Research Performance Progress Report

SUBMITTED TO

U. S. Department of Energy
National Energy Technology Laboratory

WORK PERFORMED UNDER AGREEMENT

DE-FE0013919

Project title: **Mechanisms for Methane Transport and Hydrate Accumulation in Coarse-Grained Reservoirs**

SUBMITTED BY
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July 29, 2014

DUNS number: 1702302390000

RECIPIENT ORGANIZATION
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PROJECT PERIOD: October 1, 2013 – September 30, 2017

REPORTING PERIOD END DATE: June 30, 2014

REPORT FREQUENCY: Quarterly

Signed:

Hugh Daigle

ACCOMPLISHMENTS

The project **goal** is to show, through numerical modeling, how the transport of methane, and the mechanism by which it is transported, control the development of persistent, massive hydrate accumulations in deep sediments below the seabed. The models will be based on recently collected data from Walker Ridge Block 313 (WR 313) in the northern Gulf of Mexico (Figure 1). To achieve the project goal, the project has been divided into three phases. Phase 1 of the project will focus on modifying an existing reservoir simulator (Sun and Mohanty, 2006) to include microbial methane production, salt mass balance and effects on methane stability, and sedimentation. Additional 1-D modeling will provide constraints on expected rates of methanogenesis. Phase 2 of the project will focus on simulations of dissolved methane migration mechanisms to determine if sufficient flux is available to develop the massive hydrate accumulations observed at WR 313. Phase 3 of the project will focus on simulations of free methane gas migration and recycling of methane in the gas phase as it is buried below the base of the methane hydrate stability zone.

The **objectives** of this project are to define:

1. The dissolved methane flux, organic matter abundance, and time required to develop the accumulations observed at WR 313 by short-distance migration of microbial methane into adjacent coarser-grained layers;
2. The dissolved methane flux and time required to develop the accumulations observed at WR 313 by long-distance, updip migration;
3. Whether there is enough methane in the dissolved phase in the fine-grained sediments to form the observed hydrate deposits or whether a gas phase is present, and if so what the conditions are for three-phase equilibrium;
4. The fate of hydrate that subsides beneath the base of the MHSZ and accumulates as gas, and overpressure generation associated with gas accumulation.

Tasks to be performed
PHASE 1 / BUDGET PERIOD 1
Task 1 - Project management and planning

The Recipient shall work together with the DOE project officer upon award to develop a project management plan (PMP). The PMP shall be submitted within 30 days of the award. The DOE Project Officer shall have 20 calendar days from receipt of the PMP to review and provide comments to the Recipient. Within 15 calendar days after receipt of the DOE's comments, the Recipient shall submit a final PMP to the DOE Project Officer for review and approval.

The Recipient shall review, update, and amend the PMP (as requested by the DOE Project Officer) at key points in the project, notably at each go/no-go decision point and upon schedule variances of more than 3 months and cost variances of more than 10%, which require amendments to the agreement and constitutes a re-base lining of the project.

The PMP shall define the approach to management of the project and include information relative to project risk, timelines, milestones, funding and cost plans, and decision-point success criteria. The Recipient shall execute the project in accordance with the approved PMP covering the entire project period. The Recipient shall manage and control project activities in accordance with their established processes and procedures to ensure subtasks and tasks are completed within schedule and budget constraints defined by the PMP. This includes tracking and reporting progress and project risks to DOE and other stakeholders.

Task 2 – Reservoir Model Development

The Recipient shall modify an existing general purpose reservoir simulator to include sedimentation, microbial methane production and effect of salt on hydrate equilibrium. The methane equilibrium calculation shall be modified to include changes in water activity due to dissolved salt following the method of Handa (1990). The mass conservation calculation shall be modified to include sedimentation, burial, and changes in porosity over time following the method of Bhatnagar et al. (2007). The initial conditions shall be modified to allow specification of heterogeneous properties (e.g., porosity) throughout the model domain. The boundary conditions shall be modified to allow specification of seafloor sedimentation rate and fluid flux. The Recipient shall verify code modifications with benchmark comparisons of performance with published simulation results (e.g., Bhatnagar et al., 2007).

