NATIONAL ENERGY TECHNOLOGY LABORATORY

OIL & GAS

DOE Award No.: DE-FE00-28966

Research Performance Progress Report

(Period Ending 09/30/2018)

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:
Dr. Jongwon Jung

Signature

Louisiana State University, Dept. of Civil and Environmental Engineering
DUNS #075050765
3505C Patrick Taylor Hall
Baton Rouge, LA 70803
Email: jjung@lsu.edu
Phone number: (225) 578-9471

Prepared for:
United States Department of Energy
National Energy Technology Laboratory

Submission Date

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

Office of Fossil Energy

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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

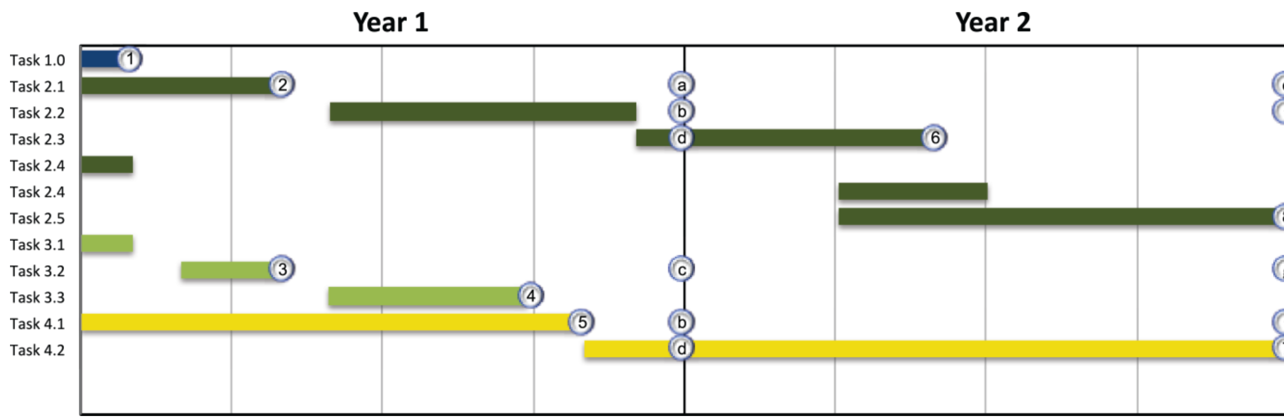

Figure 1: Project timeline, including times of activity (color bars), Milestones (numbered circles) and Success Criteria (lettered circles). A complete list of Milestones and Success Criteria are given in the Appendix.

Active Tasks this quarter included **2.5** (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, along with key results from the journal manuscripts.

<u>Task 2.5: Compressibility and permeability dependence of NGHP-02 sediment on pore-fluid chemistry</u>

This quarter, two revised manuscripts covering permeability and compressibility issues were submitted to the *Journal of Marine and Petroleum Geology* (special volume covering the NGHP-02 program). One has been accepted, and one is in review.

The accepted paper, "Pressure core analysis of geomechanical and fluid flow properties of seals associated with gas hydrate-bearing reservoirs in the Krishna-Godavari Basin, offshore India" characterizes the properties of the fine-grained overburden sediment above a prominent coarse-grained gas hydrate reservoir in Area C. A key outcome was showing the overburden permeability was lower than the permeability of the reservoir, even with the reservoir's gas hydrate in place. This paper promotes the concept of the overburden sediment being considered a "seal" element in the gas hydrate petroleum system (GHPS) concept. This proposal brings the GHPS concept into alignment with the conventional petroleum system approach. Prior to this work, the assumption in the gas hydrate literature was that the presence of gas hydrate reduced the permeability in coarse-grained reservoir sediment so dramatically that the reservoir became the seal as well as the reservoir. As described more fully in the second manuscript "Impact of fine-grained sediment on the nature and development of a gas hydrate reservoir system investigated during NGHP-02 in the Krishna-Godavari Basin, offshore eastern India" (currently under review for the special volume covering NGHP-02), assigning the seal role to the overlying sediment has two important advantages:

1) A preexisting overlying seal can slow the rate of vertical fluid flow, allowing the microbial generation of methane to generate pore-fluid methane saturations high enough to exceed the local methane solubility limit in the reservoir and thus allow gas hydrate to form. In microbial systems such as NGHP-02, if there are no limits to fluid flow rates, pore-water methane content may not be able to reach the high solubility limits required to form gas hydrate. Since the intrinsic (gas hydrate-free) permeability of a potential reservoir unit is high, the unit cannot be relied upon to limit flow rates enough to initiate the first gas hydrate growth within the reservoir.

2) During production via depressurization, a low-permeability overburden can act as a seal to prevent fluid from flowing into the depressurized reservoir. Hence, an overburden seal can increase the efficiency of gas hydrate dissociation by making the depressurization process more efficient.

A second critical finding in the manuscript is that even in the primarily coarse-grained gas hydrate reservoir sediments, the fines content is high enough for the sediment's compressibility and permeability to be controlled by the fine-grained fraction rather than the coarse-grained fraction typically used to characterize the reservoir. This will likely be a concept that needs to be reviewed in the DOE-supported Gulf of Mexico (GOM^2) project lead by U. Texas.

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 as well as sediment from two sites in the NGHP-02 field program. This quarter, a 2D-micromodel-based manuscript detailing these analyses was accepted by the *Journal of Marine and Petroleum Geology* for inclusion in their special volume covering the NGHP-02 program (Joint with Task 2.3).

The micromodel paper "Clogging behavior of fine-grained particles associated with gas hydrate production in NGHP-02 gas hydrate reservoir sediments" provides "clogging maps" (Figure 2) indicating how the clogging behavior is controlled by the relative sizes of the sediment grains and the pore throats for a given pore fluid. As expected, fines can clog larger pore throats (smaller values of the fines/pore throat size ratios) as the concentration of fines in the pore-water increases. The map also shows how that clogging behavior changes based on the pore fluid. As anticipated from Task 3 and the resulting publication in the Journal of Geophysical Research, whether fines cluster and clog more efficiently in fresh water (i.e. as gas hydrate dissociates) than in brine (i.e. pore water prior to gas hydrate dissociation) depends on the type of fine particles and their interparticle interactions. Swelling clays such as bentonite or other smectites will clog less effectively as pore water freshens during gas hydrate dissociation. Larger, platy fines such as kaolin behave in the opposite fashion. This highlights the importance of identifying the fines present in a given field setting. The presence of a water-gas meniscus was found in all cases to increase clogging, but the full influence of the meniscus could not be measured because of the resolution of our testing. Future experiments will need to utilize very small concentrations of fines in the fluid in order to characterize the full impact of the moving gas/water interface.

The two bulk NGHP-02 specimens (Figure 3) were sieved prior to testing in the micromodel to obtain the fines fraction (particles less than 75 μm). Material from the Site NGHP-02-09 was particularly coarse, with a measured median, d_{50}, grain size of approximately 754 μm. Even after sieving, both NGHP-02-09 and -16 reservoir sediments showed evidence of clogging by single sediment particles (sieving, see Figure 4), as well as by clusters of particles. Both sites showed extremely efficient clogging, meaning clogs formed even for low concentrations of fines in the micromodel fluid. Though there was a slight reduction in clogging as pore-water freshened, NGHP-02 clogging was controlled primarily by particle size, not pore-water chemistry. Because the NGHP-02 sediments showed clogging even at very low particle concentrations in the micromodel fluid, it was not possible to assess the full extent to which a moving gas-water interface could exacerbate clogging.

