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Fire in the Ice

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Gas Hydrate-Bearing Sand Reservoir Systems in the Offshore of India: Results of the India National Gas Hydrate Program Expedition 02

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The India National Gas Hydrate Program Expedition 02 (NGHP-02) was conducted from 3-March-2015 to 28-July-2015 off the eastern coast of India using the deepwater drilling vessel *Chikyu* (Figure 1). The primary goal of this expedition was to explore for highly saturated gas hydrate occurrences in sand reservoirs that would become targets for future production tests. The first two months of the expedition were dedicated to logging-while-drilling (LWD) operations, with a total of 25 holes drilled and logged. The next three months were dedicated to coring operations at 10 of the most promising sites. With a total of five months of continuous field operations, the expedition was the most comprehensive dedicated gas hydrate investigation ever undertaken.

Figure 1. The deepwater D/S Chikyu, as deployed during NGHP-02, was designed by the Japanese government for international scientific drilling operations.

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Indian National Gas Hydrate Program

The National Gas Hydrate Program (NGHP) in India was initiated by the Ministry of Petroleum and Natural Gas (MoP&NG) in 1997. In 2000 the NGHP was reconstituted by the MoP&NG under the overall coordination of the Directorate General of Hydrocarbons (DGH). NGHP is monitored by a Steering Committee chaired by the Secretary of the MoP&NG. The ultimate goal of the NGHP effort is to develop both the knowledge and technology needed to exploit gas hydrates as an energy resource in a cost effective and safe manner. In addition to the NGHP Steering Committee, the NGHP includes a Technical Committee with representatives from MoP&NG, DGH, Oil and Natural Gas Corporation Limited (ONGC), Oil India (OIL), Indian Oil Corporation Limited (IOC), GAIL (India) Limited, National Institute of Oceanography (NIO), National Geophysical Research Institute (NGRI), and the National Institute of Ocean Technology (NIOT).

One of the major milestones of the NGHP effort was the completion of the NGHP Expedition 01 (NGHP-01) in 2006. Gas hydrates discovered during NGHP-01 occurred mostly as fracture-filling material within fine-grained sediments in shelf/slope settings. In 2009, planning began for the next gas hydrate drilling expedition with a specific focus on evaluating deeper-water, toe-of-slope settings that are more conducive to the discovery of the sand-rich gas hydrate prospects considered to be more suitable for future energy production.

NGHP-02 Expedition Planning and Operations

The NGHP-02 pre-expedition drill site review included more than 80 sites among various Indian offshore basins. Of these, 25 sites from the Krishna-Godavari and Mahanadi Basins were selected as candidate test sites for NGHP-02 (Figure 2).

NGHP-02 was planned and managed by ONGC on behalf of the NGHP and the MoP&NG (Figure 3). The drilling platform was the research vessel *D/S Chikyu*, operated by the Japanese Drilling Company (JDC) and the shipboard science program was managed by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). LWD, wireline logging, and formation testing services were provided by Schlumberger. Pressure coring tools were provided by JAMSTEC, and shipboard pressure core operations and analysis were provided by Geotek Coring. Additional operational and scientific support was provided by the U.S. Geological Survey (USGS), the U.S. Department of Energy (US-DOE), the National Institute of Advanced Industrial Science and Technology (AIST), and the Japan Oil, Gas and Metals National Corporation (JOGMEC).

Operational highlights of NGHP-02 included the following:

- A total of 42 holes were drilled in 147 days, at water depths ranging from 1,519 to 2,815 meters (m), with sub-seafloor depths ranging from 239 to 567 meters below sea floor (mbsf).
- LWD was carried out in 25 holes, with the sedimentary section drilled/logged totaling 6,659 m. Wireline logging was also conducted in 10 holes.
- Conventional wireline and pressure cores were acquired in 16 holes, with a total of 390 conventional core runs made, 2,834 m of

