2020 Vol. 20, Issue 1

NATIONAL ENERGY TECHNOLOGY LABORATORY

CONTENTS

CONTACT

Joseph Stoffa

Technology Manager
Methane Hydrate R&D Program

(412) 386-5862

joseph.stoffa@netl.doe.gov

U.S. DEPARTMENT OF ENERGY

In-situ and Laboratory Evidence for High Electrical Anisotropy in Marine Hydrate

Steven Constable[1], Ryan Lu[2], Peter Kannberg[1], Laura Stern[3], Wyatt Du Frane[2], and Jeffery Roberts[2]

[1] Scripps Institution of Oceanogr aphy, La Jolla, CA
[2] Lawrence Livermore National Laboratory, Livermore, CA
[3] United States Geological Survey, Menlo Park, CA

Marine gas hydrate is electrically resistive compared to hydrate-free formations. This property is exploited in borehole logging and in marine controlled-source electromagnetic (CSEM) surveys to identify hydrate-bearing geologic layers. Well logging shows that hydrate can be electrically anisotropic, with vertical resistivities up to 10 times higher than horizontal resistivities. However, the use of logging tools capable of measuring electrical anisotropy is the exception rather than the rule. Marine CSEM surveying methods, on the other hand, are known to be sensitive to electrical anisotropy in seafloor sediments. For example, we have observed anisotropies of more than an order of magnitude using CSEM to map offshore relict permafrost.

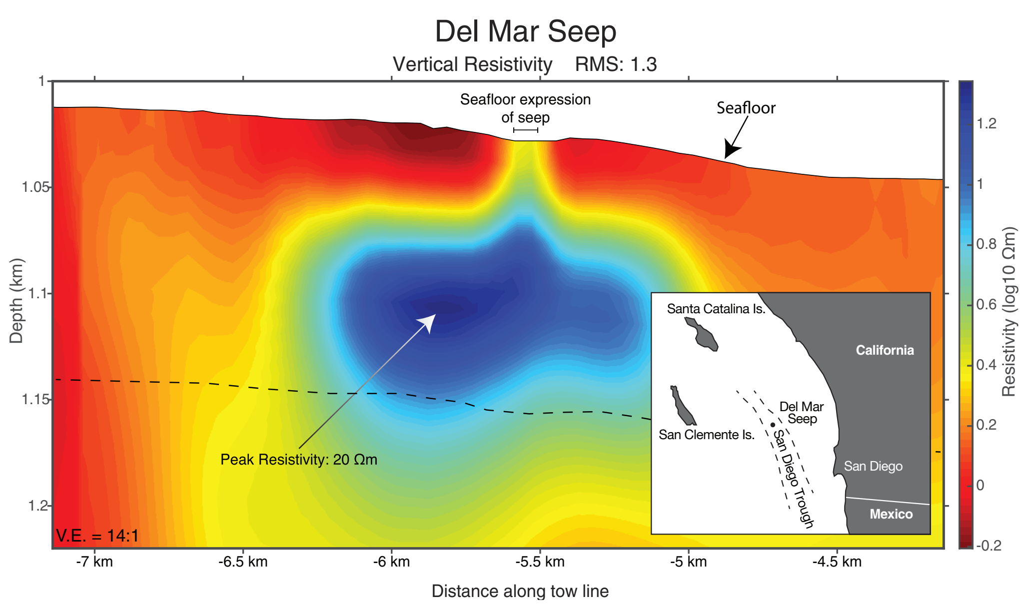


Figure 1. Vertical electrical resistivity model of the Del Mar Seep. Inset shows seep location in the San Diego Trough, off the southern California coast. Dashed line indicates the inferred depth of the gas hydrate stability field. Note the large vertical exaggeration.

We have developed a deep-towed CSEM system, which we call Vulcan, for imaging sub-seafloor gas hydrate. The Vulcan system has been used in the Gulf of Mexico (see accompanying article, p. 9), offshore Japan, and the North Atlantic. During a 2015 test of Vulcan in the San Diego Trough off southern California, we towed our CSEM system over the Del Mar Seep, a cold seep that intermittently vents methane in 1 km water depths. Inversion of the Vulcan data reveals a 100-m-thick, 1,500-m-diameter resistive feature, directly under the seep and within the gas hydrate stability field (Figure 1). We interpret this resistor to be gas hydrate formed from methane migrating to the surface along the San Diego Trough fault zone. Resistivities in the vertical direction peak at about 20 Ωm, which is large for *in-situ* CSEM measurements and suggests high concentrations of hydrate.

An isotropic resistivity model cannot fit both the amplitude and phase of the observed electromagnetic data. Instead, an anisotropic inversion, in which the vertical resistivity varies from the horizontal resistivity, is required. While anisotropy ratios (vertical resistivity divided by horizontal resistivity) of 2–3 are common in marine sediments, the observed anisotropy ratios under the seep are 20 or more (Figure 2). This degree of anisotropy is similar to what we have measured in offshore permafrost but much larger than has been previously observed in seafloor gas hydrate using CSEM methods.

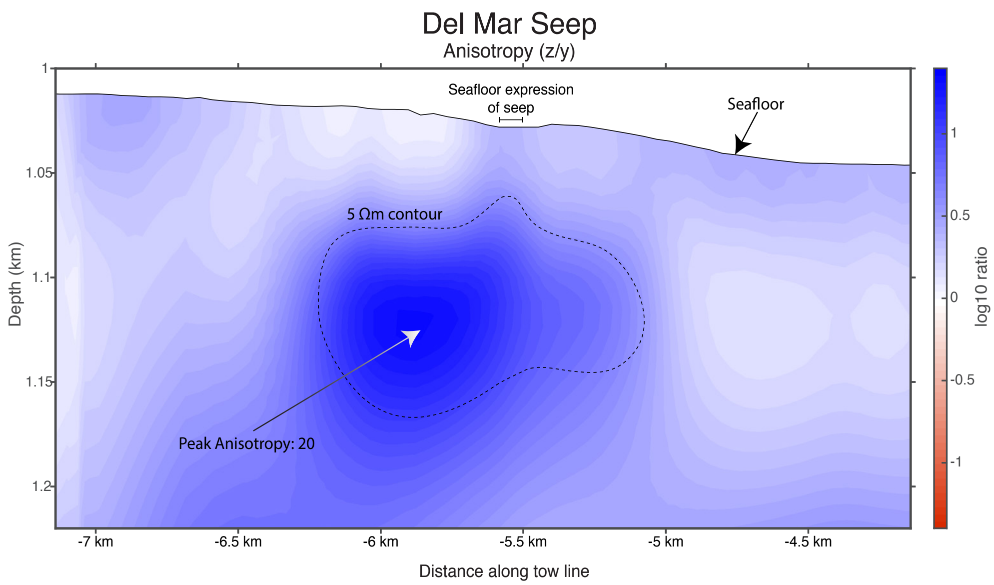


Figure 2. Ratio of vertical to horizontal resistivity for the Del Mar Seep model.

One geologic model used to explain electrical anisotropy in gas hydrate-bearing formations postulates alternating layers of water-saturated sediment and gas hydrate-bearing sediment. This model has been used to explain anisotropy in borehole logs, and it seems reasonable, given that hydrate is likely to form preferentially in particular stratigraphic layers, most likely in more permeable, coarser-grained layers.

We recently carried out laboratory testing on gas hydrate/sediment mixtures that adds nuance to this explanation (Figure 3). We mixed natural

National Energy Technology Laboratory

1450 Queen Avenue SW
Albany, OR 97321-2198
541-967-5892

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4764

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4687

Program staff are also located in Houston, TX and Anchorage, AK.

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

Customer Service:
1-800-553-7681

Fire in the Ice is published by the National Energy Technology Laboratory to promote the exchange of information among those involved in gas hydrates research and development.

This newsletter is available online at https://www.netl.doe.gov/advsearch?tid=113

Interested in contributing an article to *Fire in the Ice*?

This methane hydrate newsletter now reaches 1600 individuals, representing 20 countries. If you would like to submit an article on research results likely to be of interest to the methane hydrate R&D community, please contact Fran Toro at frances.toro@netl.doe.gov or Karl Lang at klang@keylogic.com. We look forward to hearing from you.