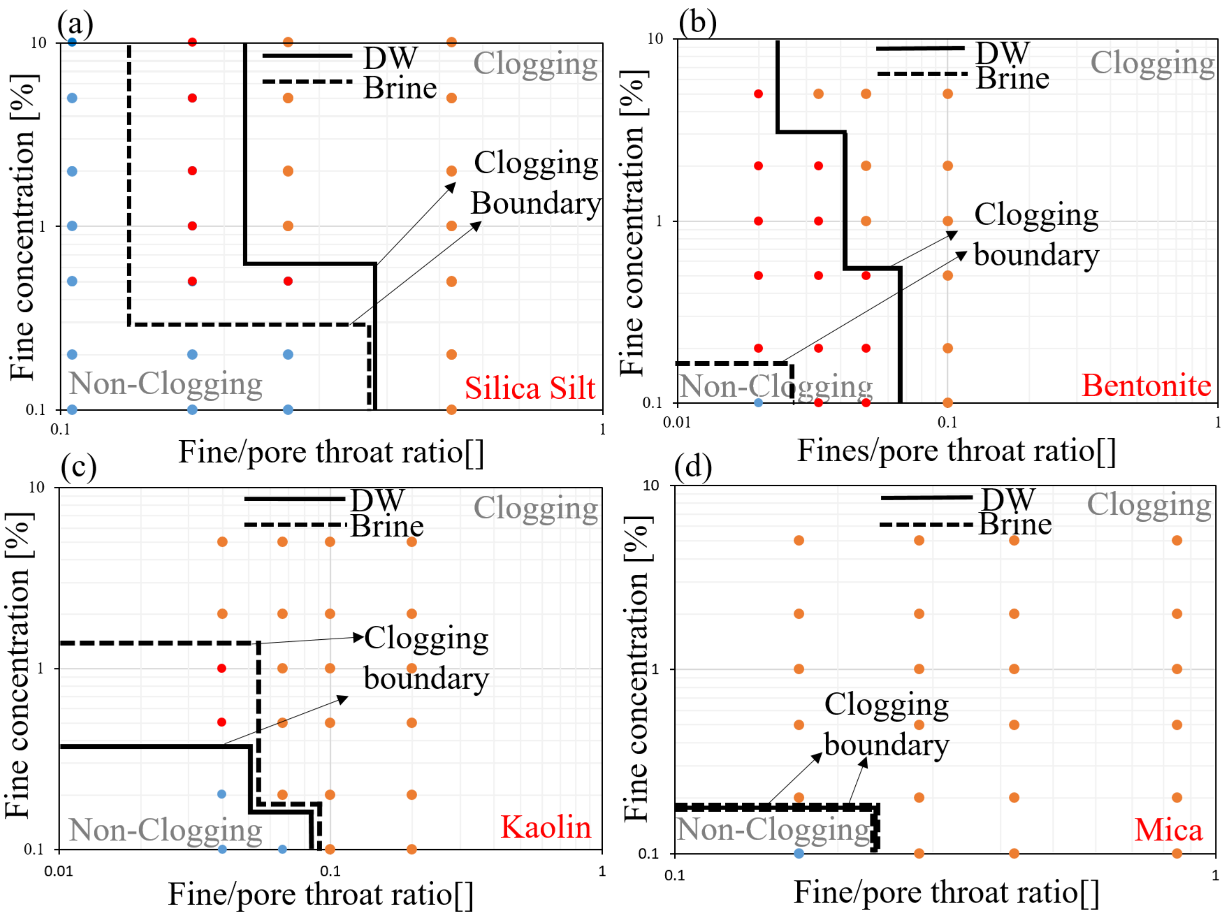

Figure 2: Boundaries between clogging and non-clogging for silica silt, bentonite, kaolin, and mica with fine/pore throat size ratio and fine particle concentration in different pore fluids (Deionized water, DW, and 2 Molar-brine (2M-brine)). Lower left part of each figure represents non-clogging conditions with blue points while the upper right part of each figure represents clogging conditions for both fluids with orange points. Red points between these two extremes represent conditions for which clogging occurs for only one fluid type. (a) Silica silt clogging potential is higher in 2M-brine compared with DW due to positive ions in the 2M-brine attracting silica silt particles into clusters, which are then more prone to clogging, (b) similarly, bentonite particles repel each other in DW and have higher clogging potential in brine due to positive ions in the fluid allowing particles to cluster. The larger gap between the DW and brine boundaries indicates bentonite's high electrical sensitivity to ionic concentration, (c) kaolin has a lower clogging