Oil & Natural Gas Technology

DOE Award No.: DE-FE0028972

Quarterly Research Performance

(Period Ending 12/31/2018)

Characterizing Baselines and Change in Gas Hydrate Systems using EM Methods

Project Period (10/01/2016 – 09/30/2019)

Submitted by:

Steven Constable

Digitally signed by Steven Constable
DN: cn=Steven Constable, o=UCSD, ou=IGPP/SIO, email=sconstable@ucsd.edu, c=US
Date: 2019.02.04 17:55:52 -08'00'

Scripps Institution of Oceanography
University of California San Diego
DUNS #: 175104595
9500 Gilman Drive
La Jolla, CA 92093-0210
Email: sconstale@ucsd.edu
Phone number: (858) 534-2409

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

10/31/2017

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

Office of Fossil Energy

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EXECUTIVE SUMMARY

During this review period we continued to collect electrical conductivity measurements and cryogenic electron microscopy on samples of gas hydrate, and have produced a first draft of a paper for submission to *JGR*. We had a *Fire in the Ice* article published on our results of electrical conductivity studies of hydrate with pore fluids, and two AGU abstracts accepted.

We have carried out preliminary inversions of data from the Orca Basin CSEM survey, which show resistors in the area targeted by GOM∧2 drilling. We also see resistors associated with a slump feature on the western side of the survey area, as well as a conductive plume above a nearby salt body.

ACCOMPLISHMENTS

Major goals of project

Methane hydrates require cool temperatures, high pressures, and methane in excess of solubility to form, conditions that are met in both marine and permafrost regions worldwide. Concentrated accumulations of structural hydrate may be the target for resource exploitation, and there have been several production tests of natural gas from hydrate, both on land, such as at the Mallik site in NW Canada or the Mt Elbert test well on the Alaska North Slope, and in the ocean, such as in the Nankai Trough and an ice platform off Prudhoe Bay.

Much naturally occurring hydrate exists at the edge of thermodynamic stability, and as such represents an environmental hazard that threatens release of a potent greenhouse gas as a consequence of warming. Also, one way to produce methane from hydrate is to destabilize the structure by depressurization.

Current geophysical surveying methods for identifying hydrates, such as seismic methods and well logging/coring, are limited. Quantifying the volume fraction of hydrate in sediments is possible with careful processing and inversion of seismic data, although the relationship between seismic velocity (or attenuation) and hydrate concentration is complicated and usually needs to be calibrated with well data. Electromagnetic (EM) methods, on the other hand, are sensitive to the concentration and geometric distribution of hydrate because regions containing hydrate are significantly more resistive when compared to water saturated zones. The current state of the art for imaging gas hydrate using EM methods is represented by the Vulcan system developed by Scripps Institution of Oceanography. This system uses multiple, 3-axis EM receivers towed at source-receiver ranges of up to 1,000 m behind an electric dipole transmitter. The whole array (transmitter and receivers) is “flown” 50–100 m above the seafloor in order to (a) reduce noise, (b) avoid seafloor infrastructure and other obstacles, and (c) allow all three components of electric field to be measured. The Vulcan system was used in 2014 and 2015 to successfully collect 1,000 km of high quality data over gas hydrate prospects in Japan, as well as two studies offshore San Diego, California.

For the next advance in this technology, under the current agreement we will collect extensive 3D Vulcan data sets over two or three sites in the Gulf of Mexico where drilling and coring of hydrate systems has been, or will be, carried out. We plan to study the Walker Ridge 313, Orca Basin, and Green Canyon 781 prospects, but as we did under previous NETL funding, we will consult with DoE and the drilling consortium before choosing final targets. With 2–3 days of data collection over each prospect, we will be able to collect at least 10 lines of data 10–20 km long. With a line spacing of 500–1,000 m, this will provide a dense data set of 100–200 line km covering 50–100 square km.

Under prior NETL funding we designed a specialty pressure cell plumbed for high-pressure gas access, in which we formed gas hydrate samples while simultaneously measuring impedance spectra. Such impedance measurements of methane hydrate are needed for modeling of gas hydrate systems, yet had never been established prior to our work. Under the current agreement, we plan to extend these laboratory experiments to further utilize the unique apparatus we have designed, and build on our previous results and baseline measurements. We will introduce additional parameters that mimic the effects of induced or environmental factors that may act to destabilize gas hydrate systems and contribute to the onset of partial dissociation to solid or liquid water.