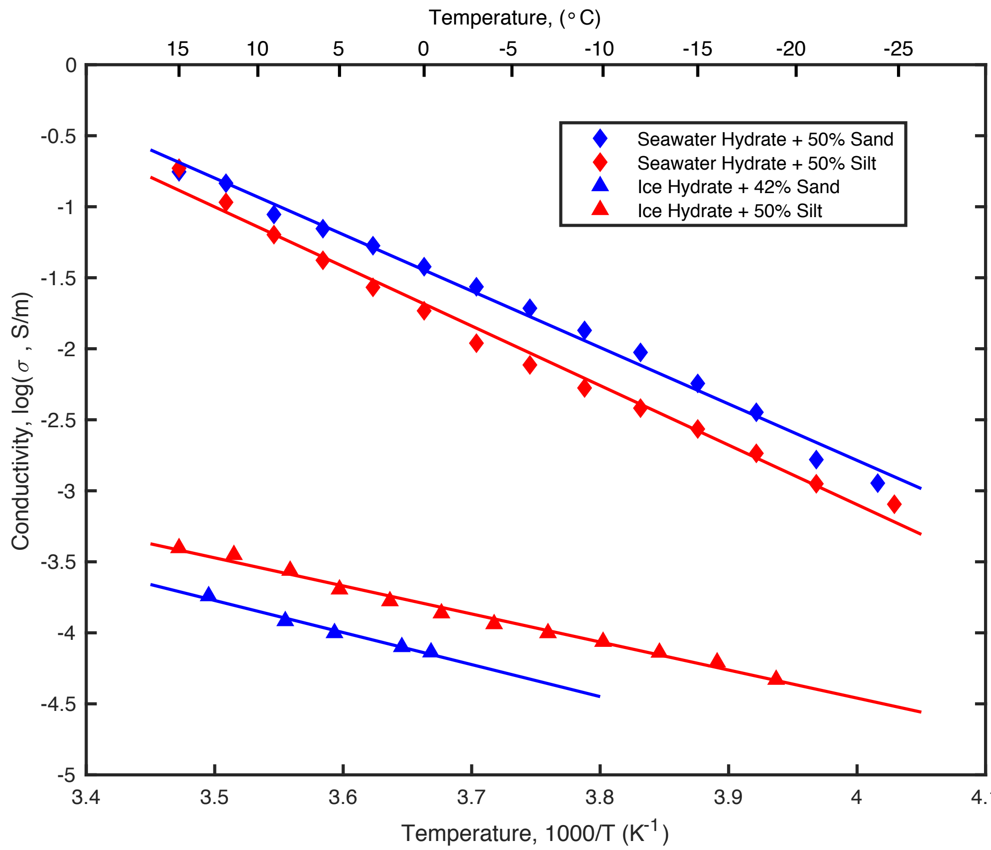


Figure 3. Laboratory measurements of electrical conductivity of silt (red) and sand (blue) mixed with methane hydrate. Samples were synthesized from pure ice water (lower curves) and frozen seawater (upper curves).

silica sediment of two different grain sizes (sand and silt) with either ice made from purified water, or ice made from flash-frozen seawater. We placed the mix in a pressure/temperature vessel and synthesized hydrate under high pressure, by cycling the temperature back and forth across the ice solidus. After full synthesis, electrical resistivity was estimated using impedance spectroscopy, in which both in-phase and out-of-phase sample resistance is measured over a range of frequencies.

Our laboratory results indicate that, although grain size has a small effect on electrical resistivity, it cannot explain the observed, high anisotropies. As one would expect, samples of hydrate made from seawater are much less resistive than samples made from pure ice. In fact, the difference in resistivity amounts to two orders of magnitude at 0° C. For our seawater-hydrate sample, we infer that most of the salt is excluded from the hydrate itself but remains present in the sample as a saturated brine phase. The overall resistivity of the sample is thought to be a composite measure of the saturated brine plus resistive sediment and hydrate grains.

How does this relate to the real-world measurements from the seep? In an open system, where hydrate forms and the residual brine is removed from the vicinity, the resistivity of sediment saturated with hydrate might be comparable to the ice-hydrate samples, i.e., a few thousand Ωm at 5° C, consistent with some borehole logs. However, if the system is closed, as in our laboratory setup, the resistivity will be much lower, similar to our seawater-hydrate samples, which have resistivities of about 10 Ωm at 5° C.

This suggests another interpretation of the high anisotropies seen beneath the Del Mar Seep. We postulate that this hydrate deposit is composed of alternating layers of hydrate and brine. Hydrate may have formed in more permeable layers, while brines, enriched by the excluded salt, developed in adjacent layers. This layering may be dependent, in part, on grain size and its effects on permeability and capillary forces; but it may also be a result of salt inhibiting hydrate formation in the brine-saturated layers.

Conceptually, this is similar to the anisotropy observed in permafrost, where brines excluded during ice formation are interbedded with layers containing ice. Note that the resolution of the CSEM method is such that, in this case, layers thinner than 5–10 m thick are not resolved, so that macro-anisotropy produces similar results to micro-anisotropy. The bulk resistivities of the Del Mar Seep model are lower than the laboratory measurements, most likely because of seawater (resistivity about 0.3 Ωm) in the system.

In summary, we deployed our Vulcan CSEM system to map a 100-m-thick, 1500-m-diameter resistive feature beneath the Del Mar Seep. We interpret it to be a hydrate-rich deposit formed by upward gas migration along the San Diego Trough fault zone. Vertical resistivity of the deposit reaches 20 Ωm, indicating high overall hydrate saturations. The resistor has a high degree of electrical anisotropy, with vertical/horizontal ratios of 20 or more. This is larger than has been previously observed in hydrate using CSEM methods and suggests a sequence composed of alternating layers of hydrate-saturated and brine-saturated sediment. This interpretation is consistent with offshore permafrost measurements and laboratory studies of hydrate synthesis using freshwater and seawater.

Acknowledgments

We thank the captain and crew of the *R/V New Horizon* and John Pinkston for assistance with the field and laboratory work, respectively; and Bill Waite and Tom Lorenson for providing comments on a draft of the article. Laboratory work was supported by the U.S. DOE award DE-FE0028972 and DOE-USGS Interagency Agreement DE-FE0026382. Prepared by LLNL under Contract DE-AC52-07NA27344. Field data collection was supported by Ocean Floor Geophysics and the Scripps Seafloor Electromagnetic Methods Consortium.

Suggested Reading

Cook, A.E., B.I. Anderson, J. Rasmus, K. Sun, Q. Li, T.S. Collett, and D.S. Goldberg, 2011. Electrical anisotropy of gas hydrate-bearing sand reservoirs in the Gulf of Mexico. Marine and Petroleum Geology, 34, 72–84, https://doi.org/10.1016/j.marpetgeo.2011.09.003.

Constable, S., P.K. Kannberg, and K. Weitemeyer, 2016. Vulcan: A deeptowed CSEM receiver. Geochemistry, Geophysics, Geosystems, 17, 1042–1064, https://doi.org/10.1002/2015GC006174.

Lu, R., L.A. Stern, W.L. Du Frane, J.C. Pinkston, J.J. Roberts, and S. Constable, 2019. The effect of brine on the electrical properties of methane hydrate. Journal of Geophysical Research: Solid Earth, 124, 10,877–10,892, https://doi.org/10.1029/2019JB018364.

Maloney, J.M., B.M. Grupe, A.L. Pasulka, K.S. Dawson, D.H. Case, C.A. Frieder, L.A. Levin, and N.W. Driscoll, 2015. Transpressional segment boundaries in strike-slip fault systems offshore southern California: Implications for fluid expulsion and cold seep habitats. Geophysical Research Letters, 42, 4080–4088, https://doi.org/10.1002/2015GL063778.

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, https://doi.org/10.1029/2018JB015859.

Exploring Flow Properties of Coarse-Grained Hydrate Reservoirs at the Pore and Core Scale

Peter B. Flemings[1], Hugh Daigle[2], Zachary Murphy[1], David A. DiCarlo[2], D. Nicolas Espinoza[2], Jung-Fu Lin[3], Stephen C. Phillips[4], Xiongyu Chen[2], Jiachao Liu[3], Tiannong S. Dong[3], Carla Thomas[4]

[1] The University of Texas at Austin, Jackson School of Geosciences, Institute for Geophysics & Department of Geological Sciences
[2] The University of Texas at Austin, Hildebrand Department of Petroleum and Geosystems Engineering
[3] The University of Texas at Austin, Jackson School of Geosciences, Department of Geological Sciences
[4] The University of Texas at Austin, Jackson School of Geosciences, Institute for Geophysics

We recently finished a three-year study of relative permeability and hydrate dissociation processes in coarse-grained, porous media. The goal was to understand macro-scale flow behavior and the pore-scale processes that drive this behavior. Insights from our work may serve to inform safe, environmentally sound, and economically viable approaches to producing gas from coarse-grained hydrate reservoirs.

This project, entitled "A multi-scale experimental investigation of flow properties in coarse-grained hydrate reservoirs during production," was a team effort by scientists from the University of Texas Institute for Geophysics, the Department of Geological Sciences, and UT's Hildebrand Department of Petroleum and Geosystems Engineering, with support from the U.S.DOE/NETL.

A full account of project activities and findings, including the project's Final Scientific/Technical report, is available on the DOE/NETL project web page, here.

Relative Permeability

Relative permeability can be used to gauge how the presence of hydrate changes the flow properties of porous media. It is therefore considered a key to predicting production behavior for hydrate-bearing reservoirs.

The most commonly used model of relative permeability of water in the presence of hydrate assumes flow through a capillary tube, where hydrate either coats the tube walls (as a grain coating) or sits within the tube (as a pore filling). This model depends only on hydrate saturation and does not take into account other properties of the porous media.