potential in brine due to the smaller face-to-face clusters that form in brines relative to the large edge-to-face clusters that form in DW, (d) Mica, which is a platy particle that clusters similarly to kaolin, also has a lower clogging potential in brine compared to DW. The DW and 2M-brine boundaries, where equivalent, are shown as slightly offset only for ease of viewing.

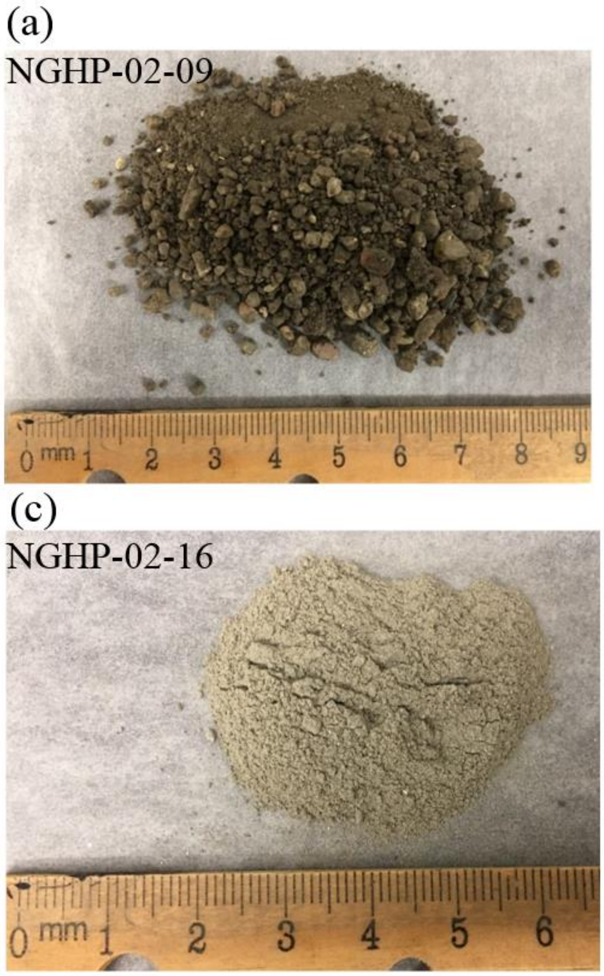

Figure 3: Site NGPH-02 gas hydrate reservoir fine sediments. (a) Oven dried Site NGHP-02-09 specimen which contains grains coarse, $d_{50} \approx 754$ μm. The initial clay content is ~12 % in the bulk specimen. (b) Oven dried Site NGHP-02-09 specimen after dry sieving to obtain only the < 75 μm fines for comparison with the 2D micromodel results for the Site NGHP-02-16 and selected pure fines. (c) Site NGHP-02-16 specimen also contains coarse grains, but $d_{50} \approx 36$ μm indicates significant fines content. (d) Site NGHP-02-16 specimen after dry sieving to obtain only the < 75 μm fines for comparison with the 2D micromodel results for the Site NGHP-02-09 and selected pure fines.