Task 3 – 1-D Modeling of Microbial Methanogenesis

Concurrently with Task 2, the Recipient shall start with a 1-D reaction-transport model that will follow the burial by sedimentation of a sand layer surrounded by fine-grained sediments. The time-dependent modeling shall track the evolution of gas hydrate formation in the sand layer and shall provide more accurate estimates of the time scales and of the gas hydrate quantities associated with short migration. The methane hydrate stability conditions shall include the effect of pore size in the sand and fine-grained layers following the method of Malinverno (2010). The rate and spatial distribution of microbial methanogenesis shall be constrained by data from scientific ocean drilling expeditions (DSDP, ODP, IODP). The results of this task shall provide first-order constraints on rates of methanogenesis which shall be used as inputs to subsequent tasks (4.1, 4.3, 5.1, 5.2).

PHASE 2 / BUDGET PERIOD 2

Task 4.1 – Short Migration of Dissolved Methane

The Recipient shall investigate short migration of dissolved methane, in which methane generated in fine-grained sediments within the MHSZ is transported by diffusion into adjacent coarse-grained layers in which it forms concentrated hydrate deposits. The simulator developed in Task 2 shall be used for this task. The model domain shall consist of dipping sand layers surrounded by fine-grained sediments. This domain shall be designed to approximate the geometries observed at WR313 with sediment physical properties defined from logs or analog data. Rates of microbial methanogenesis and fluid flow shall be altered to determine the effect each has on the resulting hydrate distribution and time required for accumulation. The model results shall be used to determine the time scale of short migration at WR313, and the distribution of hydrate resulting from short migration.

Task 4.2 – Long Migration of Dissolved Methane

The Recipient shall investigate long migration of dissolved methane, in which dissolved methane is transported by advection from a distant source to the MHSZ. The investigation shall use the simulator developed in Task 2. The model domain shall consist of dipping sand layers surrounded by fine-grained sediments, and shall be designed to approximate the geometries observed at WR313. The model shall assume no local methane generation in the MHSZ and pore water entering the MHSZ with a methane concentration equal to the local solubility. Fluid flux shall be determined assuming that fluid flow is driven by overpressures to due high sedimentation rates (Gordon and Flemings, 1998). The Recipient shall explore the time scale associated with long migration by determining how long is required for fluid flow to form hydrate deposits comparable to those observed at WR313. The Recipient shall additionally simulate situations in which active fluid flow ceases after some time, and investigate how the hydrate that is formed evolves after cessation of fluid flow.

Task 4.3 – Assessment of Flux Associated with Dissolved Methane Migration

The Recipient shall use the model results from Tasks 4.1 and 4.2 to assess the methane flux associated with methane migration in the dissolved phase by either long or short migration. The different scenarios modeled in Tasks 4.1 and 4.2 shall be analyzed to determine methane flux from each migration mechanism, and the time scales and hydrate volumes produced by each. The analysis results shall be compared to the observed hydrate accumulations at WR313 and the age of the host sediments to determine whether migration of dissolved methane could have produced the observed hydrate accumulations.

PHASE 3 / BUDGET PERIOD 3

Task 5.1 – Assessment of Methane Budget Required for Presence of Gas Phase

The Recipient shall use the results of Tasks 4.1 and 4.2 to define methane availability from local, microbial sources as well as deeper sources (thermogenic or microbial). The phase equilibrium implemented in the 3-D model in Task 2 shall be used to determine local solubility within the model domain and determine the amount of methane that may be present as a gas phase. The results of this task will be used to place limits on gas availability in Tasks 5.2 and 5.3.