We hypothesize a simpler model of hydrate relative permeability, based on the concept that the hydrate is pore filling, occupying the largest pore spaces in the reservoir, as observed in natural core samples from the field. In our model, the water relative permeability depends on the water saturation and the properties of the porous medium, and it is independent of what other phases may be present--hydrate, gas, or a combination of the two.

To test our model, we measure and compare (1) the relative permeability of water in the presence of hydrate; and (2) the relative permeability of water in the presence of gas. Our results, shown in Figure 1, indicate remarkably similar behavior for both cases. Note the similar trend in relative permeability for water in the presence of gas (blue dots in Figure 1); and for water in the presence of hydrate (green dots in Figure 1).

This result suggests that it is possible to model the water/hydrate relative

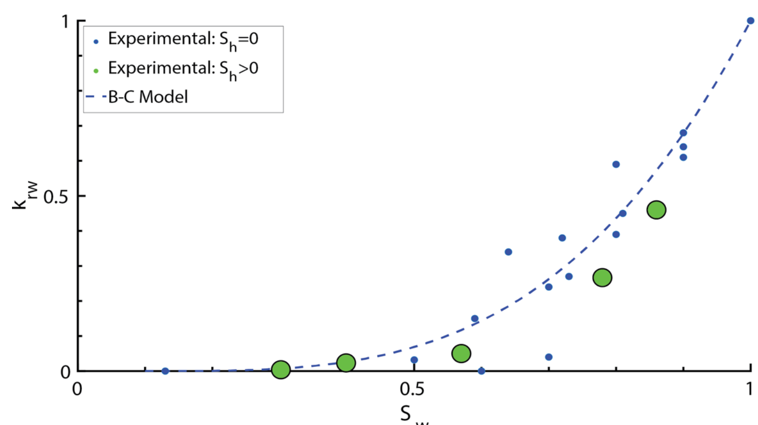
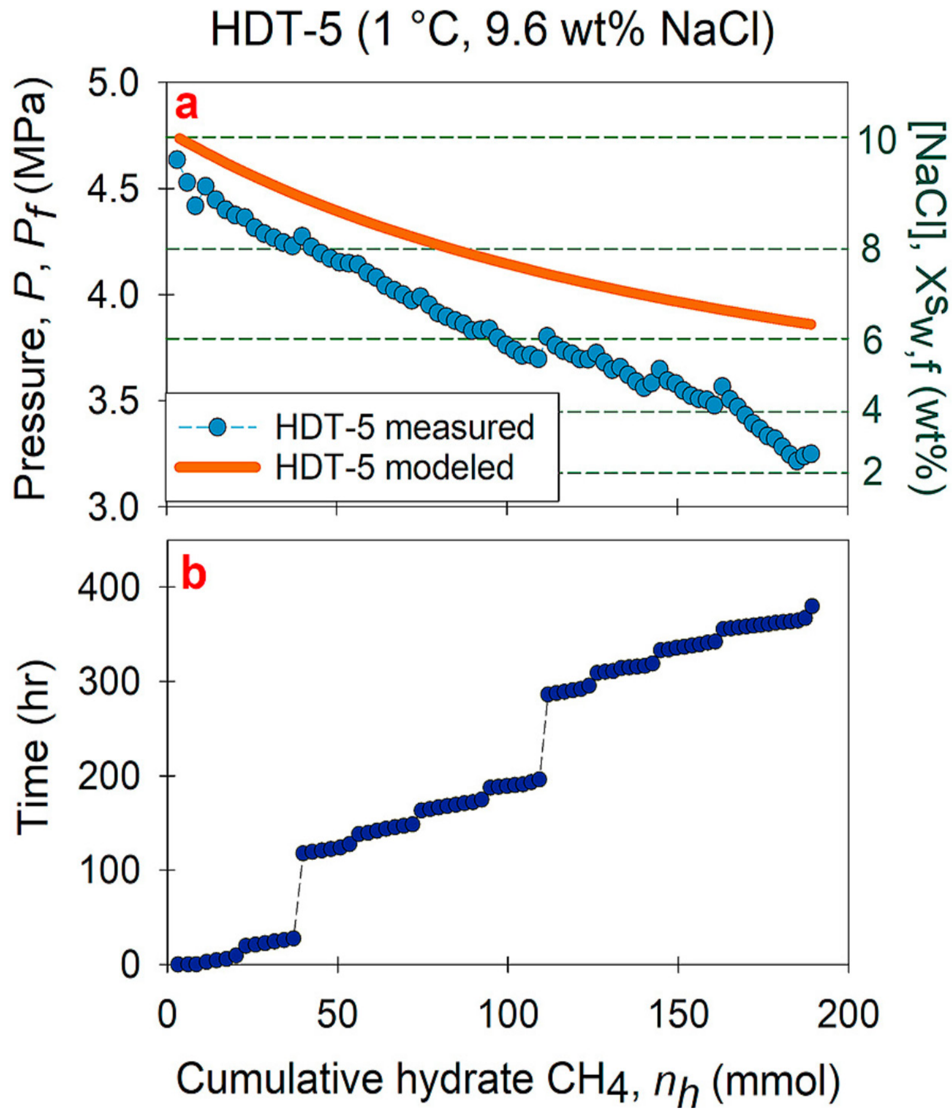


Figure 1. Wetting-phase relative permeability values for all samples tested. Blue dots: water-phase relative permeability in the presence of methane gas in synthetic samples. Green dots: water-phase relative permeability in the presence of hydrate (no gas) in synthetic samples. Dashed line: A standard Brooks-Corey model with fitting parameter nw=3.5.

Figure 2. Pressure (top) and time (bottom) vs. cumulative methane produced during dissociation of hydrate-bearing core. The pressure at the onset of dissociation (blue dot at far left) corresponds to a three phase pressure of ~9.6 wt % NaCl (right axis) salinity mixture, which is the in-situ salinity. The orange line represents the salinity at the three-phase boundary corresponding to the pressures on the y-axis at 1°C (the experimental conditions); the intersection of this line with the y-axis (left) corresponds to the pressure and salinity at the start of dissociation. Modified from Phillips et al. (2019).



permeability of a reservoir, by measuring the two-phase gas/water relative permeability of a representative sample. At any hydrate saturation, the water relative permeability will fall along the two-phase gas/water relative permeability curve. Prior to our laboratory study, this fundamental understanding was missing from the hydrate literature.

Pore-Water Salinity and Hydrate Dissociation

Our laboratory studies also demonstrate that *in-situ* pore-water salinity can be determined from the pressure and temperature present at the onset of dissociation (Figure 2a). However, if dissociation is rapid, it proceeds at a pressure and temperature predicted for fresh water conditions. This occurs even when the average salinity of the system is much higher than that of fresh water (orange line, Figure 2a).

To explain this phenomenon, we suggest that when hydrate dissociates, fresh water surrounds the dissociating hydrate, resulting in localized fresh water conditions. Therefore, at the scale of a grid block, reservoir simulation models should assume that hydrate dissociates at the freshwater phase boundary. This is a significant finding with important implications for production strategies; in deepwater settings, dissociation at the freshwater phase boundary requires 2 to 4 MPa more pressure drawdown than dissociation at seawater salinity.

Figure 3. 3D renders of segmented volume of hydrate formation experiment. Hydrate exhibits interconnected hydrate pore-habit at the top of the vessel whereas the lower half of the vessel exhibits dispersed grain-attaching hydrate and concentrated brine at grain contacts. S^*_h indicates saturation of the hydrate-rich phase including non-segmentable brine within porous hydrate. Modified from Chen et al. (2020).