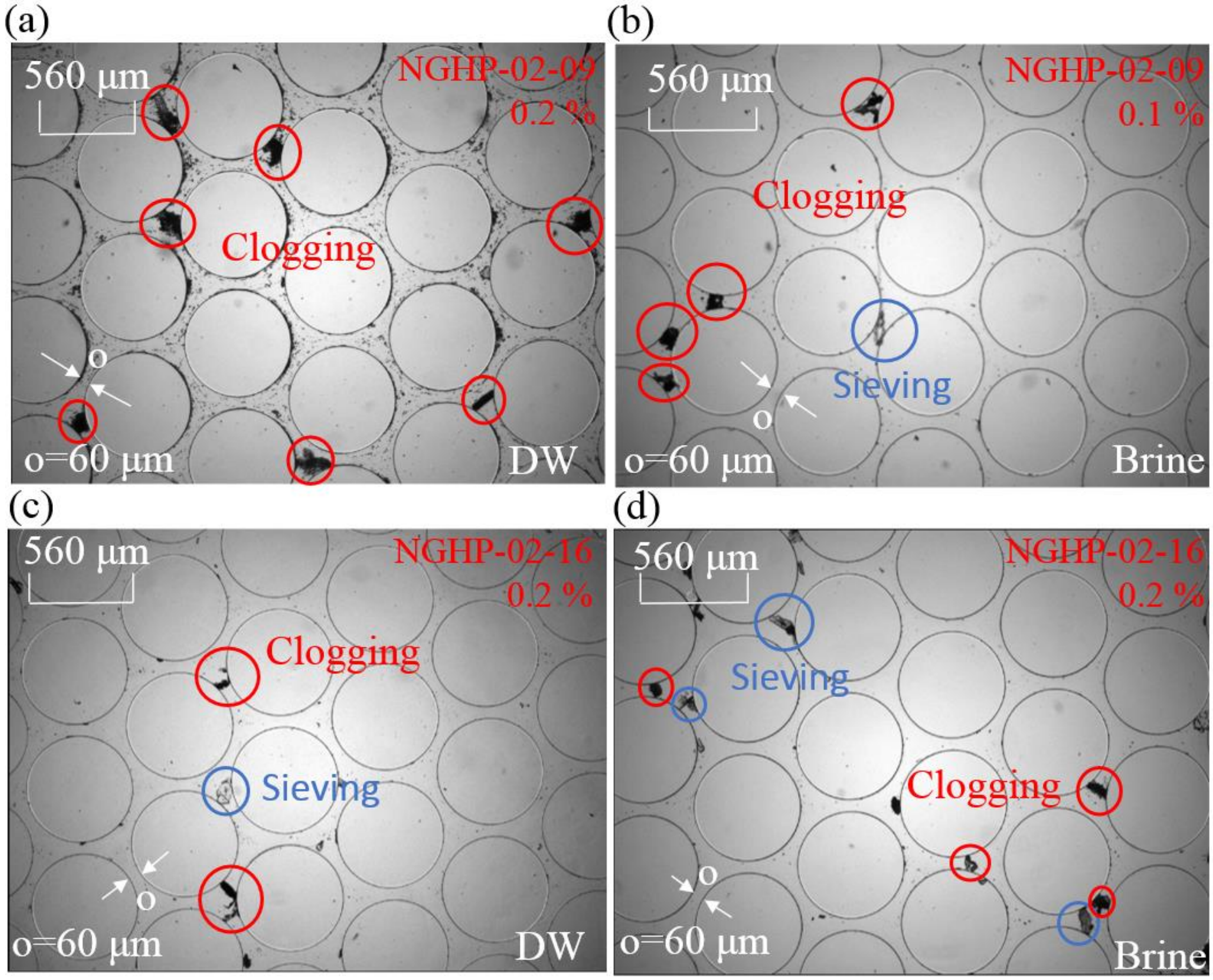

Figure 4: Snapshots of Site NGHP-02-09 and Site NGHP-02-16 sieved fine sediments (d_{50} < 75 μm) with deionized water (DW) and 2 Molar-brine (2M-brine) injection into at the critical clogging concentrations (micromodel pore throat width, o = 60 μm). (a, b) Site NGHP-02-09 fine sediment clogs at 0.2% concentration in DW, but clogs even lower concentrations (0.1%) in 2M-brine, (c, d) Site NGHP-02-16 fine sediment clogs at 0.2% concentration in both DW and brine. The overall experimental result shows both Site NGHP-02-09 and Site NGHP-02-16 fines clogging potential does not increase in DW compared with brine. Two clogging mechanisms are observable: red circles indicate pore throat clogging by clusters of fines. Blue circles indicate pore throat clogging caused by individual fine particles (likely quartz or mica) via a sieving mechanism.