Work accomplished during the project period

During the last quarter, we prepared abstracts for the Fall American Geophysical Union and started work on inversions of the Orca Basin. During this quarter we worked on preparing the talks and abstracts for the AGU meeting, and continued work on the Orca Basin data.

Laboratory Conductivity Studies

We continue to work on our understanding of the runs we made in which NaCl was added to the gas hydrate synthesis. Figure 1 is abstracted from our AGU poster on the subject. Features in the conductivity data can be related to the phase boundaries in the NaCl-H_2O-CH_4 phase diagram of deRoo et al. (1983). The sharp drop in electrical conductivity at temperatures of around -25°C, on the right side of the conductivity plot, corresponds to the phase boundary on the left side of the phase diagram where the last vestiges of water/brine are frozen out of the sample. The change in conductivity best visible in the 1.0% NaCl sample (orange) around 0°C corresponds to the ice/liquid boundary, which is relatively simple in the H_2O-CH_4 system (red in Figure 1B), but much more complicated in the system with NaCl (green in Figure 1B). In particular, hydrohalite (a solid) begins to form at this boundary.

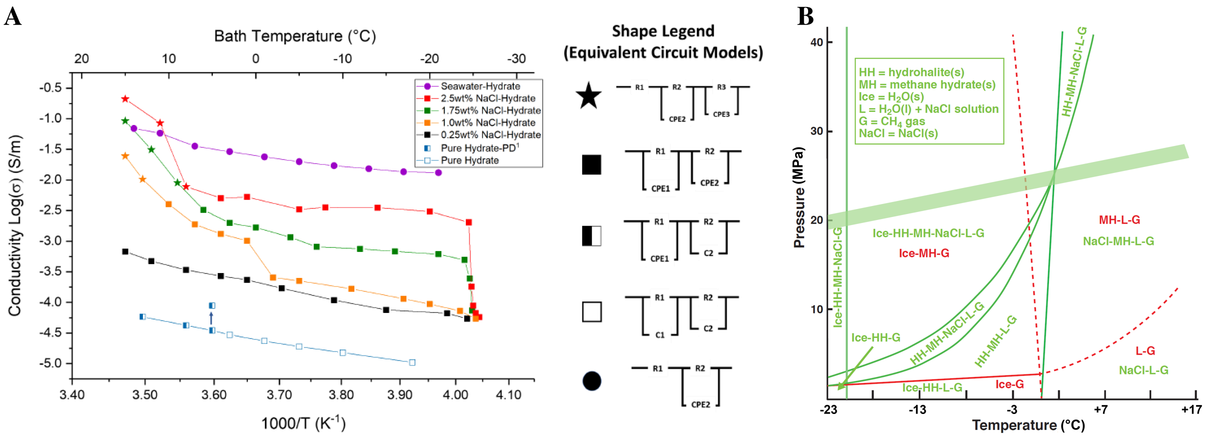

Figure 1. **A.** Arrhenius plots of conductivity runs with various NaCl concentrations. **B.** Phase diagram for the NaCl-H_2O-CH_4 system, re-drawn from deRoo et al. (1983). The red parts of the figure refer to the phase diagram of H_2O+CH_4 without the addition of NaCl. The broad green line is the approximate P-T regime of our conductivity measurements.

Gulf of Mexico Field CSEM Data

Seven lines were towed at Orca Basin, three east-west lines spanning the length of the ridge that separates northern Orca Basin from southern Choctaw Basin and four north-south lines that focus on the GOM^2 proposed drilling sites (Figure 2). The western portion of the survey crosses a slide scarp where large submarine landslides have originated (Sawyer et al., 2019). Vertical deformation of the sediments overlying a buoyant salt body exerts a primary control on the landslide triggering mechanism, however secondary controls are likely gas hydrate mediated. Within the hydrate stability field, hydrate cementation of sediment grains can have a stabilizing effect on the sediment. Conversely, at the edges of the stability field, hydrate dissociation can over-pressurize pore space, and provide a gas-filled slide plane.

In the resistivity inversions at Orca Basin (Figure 2), we see increased resistivity within the slide scarp. Within the scarp, the resistors thicken towards the slide headscarp, with the highest resistivies found at Orca Basin present at the seafloor of the slide scarp. The western area of the survey is punctuated by vertical conductive features that are hypothesized to be fault-mediated advective fluid flow bringing warmer, more saline, conductive fluids through the sediment column.

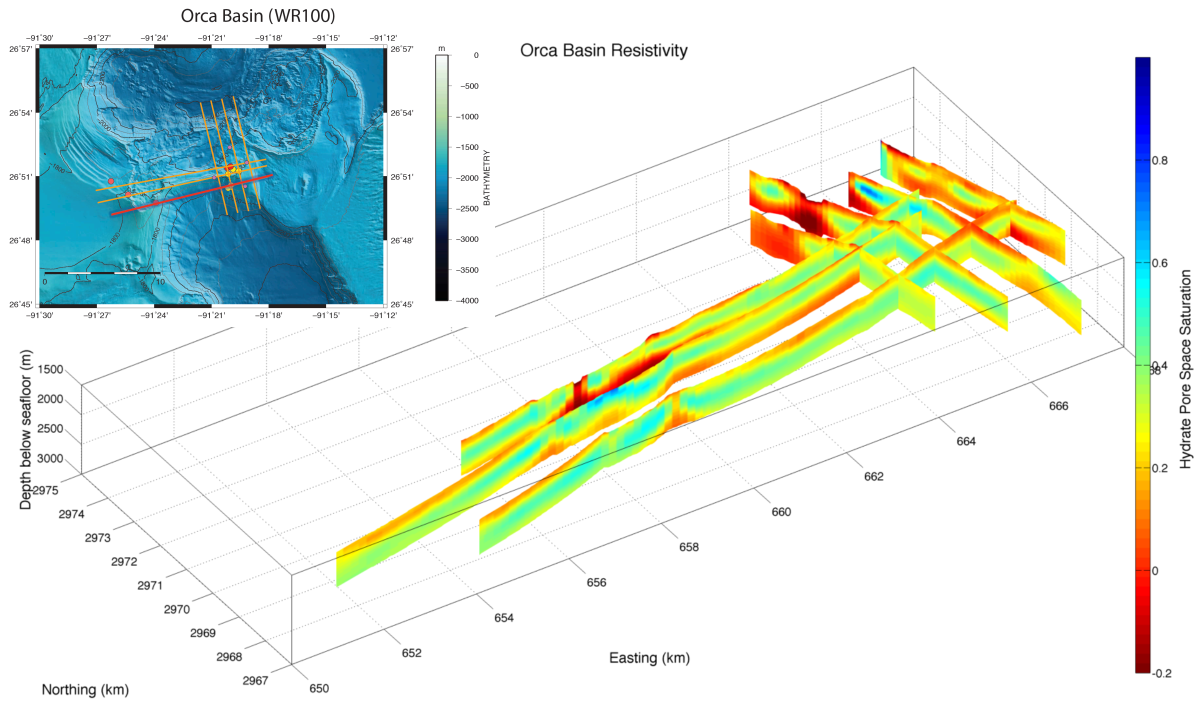

Figure 2. Resistivity inversions of all the Orca Basin CSEM tow lines.

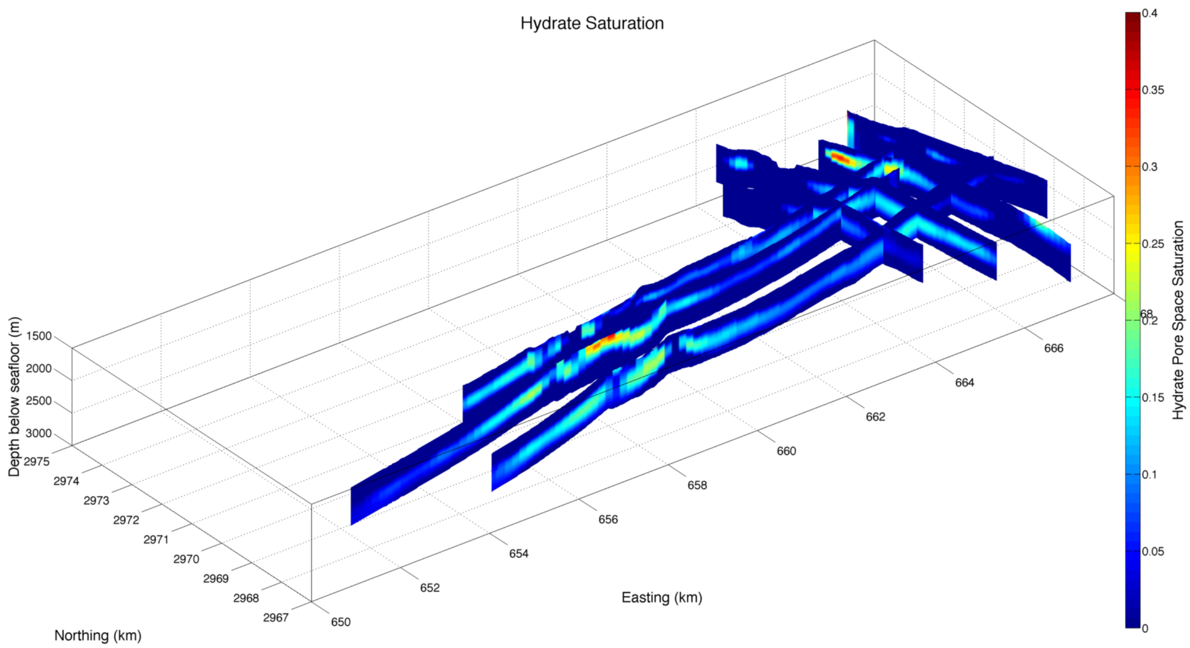

Figure 3. Pore space saturation inferred from resistivity inversions shown in Figure 2.

The eastern side of the survey region has broad resistors at or above the expected BSR depth. Resistivities peak to the south and to the northeast of the ridge crest. The southern area of increased resistivity is the site of the secondary drill site at Orca Basin. The primary drill site shows increased resistivity, but is not particularly noteworthy. The resistor to the northeast is near a shallow detached salt body, but the depth being coincident with the expected BSR suggests that this could be hydrate as well. Confounding some of the lines on the eastern side of the line is a large salt body exposed at the seafloor. The presence of this salt body decreased the goodness of fit in the inversions, and inverted lines were limited to areas that were not sensitive to this salt body.

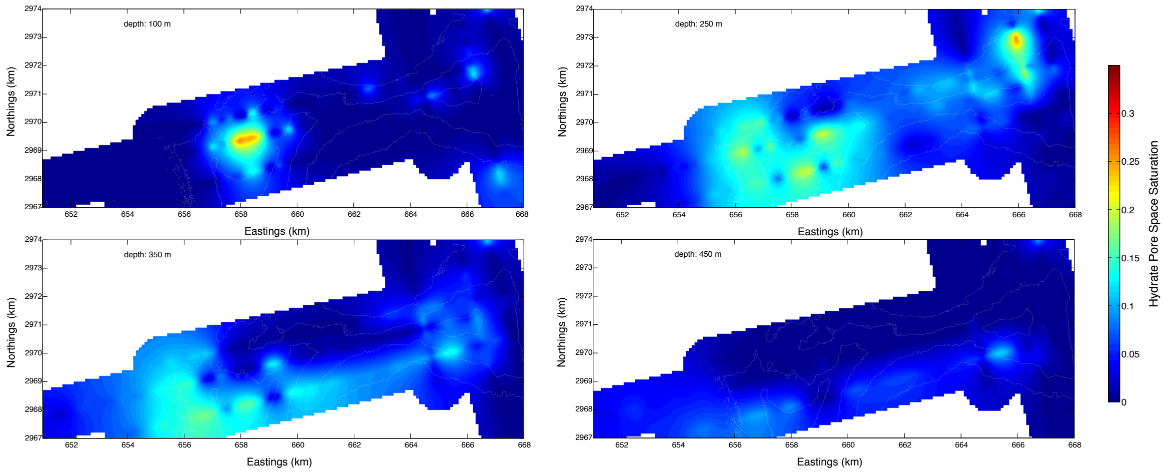

Figure 4. Depth slices of pore space saturation shown in Figure 3.

Archie's law is used calculate hydrate saturation from resistivity. Pore water conductivity is determined from regional heat flow values after Becker (1985). Archie's parameters used are from Cook and Waite (2018), and a silt/sand reservoir is assumed. Porosity curves follow the Athy equation (Athy, 1930) for a silt/sand system. The resulting fence plot of hydrate saturation shows high saturations ($\approx$30%) near the seafloor in the central portion of the slide scarp on the western side of the survey. At the proposed drill sites, hydrate saturation peaks at 15%.

Using the regularized mapping method of Constable et al. (2018), a smooth 3D model of hydrate saturation across the study area was produced. Summing hydrate saturation across this volume gives a total gas in place estimate of 100 billion m^3, or 3.5 Tcf.

The last two survey sites were at Mad Dog (GC781) and GC955. The close proximity of these sites meant that it was more efficient to leave the array in the water and deep tow from Mad Dog to GC955. Between the two sites is the Green Knoll Salt dome. Figure 5 shows the transect of resistivity inversions starting at Mad Dog, descending across the Sigsbee escarpment, rising over Green Knoll, and then across GC955. At Mad Dog, the graben structure is more conductive than the surrounding horsts. Increased reistivity is present at the base of the Sigsbee escarpment roughly coincident with the expected depth of the base of the hydrate stability zone. The salt dome shows very high resistivity, roughly 1000 Ωm, which is expected for salt. The salt body is overlain by a thin veneer of conductive sediments. At GC955, the shallow hydrate bearing fractured shale unit is present as a broad shallow resistor. The deeper resistor is coincident with a hydrate bearing sand interval.

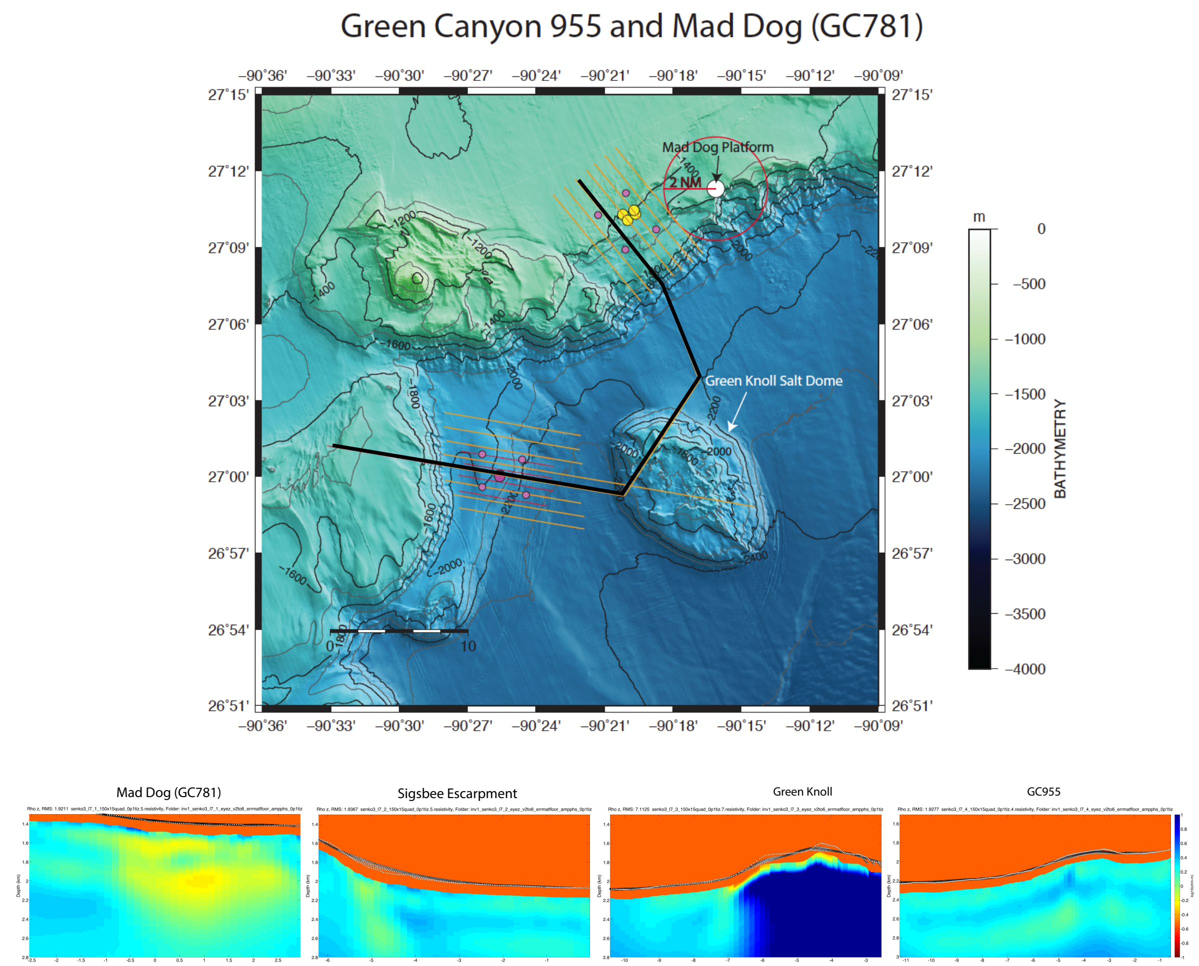

Figure 5. GC 955 and GC 781 tow lines (top). The inversions (bottom) are for the four segments of the black line, which was a single tow from GC781 to GC955.

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Athy, L. F. , 1930. Density, porosity and compaction of sedimentary rocks. *AAPG Bulletin*, **14**, 1–21.

Becker, K., 1985. Large scale electrical resistivity and bulk porosity of the oceanic crust. *Initial Rep. Deep Sea Drill. Proj.*, **83**, 410–428.

de Roo, J.L., C.J. Peters, R.N. Lichtenthaler, and G.A.M. Diepen, 1983. Occurance of methane hydrate in saturated and unsaturated solutions of sodium chloride and water in dependence of temperature and pressure. *AIChE Journal*, **29**, 652–657.

Cook, A. E., and Waite, W. F., 2018. Archie's saturation exponent for natural gas hydrate in coarse-grained reservoirs. *Journal of Geophysical Research: Solid Earth*, **123**, 2069–2089.

Constable, S., Kowalczyk, P., and Bloomer, S. , 2018. Measureing marine self-potential using an autonomous underwater vehicle. *Geophysical Journal International*, **215**, 49–60.

Sawyer, D. E., Mason, R. A., Cook, A. E., and Portnov, A., 2019. Submarine Landslides Induce Massive Waves in Subsea Brine Pools. *Scientific Reports*, **128**, 9.

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Other activities

Training and professional development.

Peter Kannberg, then a PhD student at SIO, acted as co-chief scientist on the data collection cruise. He is currently working on this project as a postdoc.

Ryan Lu, a junior scientist at LLNL, continues work on the laboratory electrical conductivity studies and learning about hydrate synthesis and the operation of the conductivity cell.

SIO PhD students Dallas Sherman and Valeria Reyes-Ortega participated in the research cruise and learnt about the operation of the CSEM instruments. Sherman assisted with an industry-operated hydrate survey later in that year.

Peter Kowalczyk and Karen Weitemeyer, of Ocean Floor Geophysics, participated in the cruise as part of the industry cost-share component, and also gained some training in the operation of the equipment, which has been used for several proprietary surveys offshore Japan.

Plans for next project period.

During the next project period we will continue to invert the GoM CSEM data, and submit the *JGR* paper on the laboratory conductivity work.

Table 1: Milestone status report.

Milestone Title	Planned Completion Date	Actual Completion Date	Verification Method	Comments on progress
First set of conductivity runs	08/1/2017	08/1/2017	Internal review	completed
Field data collection	12/1/2017	06/12/2017	200 line km collected	completed
Second conductivity runs	12/30/2017	12/30/2017	Internal review	completed
Final set of conductivity runs	8/1/2018	8/1/2018	Internal review	completed
Field data inverted	12/1/2018		2D inversions done	ongoing
Publications(s) submitted	9/1/2019		At least 1 pub. submitted	imminent
Publications(s) accepted	12/30/2019		Publication accepted	

PRODUCTS

Project Management Plan. The revised Project Management Plan was accepted on 3 February 2017.

Project Web Page. http://marineemlab.ucsd.edu/Projects/GoMHydrate2017/index.html (check out the animated movie of the deep-two over Green Canyon at http://marineemlab.ucsd.edu/Projects/GoMHydrate2017/deeptowmovie.html)

Preliminary Cruise Report. http://marineemlab.ucsd.edu/Projects/GoMHydrate2017/CruiseReportReduced.pdf

Fire in the Ice article. Electrical Conductivity of Methane Hydrate with Pore Fluids: New Results from the Lab Ryan Lu, Laura A. Stern, Wyatt L. Du Frane, John C. Pinkston, and Steven Constable. Fire in the Ice, 18, 7–12.