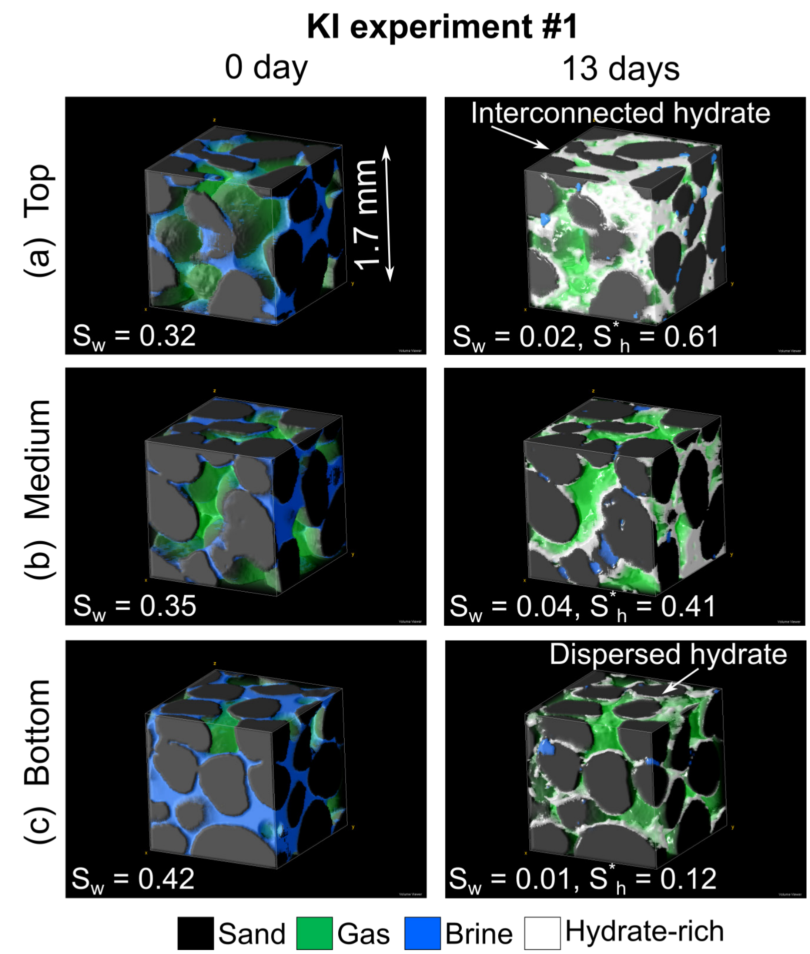
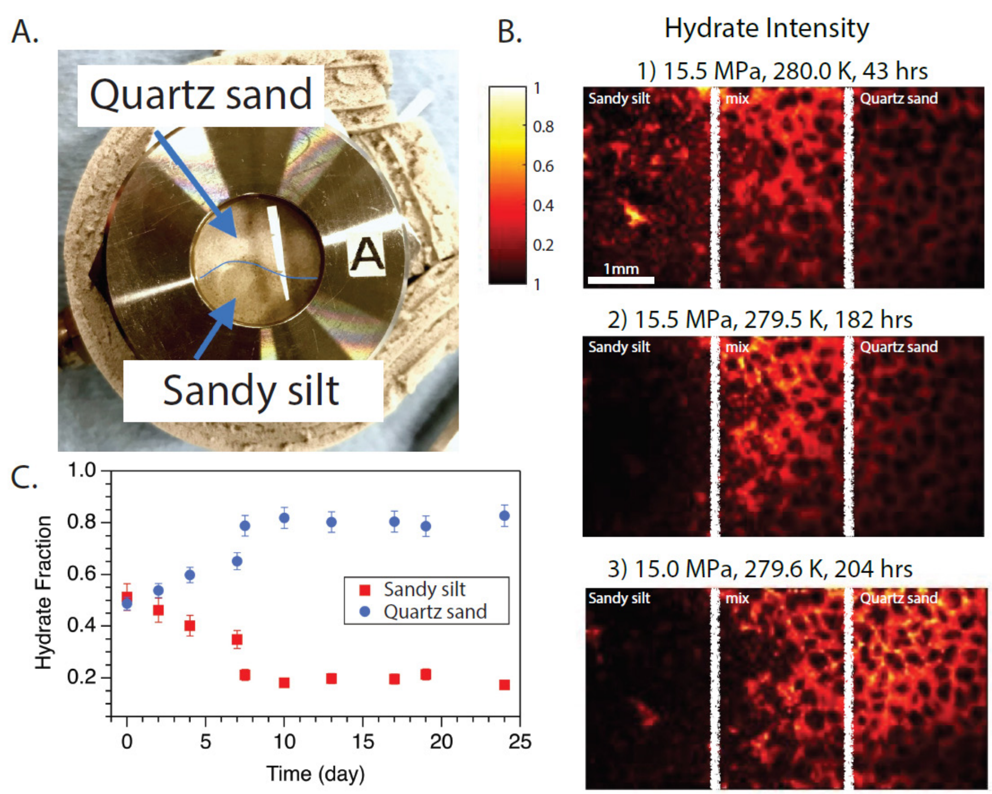


Figure 4. (A) Photo of 2 kinds of sediment loaded in the Raman chamber prior to hydrate formation: 1) natural sandy silt from core GC955-H005-06FB-2 and 2) quartz sand. The sandy silt has a median diameter of 40 µm whereas the Sand diameter ranged from 210-297 µm. (B) The temporal evolution of hydrate in the sandy silt (left column), mixed sediment (middle column), and quartz sand (right column) with increasing time at 43, 182, and 204 hours. The color bar is a relative scale and does not record absolute saturation. The sediment was saturated with methane vapor and then pressurized with 3.5 wt% NaCl to 15.5 MPa at 7. (C) Fraction of hydrate in the sandy silt versus the quartz sand layers over time.



Pore-Scale Observations

At the pore scale, hydrate formation shows significant changes in chemistry and pore habit over the timescale of laboratory experiments, e.g, hours to weeks. Micro-CT scanning during hydrate formation experiments reveals highly heterogeneous hydrate saturation and hydrate growth habits that vary from "grain-attaching" at low saturation to "pore-filling and interconnected" at high saturation (Figure 3). Understanding these changes is important, because the hydrate habit is known to influence relative permeability values.

In Micro-Raman experiments, we observe that when finer-grained sediment is placed adjacent to coarser-grained sediment, the hydrate nucleates first in the finer sediment, but evolves to higher concentrations in the coarser sediment (Figure 4). We interpret that nucleation was favored with the greater surface area of the finer sediment, but that capillary forces drive hydrate growth in the larger pores of the coarser-grained material.

Summary

We can now systematically make hydrate in porous media at a predictable saturation within hydrate cores. As a result, we can study macro-scale flow properties, including permeability and relative permeability, at a range of hydrate saturations (e.g., Figure 1). At the same time, a new generation of experimental analyses is illuminating pore-scale hydrate formation and dissociation processes. These studies show that the habit of methane hydrate in porous media is dynamic, both during hydrate formation and dissociation. We are beginning to link these pore-scale processes with macro-scale flow behavior. These insights are likely to result in improved capabilities for predicting how a hydrate reservoir system will behave during production.

Suggested Reading

Flemings, P.B., 2019. Final Scientific/Technical Report, A multi-scale experimental investigation of flow properties in coarse-grained hydrate reservoirs during production, Project DE-FE0028967. https://netl.doe.gov/sites/default/files/2020-01/FE0028967-Final-Report.pdf

Almenningen, S., Iden, E., Ferno, M.A., and Ersland, G., 2018. Salinity effects on pore-scale methane gas hydrate dissociation: Journal of Geophysical Research: Solid Earth, v. 123, no. 7, p. 5599-5608.

Brooks, R.H. and Corey, A.T., 1964. Hydraulic properties of porous media. Hydrology Papers 3. Colorado State University, Fort Collins.

Chen, X., Espinoza, D.N., Luo, J.S., Tisato, N., and Flemings, P.B., 2020. Pore-scale evidence of ion exclusion during methane hydrate growth and evolution of hydrate pore-habit in sandy sediments: Marine and Petroleum Geology, v. 117.

Kleinberg, R.L., Flaum, C., Griffin, D.D., Brewer, P.G., Malby, G.E., Peltzer, E.T., and Yesinowski, J. P., 2003. Deep-sea NMR: Methane hydrate growth habit in porous media and its relationship to hydraulic permeability, deposit accumulation, and submarine slope stability: Journal of Geophysical Research: Solid Earth, v. 108, no. B10, p. 2508.

Lei, L., Seol, Y., Choi, J.H., and Kneafsey, T.J., 2019. Pore habit of methane hydrate and its evolution in sediment matrix - Laboratory visualization with phase-contrast micro-CT: Marine and Petroleum Geology, v. 104, p. 451-467.

Murphy, Z.W., 2018. Three-Phase Relative Permeability of Hydrate-Bearing Sediments. M.S.Thesis. Hildebrand Department of Petroleum and Geosystems Engineering, University of Texas-Austin.

Phillips, S.C., Flemings, P.B., You, K., Meyer, D.W., and Dong, T., 2019. Investigation of in situ salinity and methane hydrate dissociation in coarse-grained sediments by slow, stepwise depressurization: Marine and Petroleum Geology, v. 109, p. 128-144.

Gas Hydrate Characterization in the Gulf of Mexico Using Electromagnetic Methods

Peter Kannberg and Steven Constable

Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA

Electrical resistivity is commonly used to identify subsurface formations containing methane hydrate. Resistivity measurements are typically obtained during borehole logging, where higher resistivities are known to indicate higher hydrate concentrations. Another approach, controlled source electromagnetic (CSEM) surveying, has become more common in recent years as a tool for inferring *in-situ* resistivities related to hydrate saturation in hydrate-prone regions.

In 2017, we collected 360 line-kilometers of CSEM data on Walker Ridge 313 (WR313), Orca Basin (WR100), Mad Dog (GC781), and Green Canyon 955 (GC955) in the Gulf of Mexico. All are areas with known or seismically-inferred gas hydrate deposits, and all have been drilled or targeted for future drilling. Here we present resistivity cross sections obtained at WR313, Orca Basin, and GC955 (Figure 1).