PRODUCTS

2017

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., 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.

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.

2018

(note: NGHP ScienceBase data releases will go live when the NGHP-02 special volume is finalized online)

Cao, S.C., Jang, J., Jung, J., Waite, W.F., Collett, T.S., Kumar, P., 2018. 2D micromodel study of clogging behavior of fine-grained particles associated with gas hydrate production in NGHP-02 gas hydrate reservoir sediments, 2018. *Journal of Marine and Petroleum Geology*. https://doi.org/10.1016/ j.marpetgeo.2018.09.010.

Cao, S.C., Jang, J., Jung, J., Waite, W.F., Collett, T.S., and Kumar, P., 2018b. 2D Micromodel studies of pore-throat clogging by pure fine-grained sediments and natural sediments from NGHP-02, offshore India: *U.S. Geological Survey data release*, https://doi.org/10.5066/P9PZ5M7E.

Jang, J., Cao, S., Stern, L.A., Jung, J., Waite, W.F., Impact of pore-fluid chemistry on fine-grained sediment fabric and compressibility, 2018. *Journal of Geophysical Research, Solid Earth*: Solid Earth, 123, 5495–5514. https://doi.org/10.1029/ 2018JB015872.

Jang, J., Cao, S. C., Stern, L. A., Waite, W. F., and Jung, J., 2018. Effect of pore fluid chemistry on the sedimentation and compression behavior of pure, endmember fines: *U.S Geological Survey Data Release*, https://doi.org/10.5066/F77M076K.

Jang, J., Dai, S., Yoneda, J., Waite, W.F., Stern, L.A., Boze, L.-G., Collett, T.S., Kumar, P., 2018. Pressure core analysis of geomechanical and fluid flow properties of seals associated with gas hydrate-bearing reservoirs in the Krishna-Godavari Basin, offshore India, *Journal of Marine and Petroleum Geology*. https://doi.org/10.1016/j.marpetgeo.2018.08.015.

Jang, J., Dai, S., Yoneda, J., Waite, F. W., Collett, T. S. and Kumar, P. (2018-b). Pressure Core Characterization Tool Measurements of Compressibility, Permeability, and Shear Strength of Fine-Grained Sediment Collected from Area C, Krishna-Godavari Basin, during India's National Gas Hydrate Program Expedition NGHP-02: *U. S. Geological Survey data release*, https://doi.org/10.5066/P91XJ7DP

Jang, J., Waite, W.F., Stern, L.A., Collett, T.S., Kumar, P., Impact of fine-grained sediment on the nature and development of a gas hydrate reservoir system investigated during NGHP-02 in the Krishna-Godavari Basin, offshore eastern India (in review), *Journal of Marine and Petroleum Geology*.

Jang, J., Waite, F. W., Stern, L. A., Collett, T. S. and Kumar, P., 2018b. Dependence of sedimentation behavior on pore-fluid chemistry for sediment collected from Area B, Krishna-Godavari Basin during India's National Gas Hydrate Program, NGHP-02: *U. S. Geological Survey data release*, https://doi.org/10.5066/P9FXJ1VX.