AGU abstracts:

Kannberg, P., and S. Constable, 2017: Deep-towed CSEM survey of gas hydrates in the Gulf of Mexico. Contributed paper at the Fall AGU meeting, New Orleans.

Lu, R., L.A. Stern, W.L./ Du Frane, J.C. Pinkston, J.J. Roberts and S. Constable, 2018: Electrical characterization of methane hydrate with coexisting brine. Contributed paper at the Fall AGU meeting, Washington.

Kannberg, P., and S. Constable, 2018: Quantifying Methane Hydrate in the Gulf of Mexico Using Controlled Source Electromagnetic Methods. Contributed paper at the Fall AGU meeting, Washington.

Other abstracts:

Kannberg, P., and S. Constable, 2018, Detecting methane hydrate in the Gulf of Mexico using controlled source electromagnetic methods. Contributed poster at the Galveston Gordon Conference.

The following papers acknowledge this or past DoE funded research:

Sherman, D., and S.C. Constable, 2018. Permafrost extent on the Alaskan Beaufort Shelf from surface towed controlled-source electromagnetic surveys. *Journal of Geophysical Research: Solid Earth*, **123**, 1–13, /doi.org/ 10.1029/2018JB015859.

Weitemeyer, K., S. Constable, D. Shelander, and S. Haines, 2017. Mapping the resistivity structure of Walker Ridge 313 in the Gulf of Mexico using the marine CSEM method. *Marine and Petroleum Geology*, **88**, 1013–1031, /doi.org/10.1016/j.marpetgeo.2017.08.039.

Sherman, D., P. Kannberg, and S. Constable, 2017. Surface towed electromagnetic system for mapping of subsea Arctic permafrost. *Earth and Planetary Science Letters*, **460**, 97–104.

Constable, S., P. K. Kannberg, and K. Weitemeyer, 2016. Vulcan: A deeptowed CSEM receiver. *Geochemistry, Geophysics, Geosystems*, **17**, doi:10.1002/ 2015GC006174.

Du Frane, W., L.A. Stern, S. Constable, K.A. Weitemeyer, M.M. Smith, and J.J. Roberts, 2015. Electrical properties of methane hydrate + sediment mixtures. *Journal of Geophysical Research*, **120**, 4773–4787, doi:10.1002/2015JB011940.

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Weitemeyer, K.A., S. Constable, S. and A.M. Trehu, 2011. A marine electromagnetic survey to detect gas hydrate at Hydrate Ridge, Oregon. *Geophysical Journal International* , **187**, 45-62.

Weitemeyer, K., G. Gao, S. Constable, and D. Alumbaugh, 2010. The practical application of 2D inversion to marine controlled-source electromagnetic sounding. *Geophysics*, **75**, F199–F211.

Weitemeyer, K., and S. Constable, 2010. Mapping shallow geology and gas hydrate with marine CSEM surveys. *First Break*, **28**, 97–102.

PARTICIPANTS AND OTHER COLLABORATING ORGANIZATIONS

Name:	Steven Constable
Project Role:	PI
Nearest person month worked:	1
Contribution to project:	Management, scientific direction
Funding support:	Institutional matching funds
Foreign collaboration:	Yes
Country:	Canada
Travelled:	No

Name:	Peter Kannberg
Project Role:	PhD student/SIO
Nearest person month worked:	3
Contribution to project:	Data processing and inversion.
Funding support:	This project
Foreign collaboration:	Yes
Country:	Canada
Travelled:	No

Name:	Laura Stern
Project Role:	Scientist/USGS
Nearest person month worked:	1
Contribution to project:	Gas hydrate synthesis and conductivity measurements.
Funding support:	USGS
Foreign collaboration:	No

Name:	Wyatt DuFrane
Project Role:	Scientist/LLNL
Nearest person month worked:	1
Contribution to project:	Postdoc supervision/conductivity measurements.
Funding support:	This project
Foreign collaboration:	No

Name:	Ryan Lu
Project Role:	Junior Scientist/LLNL
Nearest person month worked:	1
Contribution to project:	Conductivity measurements.
Funding support:	This project
Foreign collaboration:	No

CHANGES/PROBLEMS

There are no changes or problems arising from this review period.

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

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