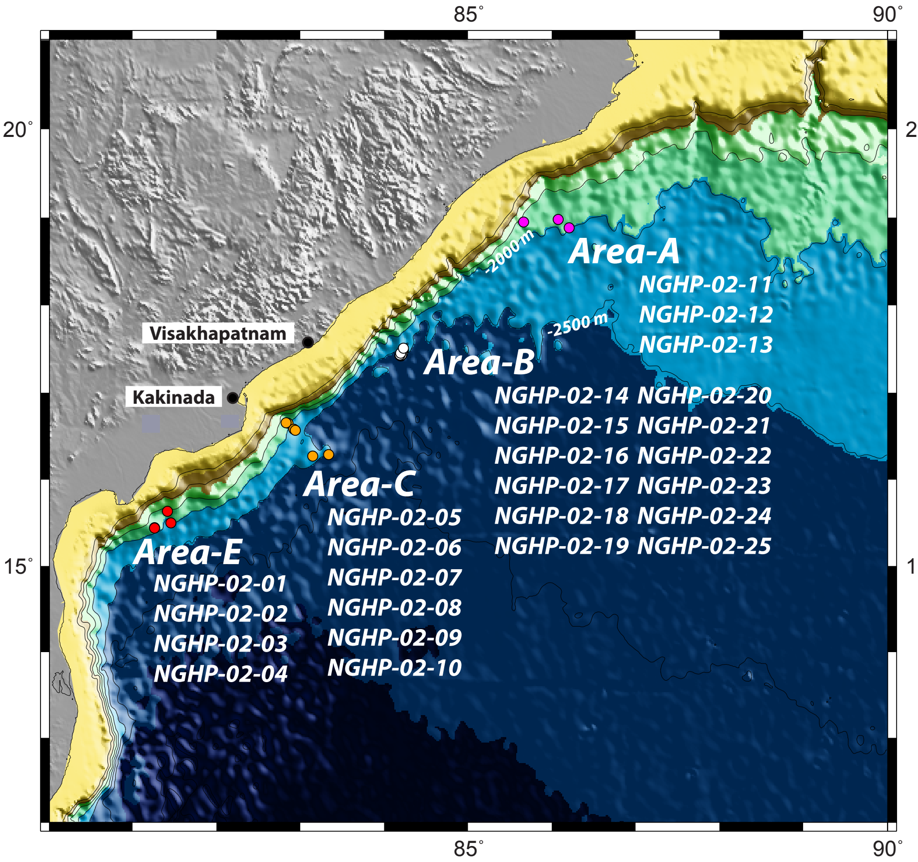


Figure 2. The National Gas Hydrate Program Expedition 02 (NGHP-02) established 25 research drill sites in the Mahanadi Basin (Area A) and the greater Krishna-Godavari Basin (Area B, Area C, and Area E).

sedimentary section cored, and 2,271 m of core recovered. Formation temperatures were measured ahead of the drill bit during piston-style (HPCS) coring operations using the third generation APCT-3 temperature tool.

- The pressure-coring-tool-with-ball (PCTB) pressure coring system was deployed for a record-setting 104 times, recovering a total of 156 m of pressurized core material.
- Pressure core subsamples were quantitatively degassed to determine the gas hydrate concentration, mechanically tested on board using the PCATS Triaxial equipment, or rapidly degassed for direct visual observation and storage in liquid nitrogen. Selected longer core samples (~1m long) were stored at pressure in storage chambers for shore based analysis at a later date (Figures 4 and 5).
- Wireline formation pressure and flow tests using the Modular Dynamic Tester (MDT) were successfully conducted in 2 holes.

NGHP-02 Expedition Findings

NGHP-02 downhole logging, coring and formation pressure testing have confirmed the presence of large, highly saturated gas hydrate accumulations in coarse-grained sand-rich depositional systems throughout the Krishna-Godavari Basin; specifically, within the regions defined during NGHP-02 as Area-B (Figures 6 and 7), Area-C (Figures 8 and 9), and Area-E.

Figure 3. NGHP-02 operations and results were reviewed onboard D/S Chikyu on 25th June 2015 by the Ministerial delegation led by Mr. Dharmendra Pradhan, Honourable Minister of Petroleum & Natural Gas (I/C), Government of India. The encouraging results from NGHP-02 have paved the way for further research on gas hydrate production tests in the offshore of India.

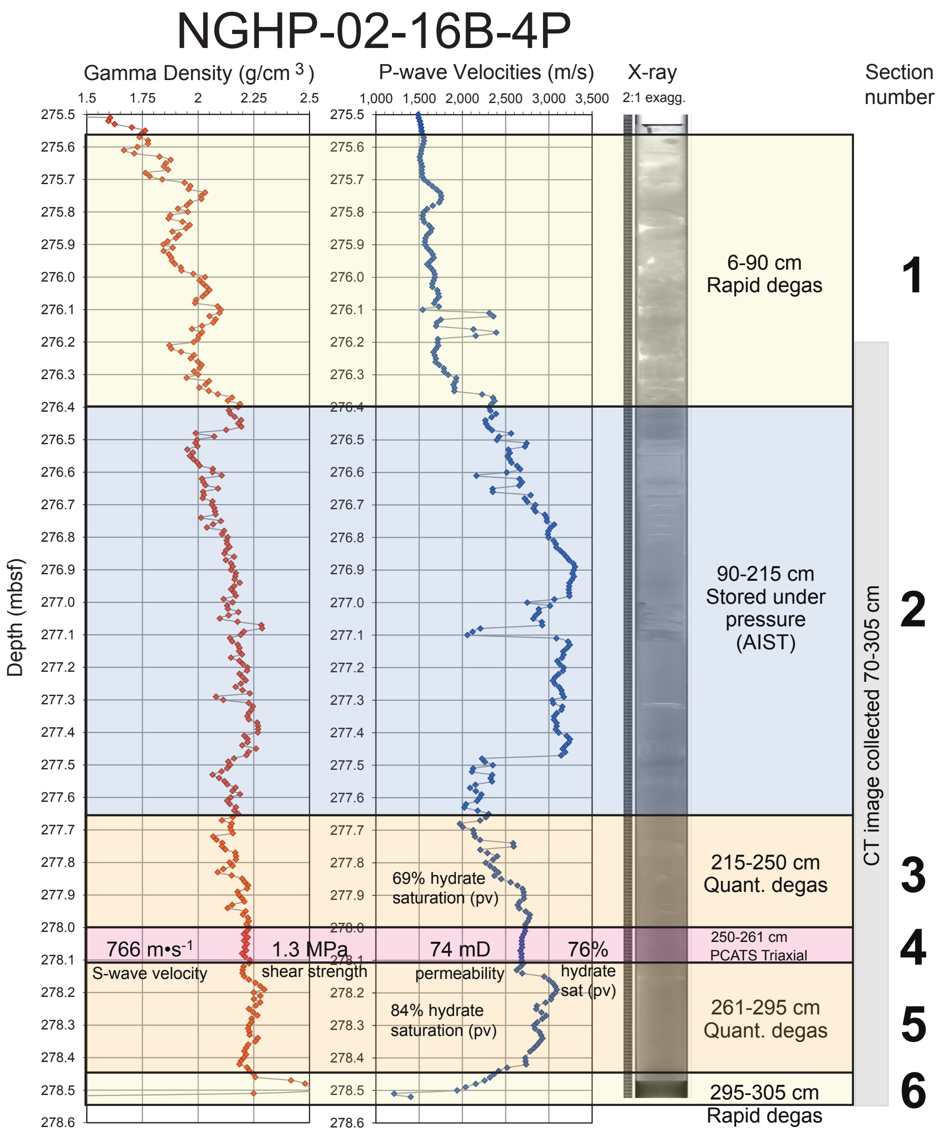


Figure 4. Geotek PCATS pressure core scans (X-ray image, P-wave, and gamma density profiles) were used to identify gas hydrate-bearing sand-rich reservoir sections as shown in this example core display primarily by elevated P-wave velocities. This core was cut into six sections while being maintained under pressure in PCATS as shown. Two core sections were quantitatively degassed to determine the gas hydrate saturations. A 125 cm long section of core was preserved for shore-based studies, and another 11 cm long section of core was tested on board using PCATS Triaxial.

Figure 5. The Geotek Coring PCATS system on the D/S Chikyu provided essential pressure core handling and analysis infrastructure. In situ pressures are maintained while cores are transferred from coring tools, analyzed in detail, cut into subsamples, and transferred into test chambers for advanced laboratory testing.

Figure 6. The primary gas hydrate target in Area-B is a large regional anticlinal structure that is cut by a well-developed BSR. Two potential reservoir systems were identified in Area-B, with the deeper reservoir (R2) imaged as a peak-leading (high velocity) seismic event just above the BSR.

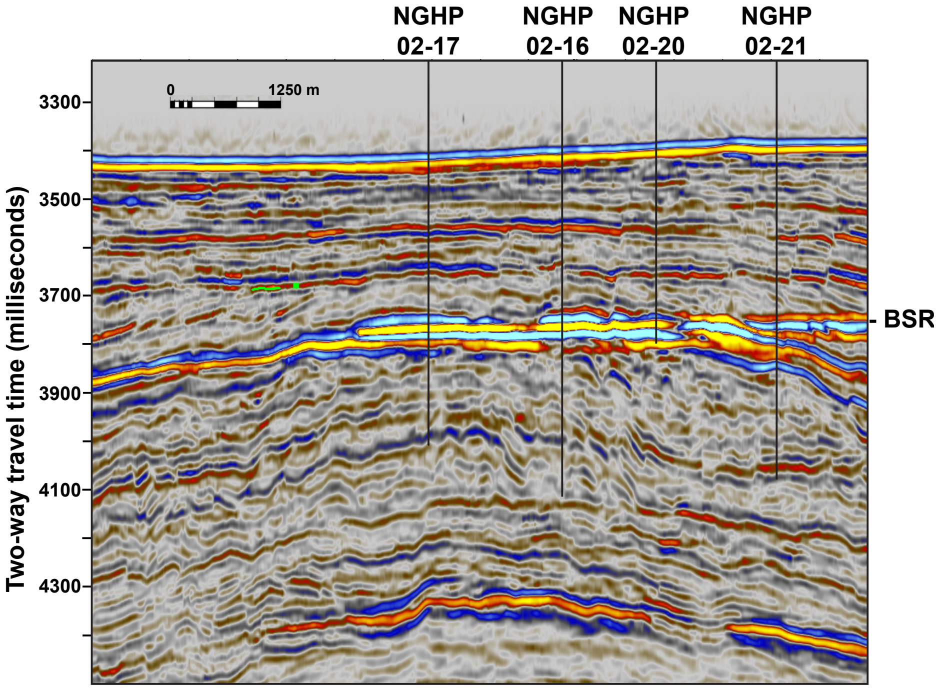
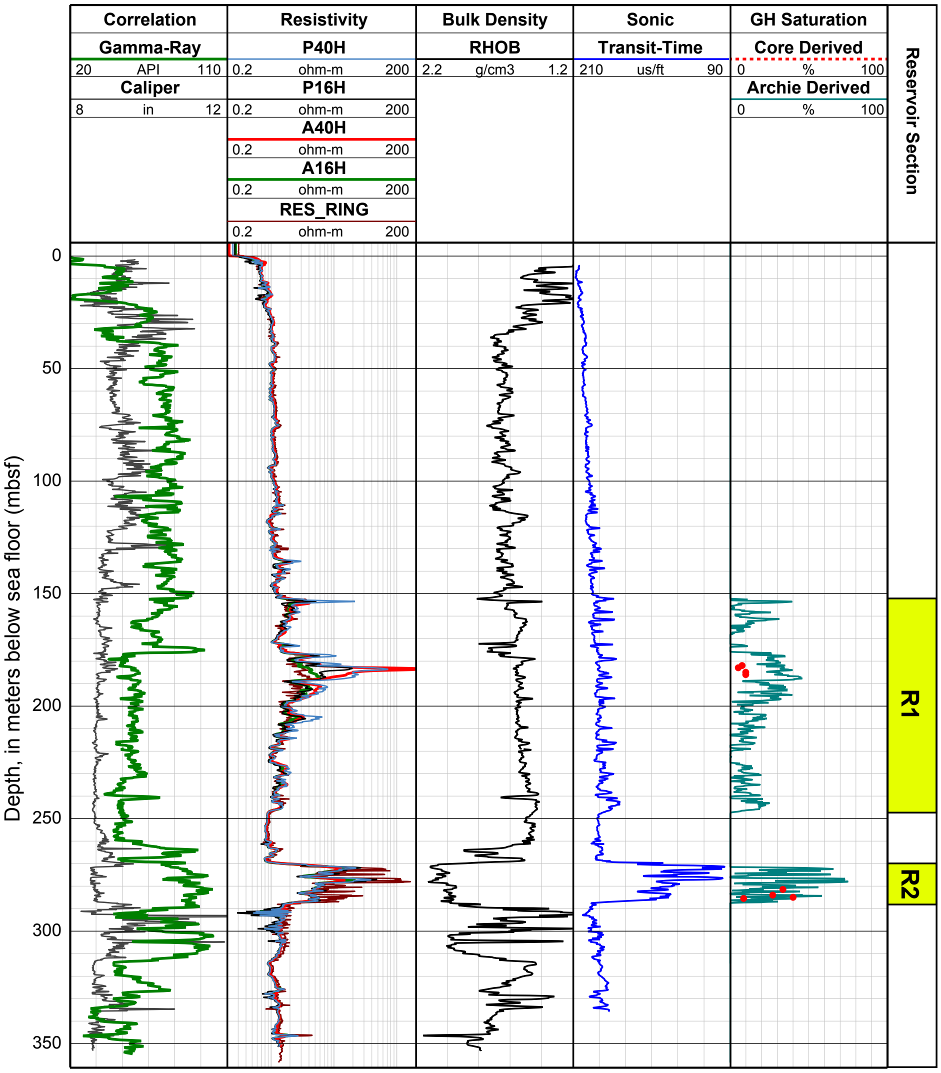