Task 5.2 – Free Gas Migration

The Recipient shall apply a previously established model of hydrate formation (multiphase-flow-controlled, nonequilibrium, neglecting transport of salinity and latent heat) to assess whether the gas phase accumulated beneath the MHSZ can contribute significantly to hydrate saturations within the MHSZ. The Recipient shall evaluate the conditions under which the accumulated gas phase drains into coarse-grained sediment. Having identified those conditions, the Recipient shall evaluate the geologic setting (dip angle, petrophysical properties and multiphase flow properties of the sediment) for which significant updip migration of the gas phase can be expected. The Recipient shall apply the hydrate formation model to geologic settings with significant expected migration to determine the hydrate saturation distribution in the updip direction. The model shall be tested for ranges of the two competing rates (namely, rate of gas accumulation at base of MHSZ and rate of hydrate formation from gas phase and water phase in the MHSZ). The Recipient shall additionally determine the pressure, temperature, and salinity conditions that will permit short migration of a gas phase within the MHSZ. The predicted saturation distributions shall be compared to observations (magnitude of hydrate saturation and its lateral extent) within coarse-grained layers at WR313. If hydrate is predicted to form in the same location and same volume as the accumulations observed at WR313, the Recipient shall determine whether the conditions that give agreement are geologically plausible, and the Recipient shall compare the flux of methane in the gas phase to the fluxes of methane by other mechanisms to be determined in Tasks 4.1 and 4.2. If the rates of methane delivery and time scale of hydrate accumulation are consistent with the accumulations observed at WR313, the Recipient shall use the results to guide the inclusion of free-gas migration phenomena into the full-physics 3D simulations of Task 5.3.

Task 5.3 – Methane Recycling at the Base of the MHSZ

The Recipient shall use the reservoir model developed in Task 2 to evaluate the fate of hydrate that moves below the base of the MHSZ as a result of sedimentation. In particular, the Recipient shall examine subsidence of dipping, hydrate-bearing sands of the type encountered at WR313. The Recipient shall model burial of a dipping sand layer through the base of the MHSZ in 3 dimensions. The Recipient shall test different scenarios of sedimentation rate, hydrate saturation in sand layers, and deep methane flux to evaluate gas accumulation below the MHSZ, supply of methane to the base of the MHSZ, and overpressure generated by the accumulation of a connected gas column. The gas column will be considered connected when it overcomes a percolation threshold of roughly 10% of the pore volume (England et al., 1987). Gas phase pressure shall be computed from gas column height and estimates of capillary pressure from analog sediments (e.g., Blake Ridge; Clennell et al., 1999). The potential to fracture overlying sediments shall be investigated by comparing the resulting pore pressure to the total vertical stress and the minimum horizontal stress.

Milestone Status Report

1.A Title: PMP submission
Planned Date: 4 December 2013
Completed Date: 22 November 2013
Verification Method: Submission of final Project Management Plan to DOE within 65 days of start of project.

1.B Title: Project kick-off meeting
Planned Date: 29 December 2013
Completed Date: 7 November 2013
Verification Method: Meeting held within 90 days of start of project.

1.C Title: Sedimentation, microbial methane production, salinity effect implementation
Planned Date: 30 June 2014
Verification Method: Implementation of sedimentation, microbial methane production, salinity effect on hydrate stability in 3-D model.

1.D Title: Benchmarking of numerical model against published results
Planned Date: 31 March 2015
Verification Method: Simulation results match those obtained from other simulators in 1-D and 2-D (e.g., Bhatnagar et al., 2007; Chatterjee et al., 2011) within 1% in time and hydrate saturation using the same input parameters.

1.E Title: Development of time and methanogenesis constraints for future modeling
Planned Date: 31 March 2015
Verification Method: Development of a model that includes time-dependent changes in methane stability in a dipping, subsiding sand layer but matches the results of Cook and Malinverno (2013) for steady-state conditions.

2.A Title: Completion of short migration modeling
Planned Date: 30 September 2016

Verification Method: Completion of simulations to evaluate conditions necessary for development of massive hydrate deposits by short migration.

2.B Title: Completion of long migration modeling
Planned Date: 30 September 2016
Verification Method: Completion of simulations to evaluate conditions necessary for development of massive hydrate accumulations by long migration.

2.C Title: Quantification of methane flux in the dissolved phase
Planned Date: 30 September 2016
Verification Method: Quantification of methane flux associated with methane migration in the dissolved phase by either long or short migration and comparison with existing estimates of methane flux in the northern Gulf of Mexico such as those presented in Frye (2008).

3.A Title: Quantification of methane availability and expected quantities of gas
Planned Date: 30 September 2017
Verification Method: Quantification of amount of methane required to form a free gas phase and comparison with existing estimates of methane flux in the northern Gulf of Mexico such as those presented in Frye (2008).

3.B Title: Completion of free gas migration models
Planned Date: 30 September 2017
Verification Method: Determinations of methane flux and time necessary to reproduce observed hydrate accumulations at WR313 by migration of free gas.