We deep-towed an EM transmitter that generates an alternating electric field that propagates through the seafloor geology. Data were recorded on 6 receivers towed behind the transmitter at distances between 550 and 1550 meters. In the presence of conductive geology, the electric fields become attenuated; conversely, in resistive geology, the fields are preserved.

Our data were inverted using a 2D inversion method that first optimizes the model-data misfit, then finds the smoothest model to fit the data. This method is designed to ensure that resistivity structures present in the final model are likely necessary to explain the observed signal.

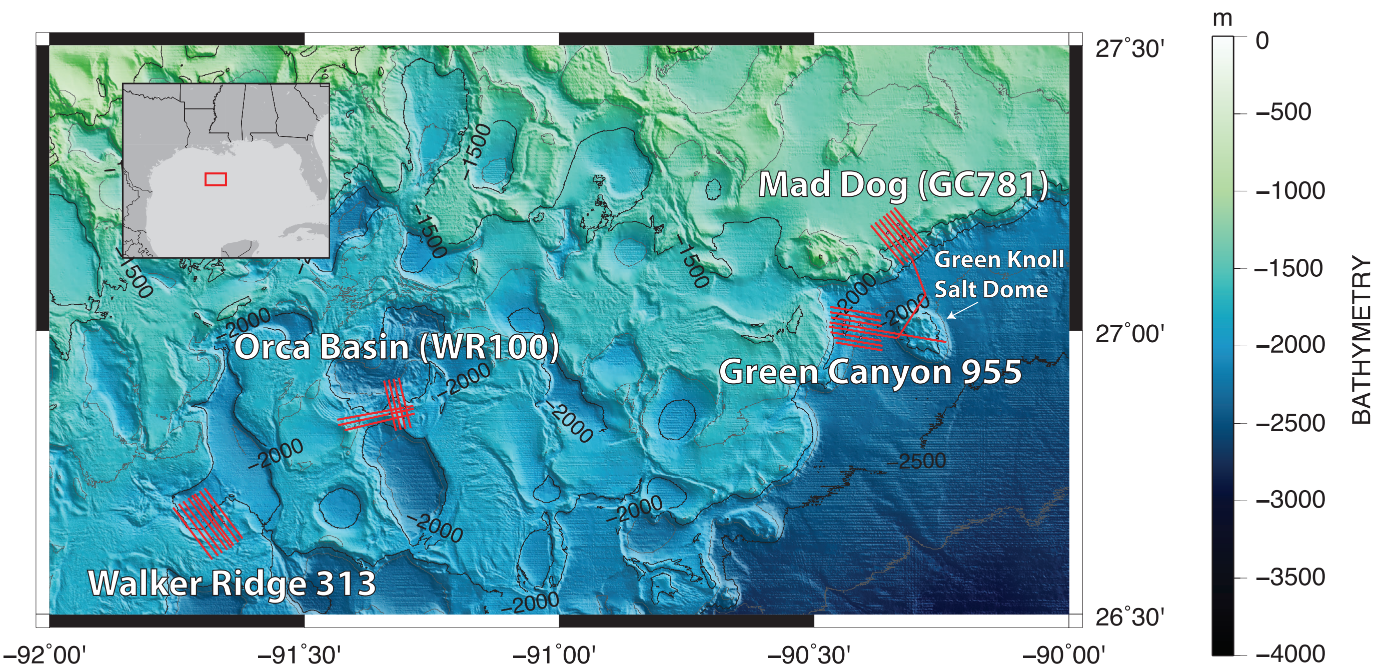
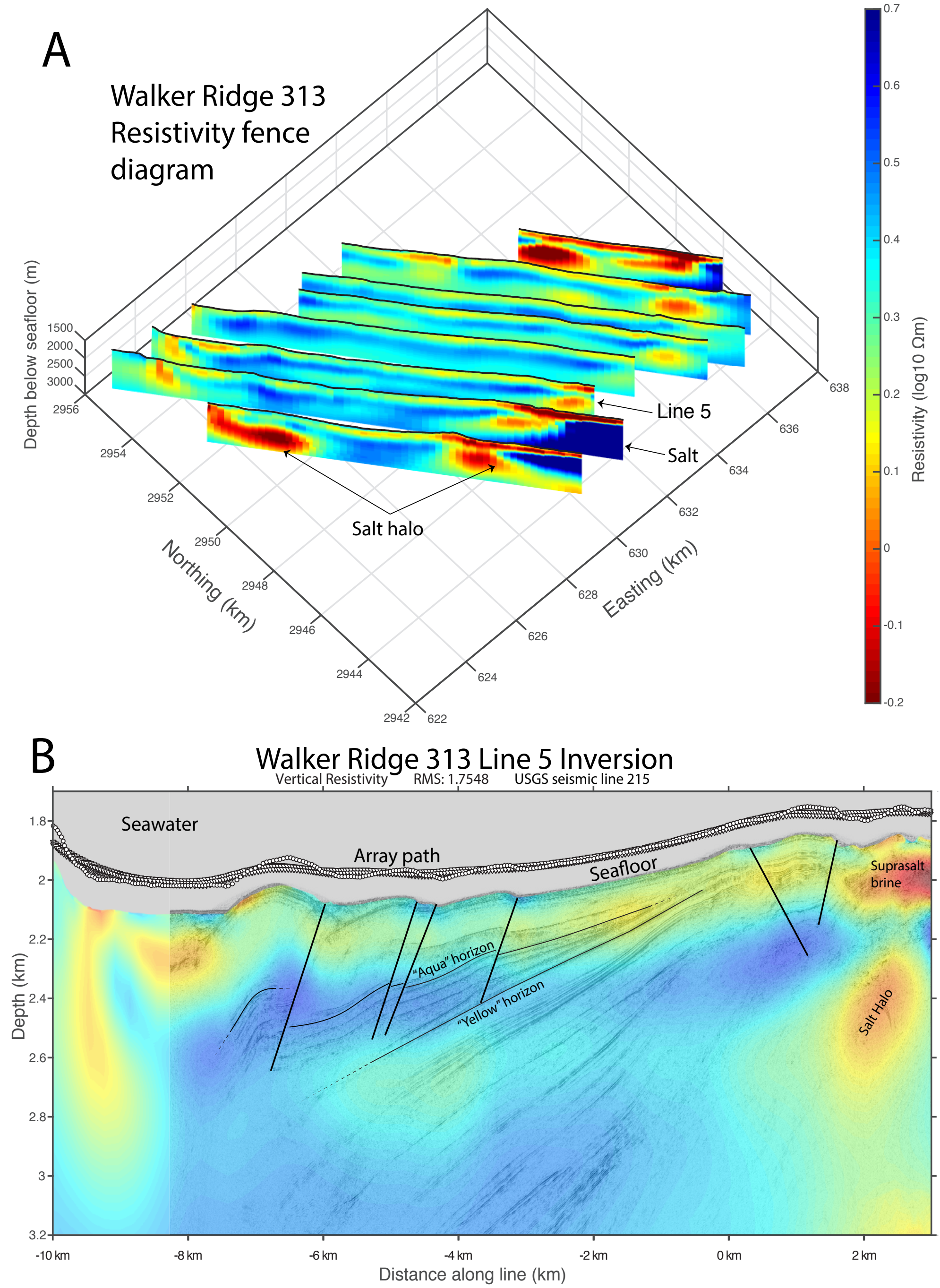


Figure 1. Map of the four survey areas. Inverted tow lines are marked as red lines on the map. Fence plots of the resistivity profiles are shown in Figures 2, 3, and 4. Mad Dog (GC781) is not included in this manuscript.

Walker Ridge 313

At WR313, data were inverted along 8 parallel profiles (Figure 2a). All inversions are anisotropic, meaning the vertical resistivity is permitted to vary from the horizontal resistivity.

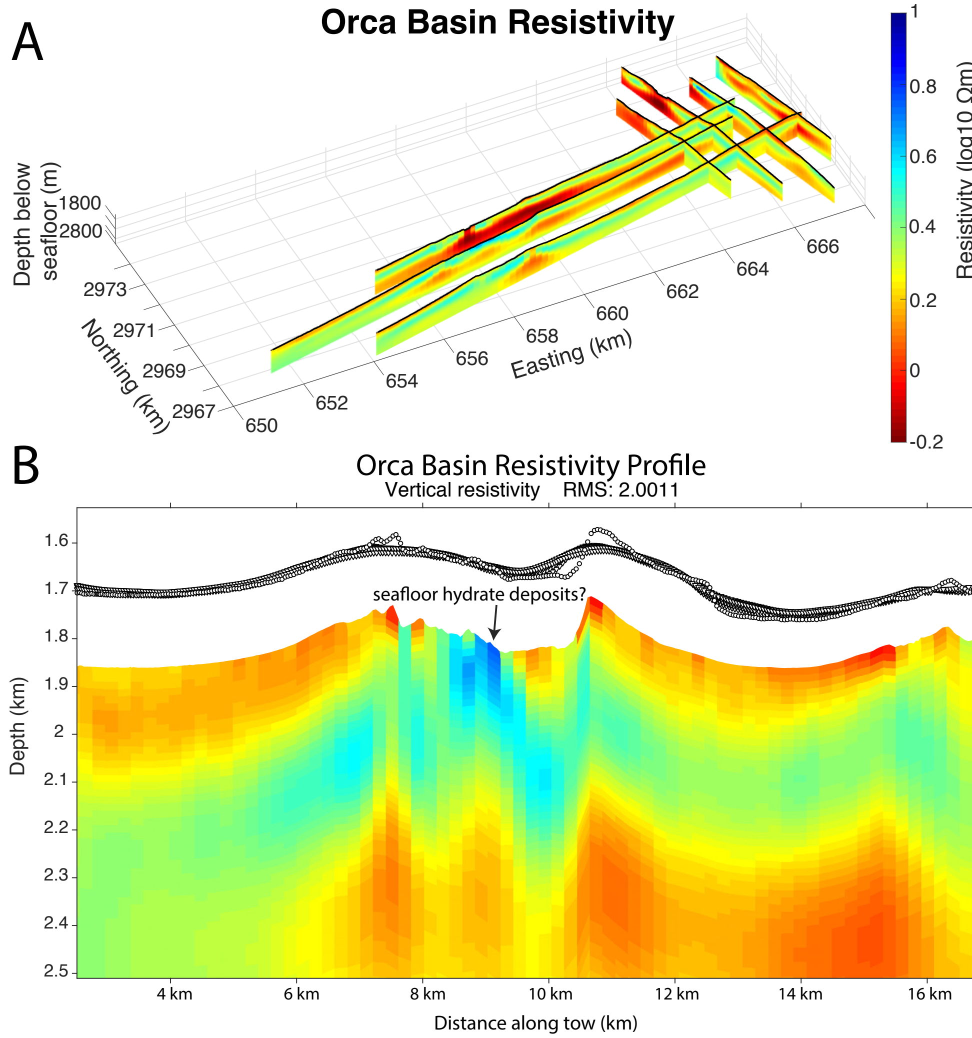
Figure 2. (A) Walker Ridge 313 fence plot showing resistivity cross sections, as viewed from the southwest. All inversions shown here have blue colors as more resistive and red colors as more conductive. The conductive brine halos surround the resistive salt bodies. (B) A single line from the fence plot is overlain on the coincident seismic profile. Increased resistivity is strongest within the depths bounded by the "Aqua" and "Yellow" horizons and adjacent to faults.



Salt tectonics profoundly affect the structure of modeled resistivity at WR313. Salt bodies flank the basin on all sides; they are apparent as regions of high resistivity surrounded by a conductive halo. This halo is interpreted to be the result of increased pore fluid salinity and temperature adjacent to the salt bodies.

Additionally, rising salt bodies control the local thrust faulting in the basin. When the resistivity models are overlain on seismic sections, increased resistivity is found in the unnamed unit that is bounded by the "aqua" and "yellow" sands (Figure 3b). Within this unit, resistivity is further enhanced adjacent to faults, which appear to form a structural trap, with hydrate concentrating in these areas. We also see increased horizontal resistivity in the vertically fractured Mendenhall Unit overlying the aqua sands, with little increase in vertical resistivity, suggesting CSEM methods are sensitive to strata-bound hydrate-bearing units such as the Mendenhall.

Figure 3. (A) Orca Basin resistivity fence plot. (B) Selected resistivity profile showing shallow hydrates that could be remnants of a hydrate system, possibly related to the slope failure observed within the slump feature.



We see a less pronounced increase in resistivity at depths where we expected to find the base of the hydrate stability field—for example, between kilometer 2 and 4 along WR313 line 5 (Figure 2b). These correspond to sand beds, which are thought to be hydrate bearing and which were the target of the logging operations during the Gulf of Mexico Gas Hydrate Joint Industry Project Leg II (JIP Leg II, DOE Project Number DE-FC26-01NT41330). The resistivity values modeled from the real data are roughly the same as those in pre-survey synthetic inversions using log resistivities from JIP Leg II.

Orca Basin

We analyzed CSEM inversions of seven lines across the ridge south of Orca Basin, including a slump feature on the western side of the ridge (Figure 3a). Increased resistivities within the slump provide a correlative, though not necessarily causative, link between hydrate and slope failure in the Orca Basin.

Historically, hydrate-mediated slope failure has been expected at the base of the hydrate stability field (BHSF), where free gas may cause overpressure, leading to slope failure. Recent studies, using both model results and observational data, suggest an alternate mechanism of hydrate-mediated slope failure caused by overpressured sediments within the hydrate stability field.

One explanation is that a vertical pipe structure of hydrate or free gas may extend above the BHSF, terminate at an impermeable barrier, or trap, and increase pore pressures laterally along the base of the trap. One of our inversions across the Orca Basin slump (Figure 3b) shows a dipping resistor that spreads laterally at the seafloor, possibly representing the relict hydrate plumbing system left behind after slope failure occurred.

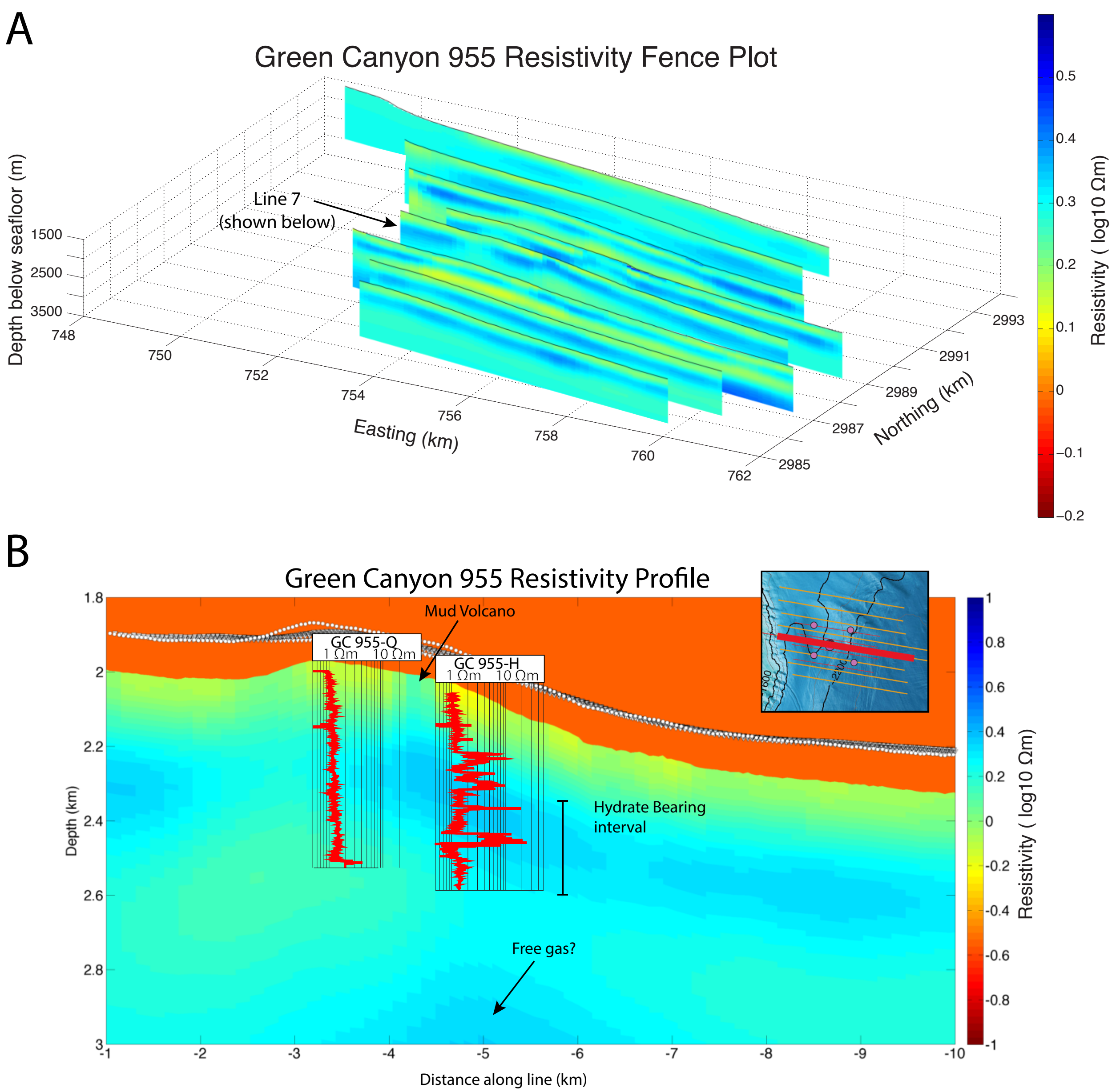


Figure 4. Resistivity fence plot at Green Canyon 955 (A). A resistivity profile across a mud volcano is shown in B. A narrow vertical resistor connects the deeper resistive body with the seafloor, a structure we often see associated with methane seeps. The resistivity profile broadly agrees with resistivity profiles from two nearby wells, though the CSEM method cannot match the resolution of well logs.

