NATIONAL ENERGY TECHNOLOGY LABORATORY

OIL & GAS

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Research Performance Progress Report (Period Ending 12/30/2018)

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

Project Period (10/1/2016 to 12/30/2018)

Submitted by:
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Signature

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

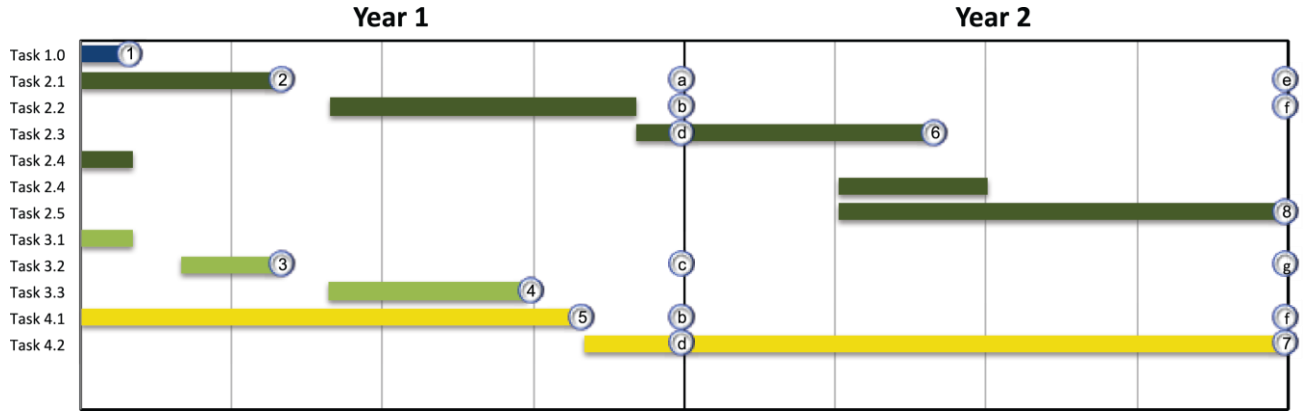

Figure 1: Project timeline, including times of activity (color bars), Milestones (numbered circles) and Success Criteria (lettered circles). A complete list of Milestones and Success Criteria are given in the Appendix.

This quarterly report covers the final calendar quarter of 2018, which is the next quarter beyond the fourth quarter of the Project's "Year 2" calendar above. This quarter's activities extend the Project Activities in Task **2** (Site-specific analysis: fines impact on compressibility and permeability) and Subtask **3.3** (Dependence of compressibility and permeability on pore-fluid chemistry in pure, endmember fines). A summary of accomplishments for each Task is provided below, along with key results from presentations made at the Fall 2018 American Geophysical Union Conference.

Task 2: Site-specific analysis: fines impact on compressibility and permeability

This quarter, results from 2D micromodel studies on sediment from the Ulleung Basin (collected during UBGH-2) were presented at the Fall 2018 American Geophysical Union Conference. Pore-water salinity was varied

in these studies, but a key finding is that for fixed concentrations of fines, clogging potential was not strongly dependent on salinity. The clogging potential was fairly high for the UBGH-2 sediments we tested (all of which were recovered from fine-grained interbeds within the gas hydrate-bearing reservoir interval), with the dominant clogging processes being mechanically driven rather than depending strongly on pore-fluid chemistry effects. For example, in addition to the fine-grained muds present in these interbeds, diatoms were common, and these diatoms could clog even the 100 micrometer pore throats via sieving (Figure 2)

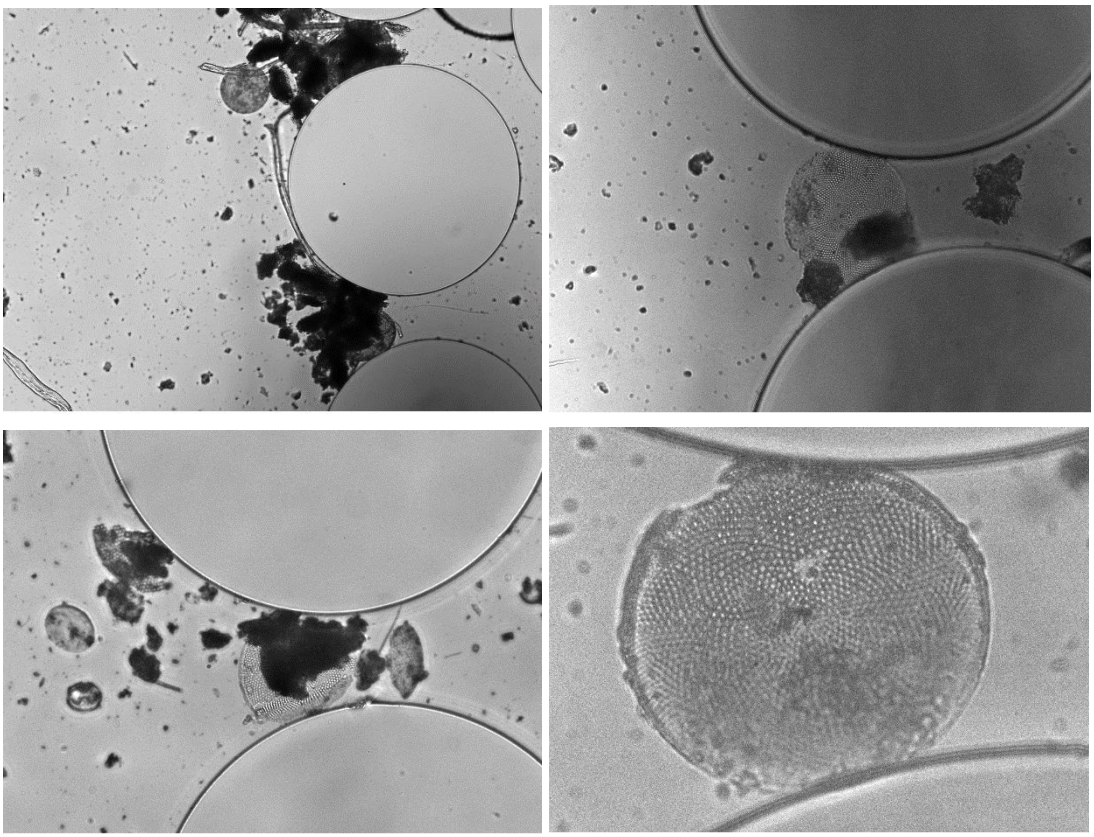

Figure 2: Diatoms mechanically clogging pore throats in a 2D micromodel. Pore throat width is 100 micrometers in all cases. Upper left: Large circle represents a sediment "grain," and UBGH-2 sediment can be seen clogging the pore throats between the "grains." The UBGH-2 sediment is diatom rich. The diatoms are the lighter, translucent disc and rod shapes. Upper Right and Lower Images: Individual disc-shaped diatoms clogging pore throats. This mechanical style of clogging is defined as "sieving."

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

In this quarter, we conducted liquid limit and compressibility tests on endmember fines as a function of pore-water salinity to establish the impact of fines on the overall reservoir compressibility during production. As shown in Figure 3, the changes in liquid limit in diatoms, mica and silica silt is smaller than those in bentonite and kaolin. The changes in bentonite are the most significant among the fines tested within this study.

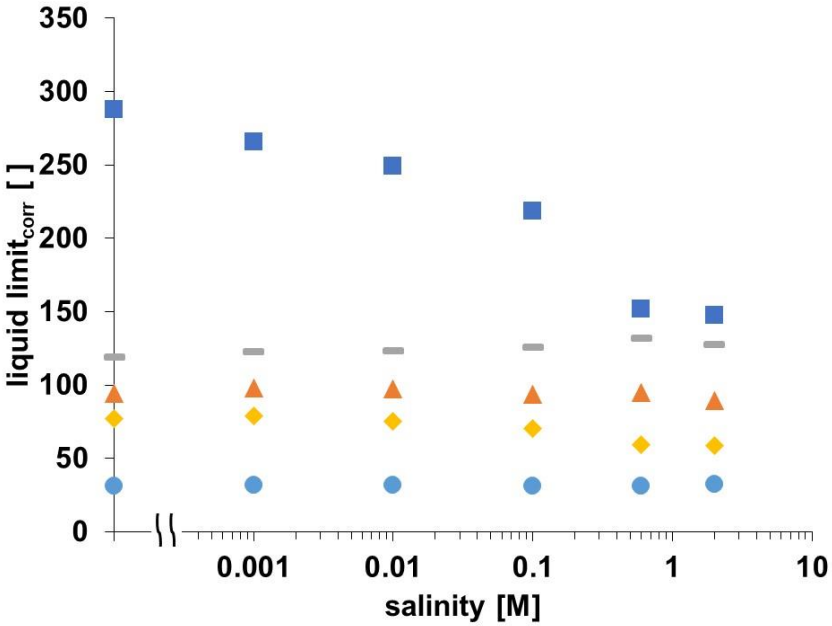

Figure 3: Dependence of liquid limit on salinity for a selection of pure fines (legend: light blue circle – silica silt, orange triangle – mica, gray bar – diatoms, yellow rhomboid – kaolin, dark blue square – bentonite). With the exception of bentonite, the liquid limits for the tested fines is essentially independent of salinity.