3.C Title: Completion of modeling efforts to assess methane recycling
Planned Date: 30 September 2017
Verification Method: Completion of simulations to assess rates of gas accumulation beneath MSHZ and effect on gas migration and overpressure generation.

What was accomplished under these goals?

Major activities

Work on Task 2 continued. We successfully implemented mass balances for sediment, microbial methane production, and salinity in the model (Milestone 1.C). Mass balances were implemented with an implicit forward in time, centered in space (FTCS) using the following equations:

Sediment:

$$\frac{\partial}{\partial t}\left[(1-\varphi)\rho_s\right]+\nabla.\left[(1-\varphi)\rho_s v_s\right]=0\,, \qquad \text{(Eq. 1)}$$

Organics:

$$\frac{\partial}{\partial t}\left[(1-\varphi)\rho_s b\right]+\nabla.\left[(1-\varphi)\rho_s v_s b\right]=-(1-\varphi)\rho_s br\,, \qquad \text{(Eq. 2)}$$

Salt:

$$\frac{\partial}{\partial t}\left[\varphi S_w \rho_w w_s\right]+\nabla.\left[\rho_w v_w w_s\right]=0\,, \qquad \text{(Eq. 3)}$$

where t is time [s], φ is porosity [m^3/m^3], ρ_s is sediment grain density [kg/m^3], v_s is sedimentation rate [m/s], b is the organic fraction in the sediments [kg/kg], r is the rate at which it is consumed for microbial methane production [kg/kg·s], S_w is fraction of pore volume filled with water [m^3/m^3], ρ_w is water density, w_s is mass fraction of salt dissolved in water [kg/kg], and v_w is the fluid flow rate [m/s]. We are now working on benchmarking our code against existing simulation results (e.g., Bhatnagar et al., 2007).

Work on Task 3 continued. Malinverno assembled particulate organic carbon (POC) measurements obtained by scientific ocean drilling in Gulf of Mexico sediments (Figure 1). POC content has been measured in 26 drill holes during legs 1, 10, and 77 of the Deep Sea Drilling Project and Expedition 308 of the Integrated Ocean Drilling Program. Nine drill holes have reliable sediment age determinations (yellow dots in Figure 1). The decrease with depth and age of sedimentary POC due to microbially-mediated organic matter remineralization constrains the total amount, rate, and vertical distribution of microbial methanogenesis. A quantified in situ methane source will be a key modeling input to test whether local diffusion of microbial methane can explain gas hydrate accumulations in sand layers.

Cook and PhD student Deborah Glosser worked on developing a 1-D reaction-transport model that will follow the burial by sedimentation of a sand layer surrounded by fine-grained sediments. Methane solubility calculations were successfully implemented in this model along with mass balance for microbial methanogenesis. Using the rates of microbial methanogenesis shown in Figure 2 and the solubility curve shown in Figure 3 results in the methane concentration shown in Figure 4. Future work will include adding compaction, variable sedimentation, lithology changes, diffusion, and advection.