APPENDIX: PROJECT TIMELINE & MILESTONE TRACKING

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

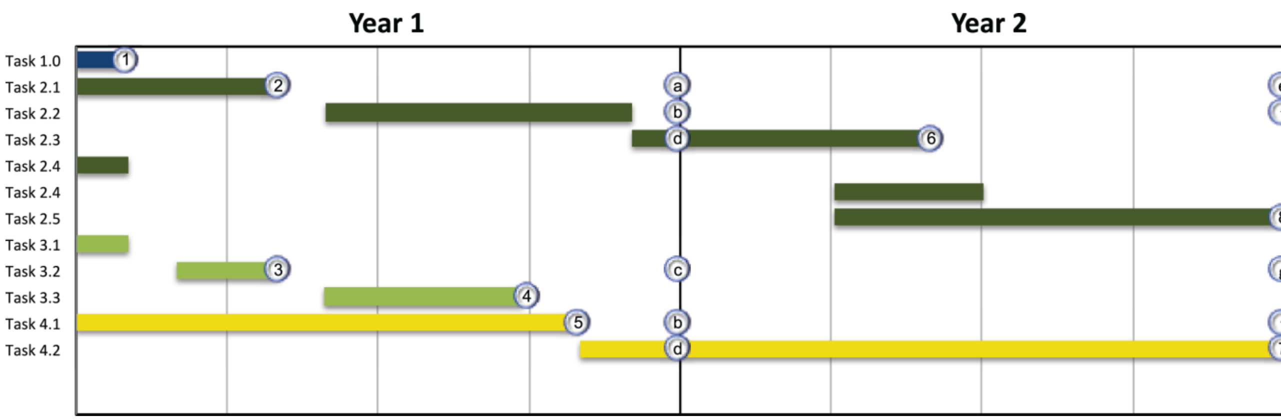

Figure A1: Updated project timeline, including times of activity (color bars), Milestones (numbered circles) and Success Criteria (lettered circles). A complete list of Milestones and Success Criteria are given below.

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: Due to logistical challenges regarding fabrication of the micromodels (all models were built by hand by S. Cao at LSU), all micromodel studies were shifted to LSU. See Milestone 7.

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.

Status: *2D micromodel studies on NGHP-02 fines have been completed, including data about mechanical clogging processes. A manuscript has been accepted by the Journal of Marine and Petroleum Geology for inclusion in their special volume covering the NGHP-02 program. Manuscript accepted in Year 2, 4Q (Joint with Task 4.2). Micromodel data has been captured in a reviewed U.S. Geological Survey ScienceBase online data release, complete with metadata.*

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.

    Status: *In situ results for compressibility and permeability were released in the NGHP-02 pressure core manuscript "Pressure core analysis of geomechanical and fluid flow properties of seals associated with gas hydrate-bearing reservoirs in the Krishna-Godavari Basin, offshore India" by Jang et al. (see "Products"). Ongoing tests across a suite of pore fluids will be incorporated into the findings of our work in the DOE-sponsored GOM² project with U. Texas:*

    https://www.netl.doe.gov/research/oil-and-gas/methane-hydrates/2017-gulf-of-mexico-drilling-and-coring-expedition

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.

   Status: Two publications provide index property, liquid limit, compressibility and permeability results from NGHP-02 sediment, both submitted to the Journal of Marine and Petroleum Geology. The Jang et al. paper "Pressure core analysis of geomechanical and fluid flow properties of seals associated with gas hydrate-bearing reservoirs in the Krishna-Godavari Basin, offshore India" has been accepted. The Jang et al manuscript "Impact of fine-grained sediment on the nature and development of a gas hydrate reservoir system investigated during NGHP-02 in the Krishna-Godavari Basin, offshore eastern India" has been revised and is in review. Data for both manuscripts are available online through the USGS ScienceBase portal.

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.

Status: Manuscript has been accepted by the Journal of Marine and Petroleum Geology. Data are available online through the USGS ScienceBase portal.

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.

Status: Manuscript has been published by the Journal of Geophysical Research: Solid Earth. Data are available online through the USGS ScienceBase portal.

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

13131 Dairy Ashford Road, Suite 225
Sugar Land, TX 77478

1450 Queen Avenue SW
Albany, OR 97321-2198

Arctic Energy Office
420 L Street, Suite 305
Anchorage, AK 99501

Visit the NETL website at:
www.netl.doe.gov

Customer Service Line:
1-800-553-7681

NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY