NATIONAL ENERGY TECHNOLOGY LABORATORY

OIL & GAS

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Research Performance Progress Report (Period Ending 3/31/2019)

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

Project Period (10/1/2016 to 3/31/2019)

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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 project's final quarter. A full list of milestones and Success Criteria is provided in the Appendix.

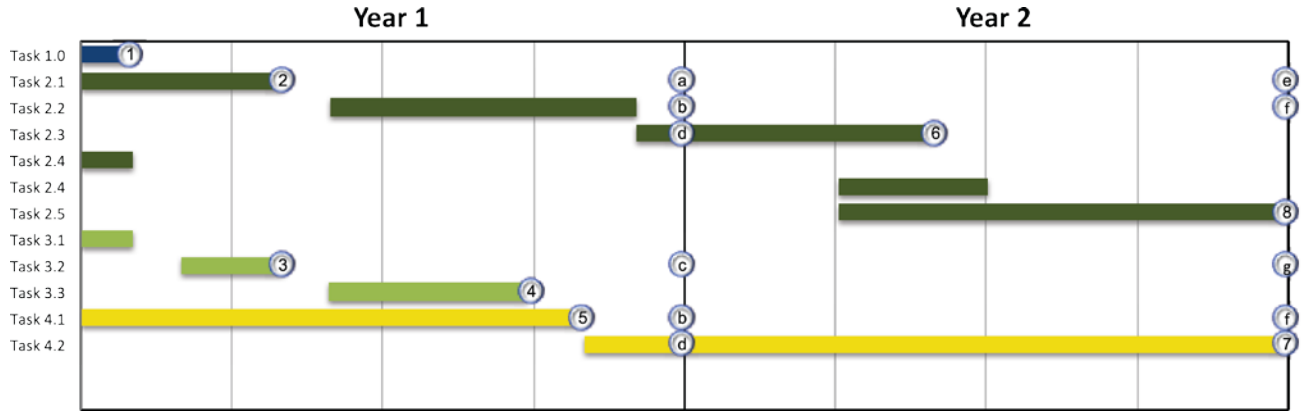

Figure 1: Project timeline, including times of activity (color bars), Milestones (numbered circles) and Success Criteria (lettered circles). A complete list of Milestones and Success Criteria are given in the Appendix.

This quarterly report covers the project's final calendar quarter. 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). Activities this quarter were limited by the month-long partial federal shutdown, which included the U.S. Geological Survey. A summary of accomplishments for each Task is provided below, along with key results from a manuscript submitted to the journal *Interpretations*.

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

This quarter, a synthesis manuscript was submitted to the journal *Interpretations*. One of the key findings regarding fine-grained sediments that has been emerging over the course of this project is the significance

of fine-grained sediment overlying a coarse-grained gas hydrate-bearing reservoir. As shown in Figure 2, the in situ permeability of the overlying sediment is lower than that in the gas hydrate-bearing reservoir, even with the reservoir's pore-space highly saturated by gas hydrate. Researchers have noted the negative impact on production that occurs when sediment overlying the gas hydrate-bearing reservoir has a finite permeability and does not act as a perfect seal (e.g. Ajayi et al., 2018, https://doi.org/10.1016/j.jngse.2017.12.026, and also Konno et al., 2018, https://doi.org/10.1016/j.marpetgeo.2018.08.001). The manuscript

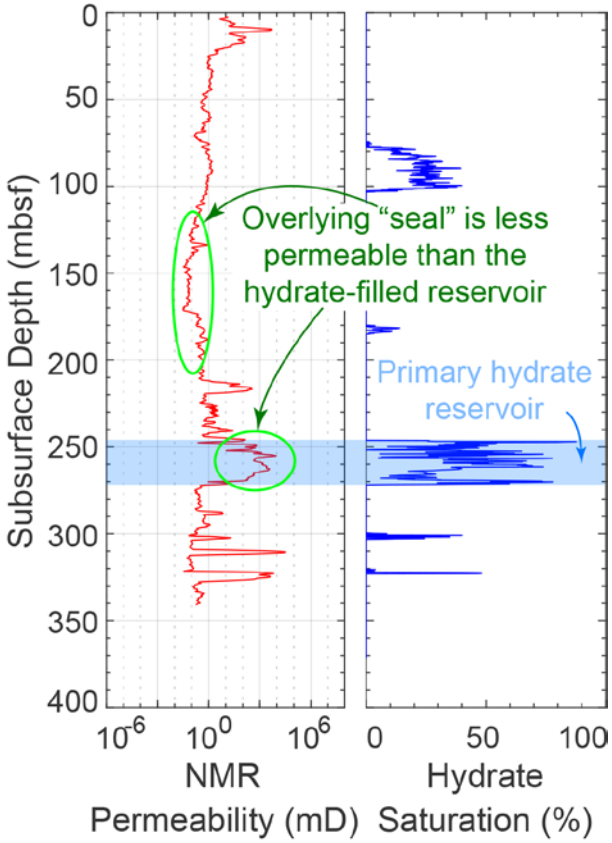

Figure 2: Logging-while drilling data for site NGHP-02-08, showing in situ permeability estimated from the downhole nuclear magnetic resonance tool (NMR), and the Archie-based, pore-space gas hydrate saturation estimate. The primary coarse-grained hydrate reservoir is shaded in blue. Even with the high hydrate saturations hosted in that sediment, the estimated permeability is higher than is estimated for the hydrate-free, fine-grained "seal" sediment overlying the reservoir. Note that hydrate saturation estimates outside of the coarse-grained interval indicate primarily gas hydrate veins in fine-grained sediment, a morphology that tends to cause the Archie approach to overestimate gas hydrate saturation.

submitted to *Interpretations* provides an overview of the NGHP-02 physical property testing that illustrates why the community should consider fine-grained sediment overlying a coarse-grained gas hydrate reservoir as the "seal" element in the gas hydrate petroleum systems approach (GHPS). Currently, the GHPS approach assumes the reservoir itself provides the "seal" that is largely responsible for retaining methane within the reservoir and preventing fluid invasion during production.

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

In this quarter, we extended the effort in this task beyond the project scope (NGHP-02, offshore India) with continued work on a peer-reviewed, journal manuscript for micromodel observations made on sediment from the UBGH-2 expedition offshore Korea.

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

In this quarter, we continued compressibility tests on mixtures of coarser sediments (silica silt) with endmember fines as a function of pore-water salinity to establish the impact of fines on the overall reservoir compressibility during production. Moving beyond the timeframe of this project, the compressibility data is intended for a peer-reviewed journal publication that provides an overview, or "map" of the compressibility effects fines have as a function of fines type, fines concentration, effective stress, and pore-water salinity.

Compressibility will be a significant issue moving forward because as noted in a previous update, deepwater systems will likely require significant depressurization to initiate gas hydrate dissociation. For the NGHP-02 reservoir modeling, for instance, effective stresses between 10 and 25 MPa were applied (e.g Boswell et al., 2018, https://doi.org/10.1016/j.marpetgeo.2018.09.026; Konno et al., 2018, https://doi.org/10.1016/j.marpetgeo.2018.08.001; Myshakin et al., 2018, https://doi.org/10.1016/j.marpetgeo.2018.10.047; and Moridis et al., 2018, https://doi.org/10.1016/j.marpetgeo.2018.12.001).

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.

2019

Jang, J., Waite, W.F., Stern, L.A., Gas hydrate petroleum systems: what constitutes the "seal?". Manuscript submitted to the SEG/AGU collaborative journal *Interpretations*.

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.

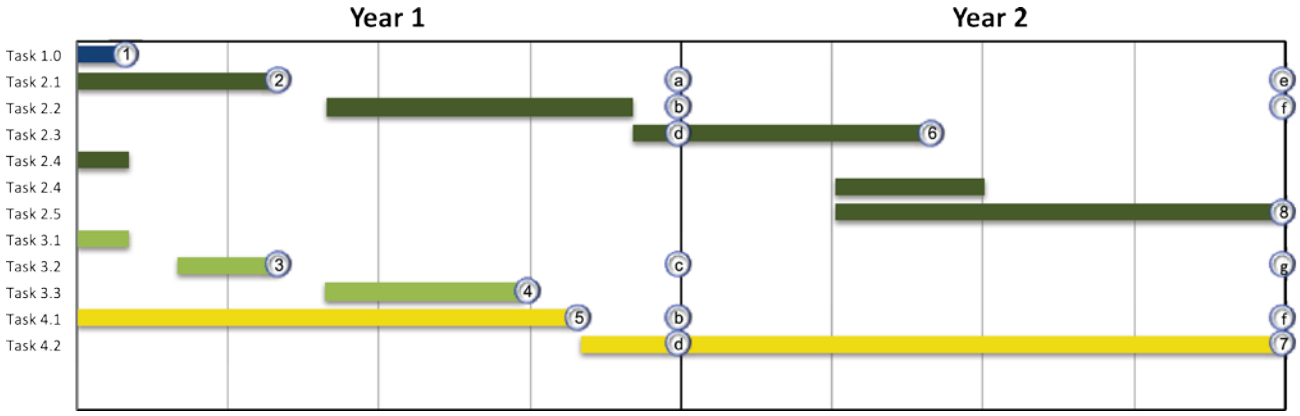

Figure A1: Updated project timeline, including times of activity (color bars), Milestones (numbered circles) and Success Criteria (lettered circles). A complete list of Milestones and Success Criteria are given below.

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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