Green Canyon 955

Eight CSEM lines were towed at Green Canyon 955 (Figure 4a). Well logs from GC955 are in rough agreement with our inversions, with GC955 hole H showing significant increased resistivity interpreted to be hydrate, while hole Q, located upslope, shows no increased resistivity (Figure 4b). Below the hydrate-bearing interval is another resistor that is coincident with the depth of seismically inferred free-gas-bearing sediments.

Additionally, an area of increased resistivity between holes H and Q is coincident with a mud volcano known to be present on the seafloor. The resistivity signature beneath the mud volcano resembles that of methane seeps imaged at other locations around the world; it reveals a broad, deep resistor connected to the seafloor by a narrow resistive pipe.

In conclusion, at each of the proposed drilling sites, we found increased resistivity, which we interpret as evidence of increased hydrate concentrations. However, not only were the alternate sites in some cases more resistive than the primary sites, at WR313 the strongest resistors were not at the locations targeted for drilling. Anisotropic CSEM inversions are sensitive to strata-bound hydrate, such as the Mendenhall Unit at WR313, which cannot be detected using acoustic methods. At the Orca Basin slump feature, the resistive structure modeled here is consistent with hydrate-mediated slope failure models.

Acknowledgments

We thank the captain and crew of the *R/V Point Sur*. This work was supported by U.S. DOE award DE-FE0028972, U.S. BOEM award M17AC00015, Ocean Floor Geophysics, and the Scripps Seafloor Electromagnetic Methods Consortium.

Suggested Reading

CSEM Data Acquisition System:
Constable, S., Kannberg, P.K., and Weitemeyer, K., 2016. Vulcan: A deep-towed CSEM Receiver. Geochem. Geophys. Geosyst., 17, 1042–1064. https://doi.org/10.1002/2015GC006174

Orca Basin Geology:
Sawyer, D.E., Mason, R.A., Cook, A.E., & Portnov, A., 2019. Submarine landslides induce massive waves in subsea brine pools. Nature- Scientific Reports, 128, 9, 1, 2045-2322. https://doi.org/10.1038/s41598-018-36781-7

Hydrate-mediated Slope Failure:
Elger, J., Berndt, C., Rücke, L., Krastel, S., Gross, F., and Geissler, W.H., 2018. Submarine slope failures due to pipe structure formation. Nature Communications, 9, 1, 715. https://doi.org/10.1038/s41467-018-03176-1

Gulf of Mexico Gas Hydrate Joint Industry Project Leg II Overview:
Collett, T.S., Lee, M.W., Zyrianova, M.V., Mrozewski, S.A., Guerin, G., Cook, A.E., and Goldberg, D.S., 2012. Gulf of Mexico Gas Hydrate Joint Industry Project Leg II logging-while-drilling data acquisition and analysis. Marine and Petroleum Geology, 34, 1, 41-61. https://doi.org/10.1016/j.marpetgeo.2011.08.003

Claire McKinley Awarded NAS/NETL Methane Hydrate Research Fellowship

Meet Claire McKinley, recipient of the prestigious NAS/NETL Methane Hydrate Research Fellowship. Claire is the 11th recipient of the fellowship, which was created in 2007 to support highly qualified graduate and post-graduate scientists engaged in research on methane hydrate. McKinley's award will help fund two years of her research on "Evaluating the Extent of Microbial Fe-Reduction and its Role in the Global Methane Cycle." The work is being conducted at the University of Washington (UW), under the direction of faculty PI, Evan Solomon, who was himself a recipient of the Methane Hydrate Research Fellowship during 2008-2009.

McKinley grew up in Portland, Oregon and took an interest in the earth sciences in high school, while working as a student volunteer at the Outdoor School, a field-based learning program designed to give students hands-on experience in natural science and conservation. After high school, Claire attended Boston University, where she gained undergraduate research experience studying the geochemistry of volcanic ash from a Deep Sea Drilling Project site in the Northwest Pacific Ocean. She went on to pursue her PhD in oceanography at Texas A&M University, where she studied geochemical indicators used to track changing conditions in paleo-ocean basins. Upon completion of her PhD, Dr. McKinley took her current post at UW studying pore water collected from sediments on New Zealand's Hikurangi margin.

Claire is passionate about earth science teaching and learning, and she approaches teaching from a unique position as a rigorous scientist and creative communicator. Check out this visually appealing cartoon she developed to teach earth history and oceanography:

https://medium.com/spiralbound/geopoetry-space-and-time-104e80295938

Congratulations to Dr. McKinley on her NAS/NETL Research Fellowship!

Scientific Results Volume Published on India NGHP-02

The India National Gas Hydrate Program Expedition 02 (NGHP-02) Scientific Party has published a Journal of Marine and Petroleum Geology (JMPG) Special Issue, entitled:

Marine Gas Hydrate Reservoir Systems Along the Eastern Continental Margin of India: Results of the National Gas Hydrate Program Expedition 02.

The JPMG Special Issue (2019; Volume 108; https://www.sciencedirect.com/journal/marine-and-petroleum-geology/vol/108/suppl/C) presents results of this comprehensive gas hydrate scientific drilling investigation sponsored by the Government of India. The results volume is made up of four summary reports and 41 research articles, including reports on the discovery of several significant gas hydrate accumulations suitable for production testing.

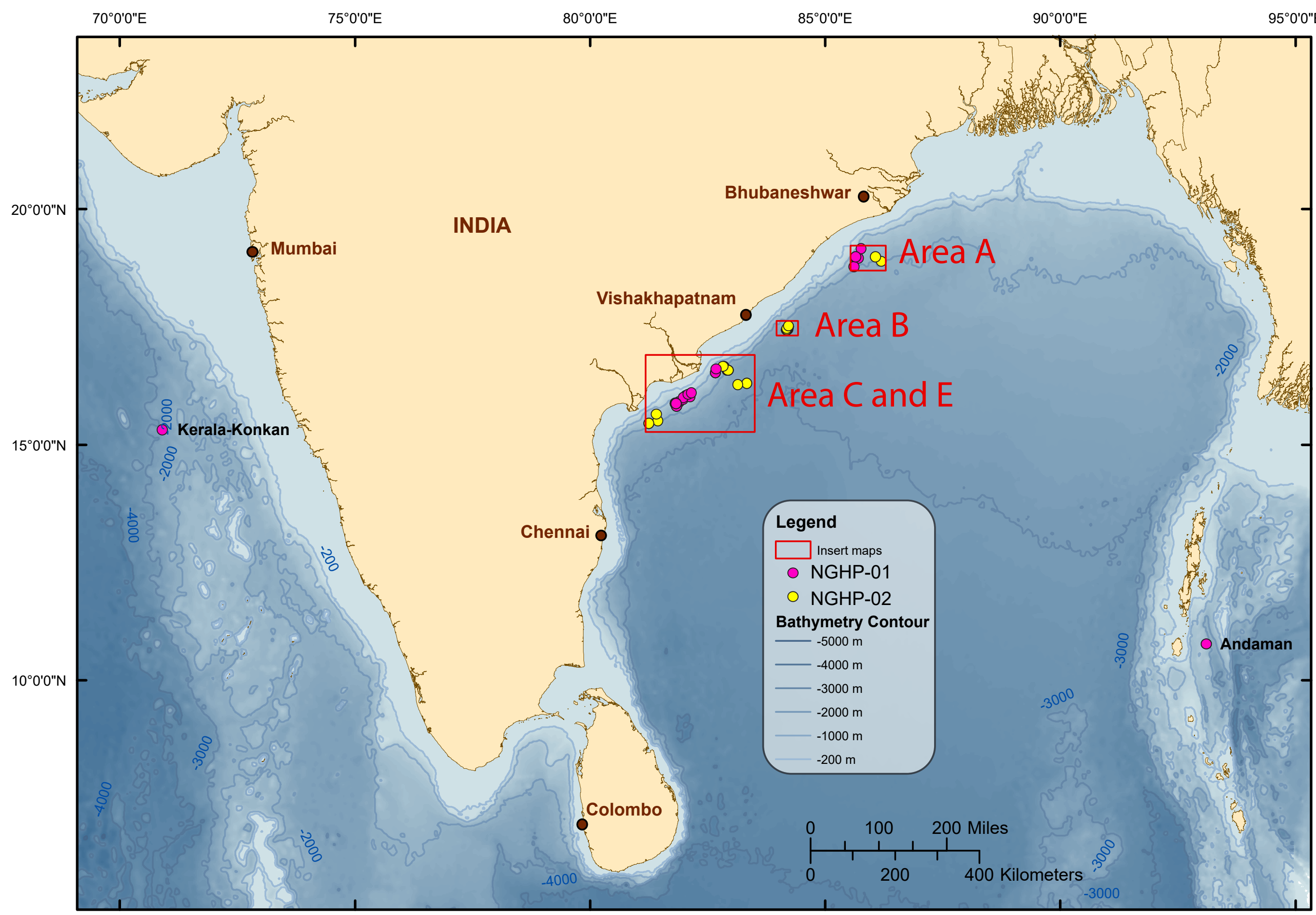
Summary Reports Featured

The summary reports present the operational and scientific results of the NGHP-02 Expedition. The first summary report, "India National Gas Hydrate Program Expedition 02: Operational and Technical Summary," focuses on the tools and operational procedures for the NGHP-02 Expedition that led to the acquisition of an unprecedented amount of high-quality downhole logging and core data from numerous pore-filling, fracture-filling, and sediment-displacement types of gas hydrate occurrences. The Open-Access summary report titled "India National Gas Hydrate Program Expedition 02 Summary of Scientific Results: Gas Hydrate Systems Along the Eastern Continental Margin of India" documents gas hydrate occurrences discovered during the NGHP-02 Expedition and examines geologic controls on the gas hydrate systems along the eastern continental margin of India. The "India National Gas Hydrate Program Expedition 02 Summary of Scientific Results: Evaluation of Natural Gas Hydrate-Bearing Pressure Cores" summary report presents a systematic review of select findings and implications of the coordinated pressure-core evaluation program as described in numerous technical reports within this Special Issue. The summary report titled "India National Gas Hydrate Program Expedition 02 Summary of Scientific Results: Numerical Simulation of Reservoir Response to Depressurization" addresses the key issues associated with understanding the potential production response of two gas hydrate accumulations discovered during the NGHP-02 Expedition to scientific depressurization experiments.

NGHP-02 Results Volume continued

Technical Articles

The technical articles included in this JPMG Special Issue span a broad range of topics. The formation of highly concentrated gas hydrate accumulations, which are more suitable for energy extraction, requires the presence of relatively coarse-grained sediments with porosity sufficient to support the migration and accumulation of gas and the nucleation of gas hydrate. The results of downhole logging, coring, and formation pressure testing operations during NGHP-02 confirmed the presence of extensive sand-rich depositional systems throughout the deepwater portions of the Krishna-Godavari and Mahanadi Basins.



National Gas Hydrate Program Expedition 01 (NGHP-01) and National Gas Hydrate Program Expedition 02 (NGHP-02) drill site map depicting the location of the drill sites established in the Krishna-Godavari (Area B, Area C, and Area E), Mahanadi (Area A), Kerala-Konkan (west coast of India), and Andaman (western edge of the Andaman Sea) deep offshore areas of India.

NGHP-02 Results Volume continued

Two areas of the Mahanadi Basins. Two areas of the Krishna-Godavari Basin, referred to as Areas B and C, contain substantial gas hydrate accumulations in sand-rich systems and therefore represent ideal candidate sites for future gas hydrate production testing.

In the Krishna-Godavari Basin, extensive reservoir systems were confirmed with sediment grain-sizes ranging from coarse-silt to gravel. Reservoirs in this area range from fully- to partially-filled with gas hydrate. The gas included with the hydrate accumulations is determined to be from only microbial sources—in part migrated into these reservoirs from deeper systems. The controls on gas hydrate occurrence are complex and varied, and they depend on the substantial reservoir heterogeneity in these systems. Hydrate occurrence requires sufficient permeability throughout the reservoirs and seals to allow pervasive fluid flow into and through the hydrate-bearing systems. These discoveries represent confirmation of the exploration approach that was employed for this expedition; the approach focuses on direct detection of hydrate reservoirs supported by comprehensive petroleum systems analyses.

The work conducted on the NGHP-02 cores provided confirmation of insights from prior work. For example, core studies confirmed strong correlations between sediment properties (grain size, sorting, mineralogy), gas hydrate saturation, and sediment strength. The effort further confirms recent findings regarding the variability in gas hydrate reservoir quality, most notably the occurrence of permeabilities measured in the tens of milli-Darcys within highly saturated core samples. The studies also indicated new insights, including recognition of potential impacts of post-depressurization reservoir consolidation on effective permeabilities.

To assess the potential response of discovered gas hydrate deposits to depressurization, comprehensive geologic models were constructed to enable numerical simulation of expected results for two sites. Both sites (Area C: NGHP-02-09 and Area B: NGHP-02-16) feature thick sequences of thinly-interbedded reservoir and non-reservoir facies at sub-seafloor depths less than 300 m and sub-sea depths of 2900 m or more. These settings pose significant challenges to current modeling capabilities.

First, the thinly-interbedded reservoir architecture complicates the determination of basic reservoir parameters, from both log and core data, due to measurement resolution issues. Second, the fine-scale variation in sediment properties imparts large contrasts in key parameters over very short distances, creating high gradients that

NGHP-02 Results Volume continued

necessitate careful design of high-definition simulation grids. Third, the deposits include internal sources of water, as well as a range of complex boundary conditions, including variable permeability within the overlying mud-rich "seals." These factors complicate reservoir depressurization and must all be addressed in order to confirm the viability of modeled accumulations for scientific testing; identify key challenges related to the selection of specific test sites; and optimize the design of test wells.

Technical Highlights

Salient technical highlights to emerge from the NGHP-02 expedition and this JMPG Special Issue can be summarized as follows:

- The addition of the NGHP-02 discoveries to the inventory of known gas hydrate occurrences has increased awareness of the complexities in the evaluation of gas hydrate systems.
- The nature of the discovered gas hydrate occurrences during NGHP-02 closely matched the pre-drill predictions, confirming the project's depositional models for sand-rich depositional facies in the Krishna-Godavari and Mahanadi Basins.
- The availability of gas to charge several of the discovered reservoir systems appears to be a limiting factor for the formation of highly concentrated gas hydrate accumulations in some settings along the eastern margin of India, particularly in the Mahanadi Basin.
- NGHP-02 established the existence of a well developed gas hydrate system in Area C of the Krishna-Godavari Basin, with the discovery of a large slope-basin depositional system that includes sand-rich, gas-hydrate-bearing channel-levee accumulations at Sites NGHP-02-08 and -09.
- The acquisition of closely-spaced LWD and core holes in the Area B L1 Block gas hydrate accumulation have provided one of the most complete three-dimensional petrophysical-based views of any known gas hydrate reservoir system in the world.
- Areas B and C contain important gas hydrate accumulations and represent ideal sites for future gas hydrate production and geomechanical testing.

Spotlight on Research

SETH HAINES

U.S. Geological Survey
Denver, Colorado

Seth Haines is a scientist with a passion for mountain adventures. He works as a Research Geophysicist at the USGS in Denver, where a typical day finds him at his computer processing and interpreting seismic data, writing Matlab code, or preparing scientific journal articles for publication. For Seth, the perfect antidote to a week of research is a weekend in the Colorado Rockies, preferably on a mountain bike or a pair of backcountry skis.

For skiing, he prefers alpine touring (AT) or telemark equipment. These skis work well for climbing and descending steep mountain slopes. A well-rounded day in the backcountry might include an arduous climb to a remote summit; followed by a majestic vista, with no chairlifts to be seen; and finally, an invigorating descent, carving turns through fresh, untracked powder. That is perhaps the ideal, but Seth also enjoys skiing gentler terrain on lightweight cross-country skis. The rewards are different but also gratifying—fresh air, exercise, tranquility, and time with friends.

Seth grew up in rural Vassalboro, Maine. Soon after learning to walk, he was skiing and exploring the woods and mountains of his home state. Through that upbringing, he developed a strong connection to the outdoors, and this grew into a lifelong love of wilderness excursions.

Seth attended Middlebury College, in the Green Mountains of Vermont, where he completed a double major in geology and physics. The physics major was planned; the geology major was not. According to Seth, "being a physics major was a solid choice for a nerdy young person such as myself, but I fell into geology and geophysics mostly by luck." During his freshman year, he took a class on the geology of the Appalachian Mountains, and he was hooked. He recalls, "it was pretty great to get course credit for hiking around Vermont, looking at rocks, and figuring out how all the pieces fit together and how the mountains got there."

Geophysics was the natural integration of physics and geology. An NSF-sponsored project provided the opportunity to acquire seismic data in the Ross Sea of Antarctica, leading to a senior thesis and further cementing Seth's interest in geology and geophysics as a career path. Seth went on to pursue M.S. and Ph.D. degrees in geophysics at Stanford, first doing research on the tectonic evolution of the Tibetan Plateau and then working to develop seismoelectric surveying methods for detection of shallow subsurface geologic features.

Seth currently applies seismic and related geophysical methods to the characterization of subsurface hydrate deposits. In addition, as a separate research focus area, he is developing methods to quantify environmental and water-related impacts of oil and gas production. And he is always on the lookout for the next adventure in the mountains.

If you or someone you know would like to be the subject of the newsletter's next "Spotlight on Research," please contact Karl Lang (klang@keylogic.com) or Fran Toro (frances.toro@netl.doe.gov). Thank you!

NATIONAL ENERGY TECHNOLOGY LABORATORY