After the liquid limit tests, we conducted compressibility on diatoms, silica silt, kaolin and bentonite. We used incremental loading 1-D consolidation tests at four salinities: deionized water, 0.01M, 0.6M, 2M. The compressibility scales with the initial void ratio, which itself is determined by the liquid limit. At high vertical stress (1MPa), however, the void ratio converges to a terminal void ratio that is independent of salinity.

At low effective stress, the salinity affects the initial fabric and determines the compressibility. This occurs for different reasons and with opposite effects that depend on the type of fine being studied. In silica silt and diatoms, ions in the brine can cause the fines to form more compressible sediment fabrics (e.g. Figure 3, showing increased compressibility with increasing salinity for silica silt and diatoms). The kaolin and bentonite, on the other hand, are more compressible in low ionic concentration pore water because the lack of pore-water ions allows kaolin and bentonite to form open, loose fabrics (Figure 4).

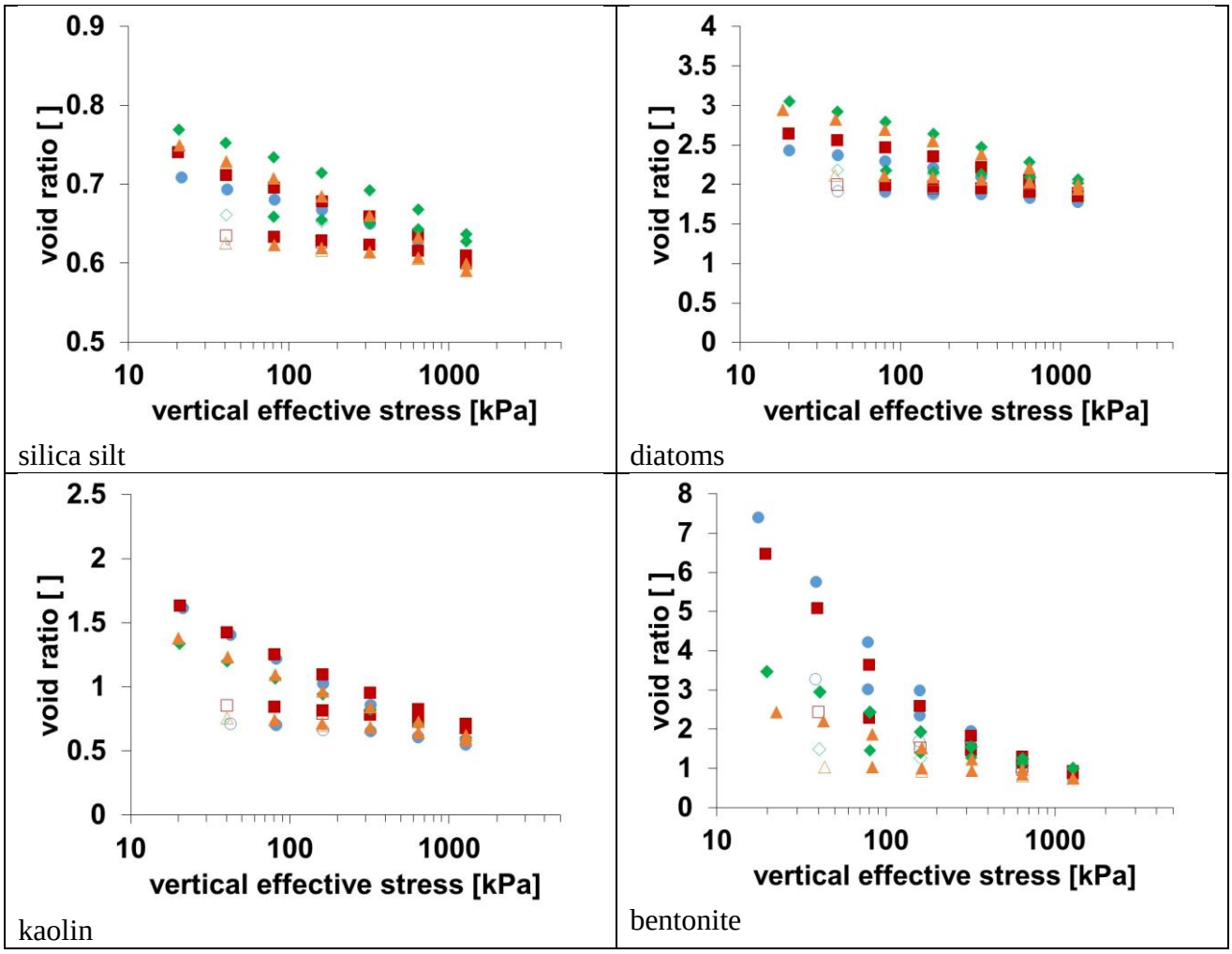

Figure 4: Dependence void ratio on effective stress for a selection of pure fines (legend: blue circle – deionized water, red square – 0.01M, orange triangle – 0.6M, green rhomboid – 2M). Steeper slopes mean higher compressibilities. Note that while silica silt and diatoms become more compressible with increasing ionic concentration, the opposite occurs for kaolin and bentonite. Above 1 MPa effective stress, salinity-based compressibility differences are minimized.

For deepwater systems that require significant depressurization to initiate gas hydrate dissociation, the imposed effective stresses will exceed 1MPa. For the NGHP-02 reservoir modeling, for instance, effective stresses between 10 and 25 MPa were applied (e.g Boswell et al., Konno et al., Myshakin et al., and Moridis et al., 2018, Journal of Marine and Petroleum Geology, special volume covering NGHP-02 – all in press). Above 1 MPa, Figure 4 suggests salinity impacts on the compressibility of fine-grained sediments would be minimal.

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., Boze, L.G., Jung, J., Waite, W.F, 2018. Volume change in fine-grained sediments due to pore water salinity changes: gas hydrate-bearing sediments and pore water freshening during gas hydrate dissociation, presented poster at: Fall American Geophysical Conference, December 9-14, 2018, Washington D.C.

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.

Jung, J., Cao, S., Jang, J., Waite, W.F., Lee, J.Y., 2018. Clogging behavior of fines associated with gas hydrate production, from pure fines to NGHP-02 and UBGH-02 reservoir fines, presented talk at: Fall American Geophysical Conference, December 9-14, 2018, Washington D.C.

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.

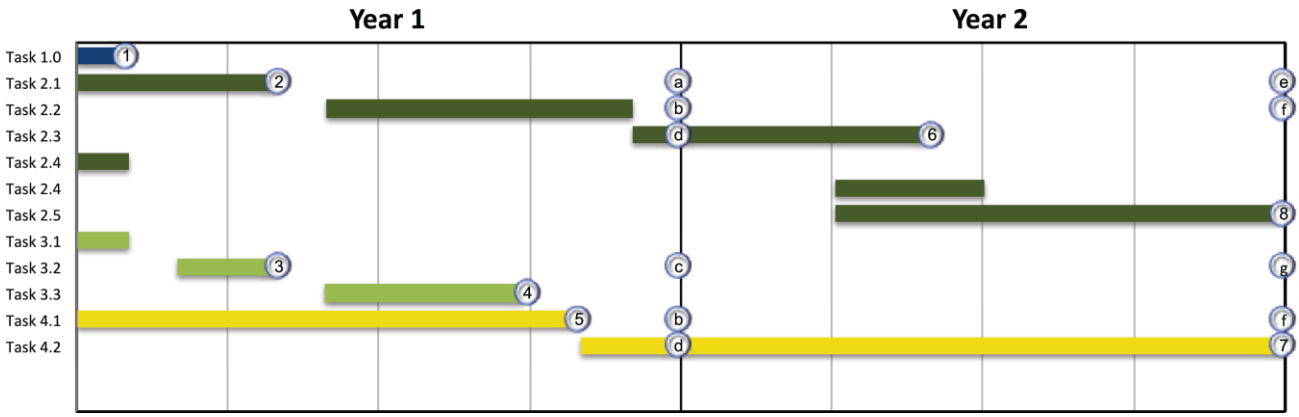

Figure A1: Updated project timeline, including times of activity (color bars), Milestones (numbered circles) and Success Criteria (lettered circles). A complete list of Milestones and Success Criteria are given below.

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.

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