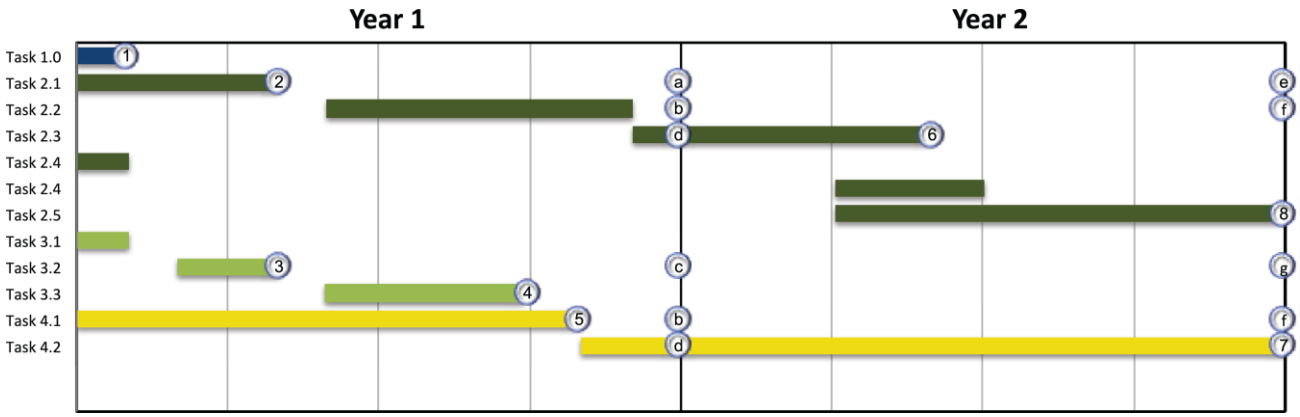

Figure A1: Updated project timeline, including times of activity (color bars), Milestones (numbered circles) and Success Criteria (lettered circles). A complete list of Milestones and Success Criteria are given below.

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- 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 25-30, 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.

   Status: LSU contribution completed. Data from this task is partly included in the conference abstract submitted to the Fall American Geophysical Union Conference (December 11-15, 2017 in New Orleans, LA). Remaining data are being incorporated into a manuscript for peer-reviewed journal publication. Micromodels to be used at the USGS will be constructed at LSU in the first quarter of BP 2 and shipped to the USGS.

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.

   Status: 2D micromodel studies on NGHP-02 fines have been completed, including data about mechanical clogging processes. A manuscript has been prepared for submission to the Journal of Marine and Petroleum Geology for inclusion in their special volume covering the NGHP-02 program. Submission planned for early in Year 2, 3Q (Joint with Task 4.2).

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

September 30, 2018. Results will be verified through duplicate measurements of targeted specimens using USGS equipment.

8. Task 2, Site-specific dependence of compressibility and permeability on pore fluid chemistry (USGS). This data acquisition component of Task 2 will be completed September 30, 2018. Results will be verified for brines and freshened pore water by comparisons with pressure core data obtained elsewhere in the NGHP-02 project.

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 an April 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.

   Status: LSU contribution completed. Data from this task is partly included in the conference abstract submitted to the Fall American Geophysical Union Conference (December 11-15, 2017 in New Orleans, LA). Remaining data are being incorporated into a manuscript for the NGHP-02 special science volume, with an April 2018 submission deadline.

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.

Status: LSU contribution completed. Data from this task is partly included in the conference abstract submitted to the Fall American Geophysical Union Conference (December 11-15, 2017 in New Orleans, LA). Remaining data are being incorporated into a manuscript for the NGHP-02 special science volume, with an April 2018 submission deadline

End of Budget Period 2

e. Subtasks 2.1, 2.4, 2.5: NGHP-02 fines properties (Offshore India). Index property measurements, liquid limit, compressibility and permeability 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. 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 2.

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.

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