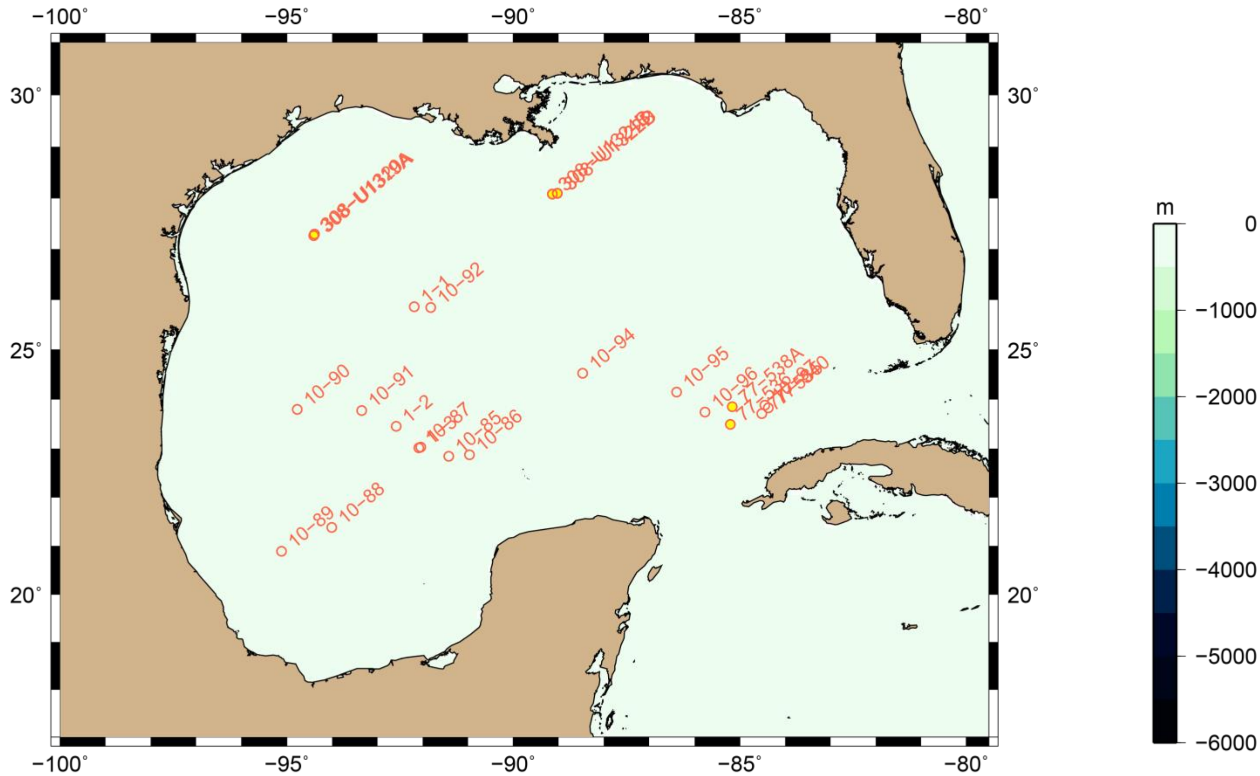

Figure 1. Location of scientific ocean drilling boreholes with POC data.

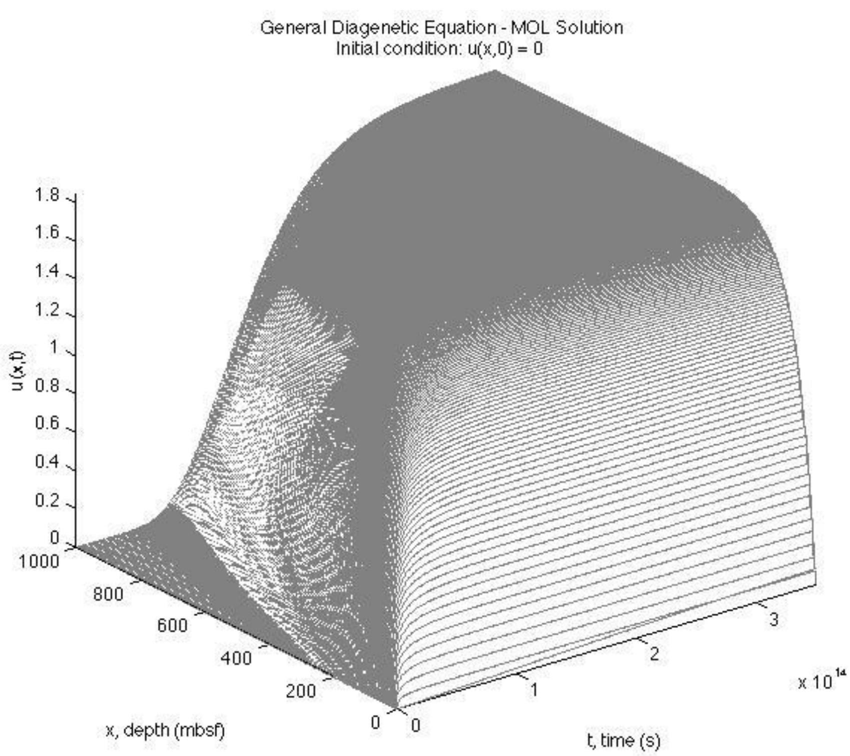

Figure 2. Rates of microbial methanogenesis used to test numerical model.

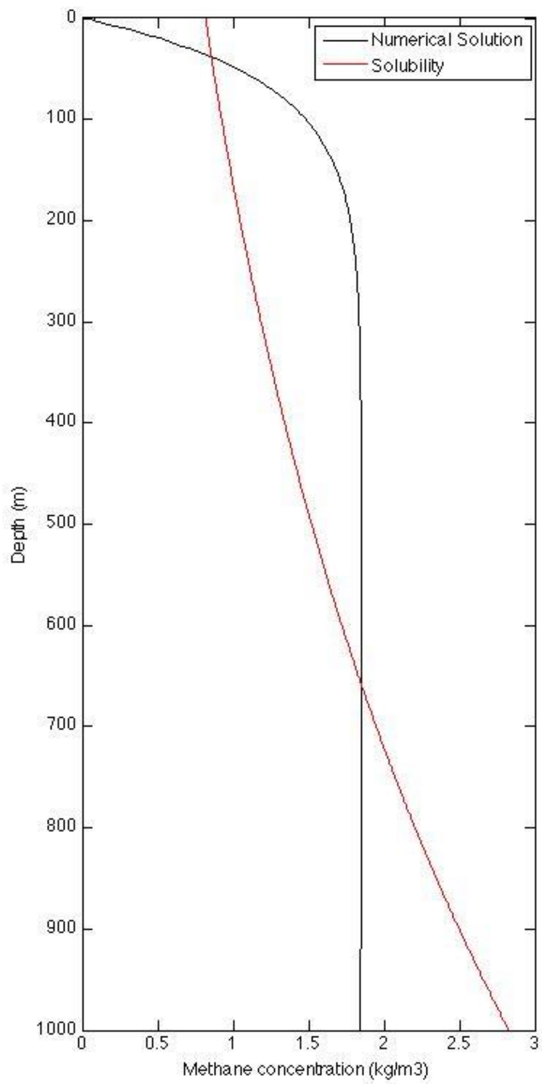

Figure 3. Methane solubility curve.

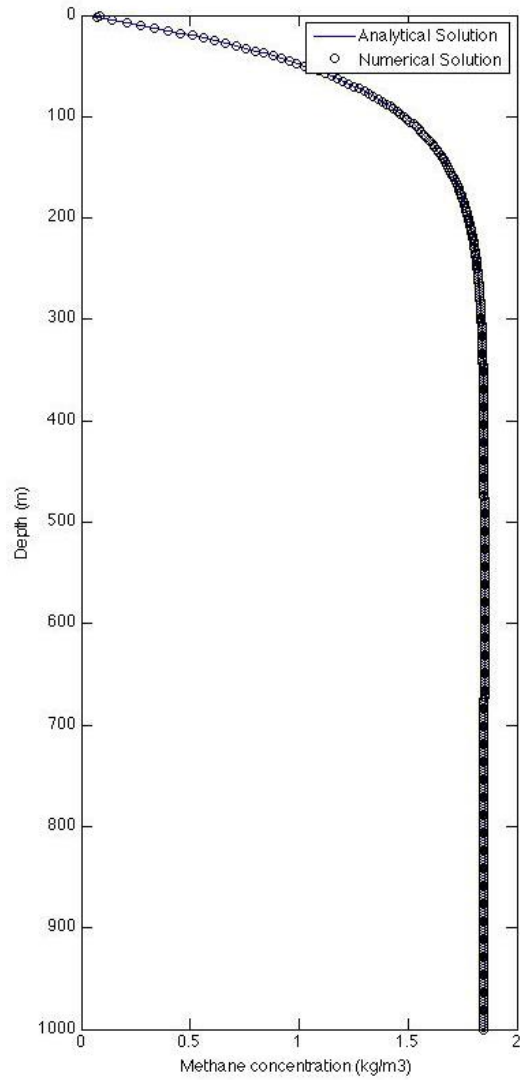

Figure 4. Computed methane concentration with analytical solution showing good match.

In connection with Task 3, Daigle and PhD student Michael Nole continued work on developing a method to determine permeability and pore size from the LWD logs run at WR313. They investigated offset data from the Mississippi Canyon area (drilled during Integrated Ocean Drilling Program Expedition 308) and the Keathley Canyon area (drilled as part of the Gulf of Mexico Gas Hydrates JIP) that have grain size and permeability measurements in addition to log data. Once their model has been tested and validated, it will be used as part of the inputs for the model in Task 2 and Task 3.

Specific objectives
Milestone 1.C (Sedimentation, microbial methane production, salinity effect implementation) was planned for the end of this quarter. This milestone was met successfully with implementation of these parameters in the reservoir simulator.

Significant results and key outcomes
Preliminary results of the work of Daigle and Nole has shown that pore size and permeability may be easily computed from log data, pending further validation.

Malinverno's work has provided crucial constraints on rates of microbial methanogenesis in sediments in the northern Gulf of Mexico.

What opportunities for training and professional development has the project provided?

PI Daigle and PhD student Nole attended the Offshore Technology Conference in Houston in May to view sessions on methane hydrates in marine sediments and interact with other hydrate researchers.

PI Daigle attended the 6th International Conference on Porous Media in Milwaukee in May to interact with others in the pore-scale modeling community.

PI Daigle and co-PI Mohanty have been working with PhD student Michael Nole on code development. This work has involved weekly meetings and independent work.

Co-PI Cook has been working with PhD student Deborah Glosser on modeling microbial methanogenesis. This work has involved weekly meetings and independent work.

How have the results been disseminated to communities of interest?

None applicable to this quarter.

Plans during next reporting period to accomplish goals
Work will continue on Task 2 (Reservoir model development) and Task 3 (1-D modeling of microbial methanogenesis). For Task 2, we will begin benchmarking the code against existing model results. For Task 3, Malinverno will continue constraining rates of microbial methanogenesis, and Cook will continue building the 1-D numerical simulator to model microbial methanogenesis.

Nole will attend the International Conference on Gas Hydrates in July.

We plan to prepare and submit abstracts for the American Geophysical Union Fall Meeting. These abstracts are due on August 6th.

PRODUCTS

None this period.

PARTICIPANTS AND OTHER COLLABORATING ORGANIZATIONS

Name: Hugh Daigle
Project role: PI
Nearest person month worked: 1
Contribution to project: Project management; assisted with code development
Collaborated with individual in foreign country: No

Name: Kishore Mohanty
Project role: Co-PI
Nearest person month worked: 1
Contribution to project: Assisted with code development
Collaborated with individual in foreign country: No

Name: Steven Bryant
Project role: Co-PI
Nearest person month worked: 1
Contribution to project: Assisted with code development
Collaborated with individual in foreign country: No

Name: Michael Nole
Project role: Graduate Student
Nearest person month worked: 3
Contribution to project: Primary worker on developing computer code
Collaborated with individual in foreign country: No

Name: Ann Cook
Project role: Co-PI
Nearest person month worked: 1
Contribution to project: Worked on gathering specific data for modeling of microbial methanogenesis, developing methanogenesis code
Collaborated with individual in foreign country: No

Name: Alberto Malinverno
Project role: Co-PI
Nearest person month worked: 1
Contribution to project: Provided data for microbial methanogenesis modeling
Collaborated with individual in foreign country: No

IMPACT

What is the impact on the development of the principal discipline of the project?

The central focus of this project is refining our understanding of the methane migration pathways that feed methane hydrate deposits in marine sediments. Understanding migration pathways is an important component of understanding methane hydrates as a petroleum system, a necessary step towards prospecting for economically recoverable hydrate deposits. Additionally, our results will help refine our understanding of the carbon cycle in marine sediments, and specifically how methane is transported and sequestered.

What is the impact on other disciplines?

The results of this project will be important for other engineering disciplines in which researchers are developing methods for extracting methane from the subsurface since it will provide information on how methane is distributed in sediments at different scales. In addition, the results will be of interest to the economics and risk assessment fields since we will develop methods to determine more precisely how much hydrate may be present in subsurface reservoirs.

What is the impact on the development of human resources?

This project will provide funding for three graduate students to conduct collaborative research on methane hydrates and give them an opportunity to participate in important hands-on learning experiences outside the classroom.

What is the impact on physical, institutional, and information resources that form infrastructure?

Our results may be used for better design of subsea oil and gas infrastructure since more precise assessment of hydrate resources will allow better assessment of hydrates as a hazard. In addition, production infrastructure specifically for hydrate reservoirs may be improved by our results since we will allow more accurate determination of the volumes of methane expected to exist in the subsurface.

What is the impact on technology transfer?

Our results will be disseminated at conferences and in peer-reviewed publications.

What is the impact on society beyond science and technology?

The impact of this work on society will be twofold. First, the better understanding of hydrates in a petroleum systems framework will allow for more efficient production of natural gas from these deposits, which will provide an additional energy resource. Second, the better understanding of methane cycling and distribution in the subsurface will influence regulatory decisions involving hydrates as geohazards or climate change agents.

What dollar amount of the award's budget is being spent in foreign country(ies)?
None

CHANGES/PROBLEMS
None

SPECIAL REPORTING REQUIREMENTS
None

BUDGETARY INFORMATION
See attached spreadsheet.

Variances: Subcontract money still needs to be disbursed. UT OSP is working on this.

References

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Baseline Reporting Quarter	Budget Period 1														
	Q1		Q2		Q3		Q4		Q1		Q2		Q3		Q
	10/1/13 - 12/31/13		1/1/14 - 3/31/14		4/1/14 - 6/30/14		7/1/14 - 9/30/14		10/1/14 - 12/31/14		1/1/15 - 3/31/15		4/1/15 - 6/30/15		7/1/15 -
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4
Baseline Cost Plan															
Federal Share	$ 97,351	$ 97,351	$ 97,351	$ 194,701	$ 97,351	$ 292,052	$ 97,351	$ 389,403	$ 97,351	$ 486,753	$ 97,351	$ 584,104	$ 108,258	$ 692,362	$ 108,258
Non-Federal Share	$ 24,377	$ 24,377	$ 24,377	$ 48,754	$ 24,377	$ 73,132	$ 24,377	$ 97,509	$ 24,377	$ 121,886	$ 24,377	$ 146,263	$ 29,698	$ 175,961	$ 29,698
Total Planned	$ 121,728	$ 121,728	$ 121,728	$ 243,456	$ 121,728	$ 365,184	$ 121,728	$ 486,911	$ 121,728	$ 608,639	$ 121,728	$ 730,367	$ 137,956	$ 868,323	$ 137,956
Actual Incurred Cost															
Federal Share	0	0	$ 4,053	$ 4,053	$ 59,844	$ 63,897									
Non-Federal Share	0	0	0	0	$ 11,969	$ 11,969									
Total Incurred Costs	0	0	0	0	$ 71,813	$ 75,866									
Variance															
Federal Share	$ (97,351)	$ (97,351)	$ (93,298)	$ (190,648)	$ (37,507)	$ (228,155)									
Non-Federal Share	$ (24,377)	$ (24,377)	$ (24,377)	$ (48,754)	$ (12,408)	$ (61,163)									
Total Variance	$ (121,728)	$ (121,728)	$ (117,675)	$ (239,403)	$ (49,915)	$ (289,318)									

	Budget Period 2								Budget Period 3							
4	Q1		Q2		Q3		Q4		Q1		Q2		Q3		Q4	
9/30/15	10/1/15 - 12/31/15		1/1/16 - 3/31/16		4/1/16 - 6/30/16		7/1/16 - 9/30/16		10/1/16 - 12/31/16		1/1/17 - 3/31/17		4/1/17 - 6/30/17		7/1/17 - 9/30/17	
Cumulative Total	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
$ 800,620	$ 108,258	$ 908,878	$ 108,258	$ 1,017,136	$ 108,258	$ 1,125,394	$ 108,258	$ 1,233,652	$ 111,371	$ 1,345,023	$ 111,371	$ 1,456,395	$ 111,371	$ 1,567,766	$ 111,371	$ 1,679,137
$ 205,658	$ 29,698	$ 235,356	$ 29,698	$ 265,053	$ 29,698	$ 294,751	$ 29,698	$ 324,448	$ 30,888	$ 355,336	$ 30,888	$ 386,225	$ 30,888	$ 417,113	$ 30,888	$ 448,001
$ 1,006,278	$ 137,956	$ 1,144,234	$ 137,956	$ 1,282,189	$ 137,956	$ 1,420,145	$ 137,956	$ 1,558,100	$ 142,260	$ 1,700,360	$ 142,260	$ 1,842,619	$ 142,260	$ 1,984,879	$ 142,260	$ 2,127,138