Figure 7. Two potential reservoir systems were identified in the wells logged and cored in Area-B, including an "upper" reservoir faces (R1) with both pore-filling and fracture-filling gas hydrate and a second "lower" (R2) sand-rich reservoir section characterized by high gas hydrate saturations. Note that the Archie well log evaluation techniques overestimate gas hydrate saturations in fracture-filling gas hydrate accumulations such as in reservoir R1.



The most significant scientific accomplishments of NGHP-02 included the following:

- The nature of the discovered gas hydrate occurrences closely matched pre-drill predictions, confirming the project-developed depositional models for the 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.
- The existence of a fully developed gas hydrate petroleum system was established in Area-C of the Krishna-Godavari Basin with the discovery of a large slope-basin interconnected depositional system, including a sand-rich, gas hydrate-bearing channel-levee prospect at Sites NGHP-02-08 and -09 (Figures 8 and 9).
- 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 (Figures 6 and 7).
- Wireline formation pressure testing, nuclear magnetic resonance (NMR) log data, and shipboard pressure core analysis have shown that the effective permeabilities of hydrate-bearing sand reservoirs are possibly significantly higher than those interpreted from previous field and laboratory studies.
- Area-B and Area-C contain important world-class gas hydrate accumulations and represent ideal sites for the consideration of future gas hydrate production testing.

Future NGHP Plans

Post-expedition studies are underway on the unprecedented number of core samples and data sets collected during NGHP-02. Preliminary work is also underway on planning of a future gas hydrate production testing program that will likely involve one or more of the gas hydrate-bearing sand reservoir systems discovered during NGHP-02.

Figure 8. Available 3-D seismic data volumes from Area-C in the Krishna-Godavari Basin imaged a wide range of deepwater depositional systems with apparent sand-rich facies including the channel-levee system targeted at Sites NGHP-02-08 and -09.

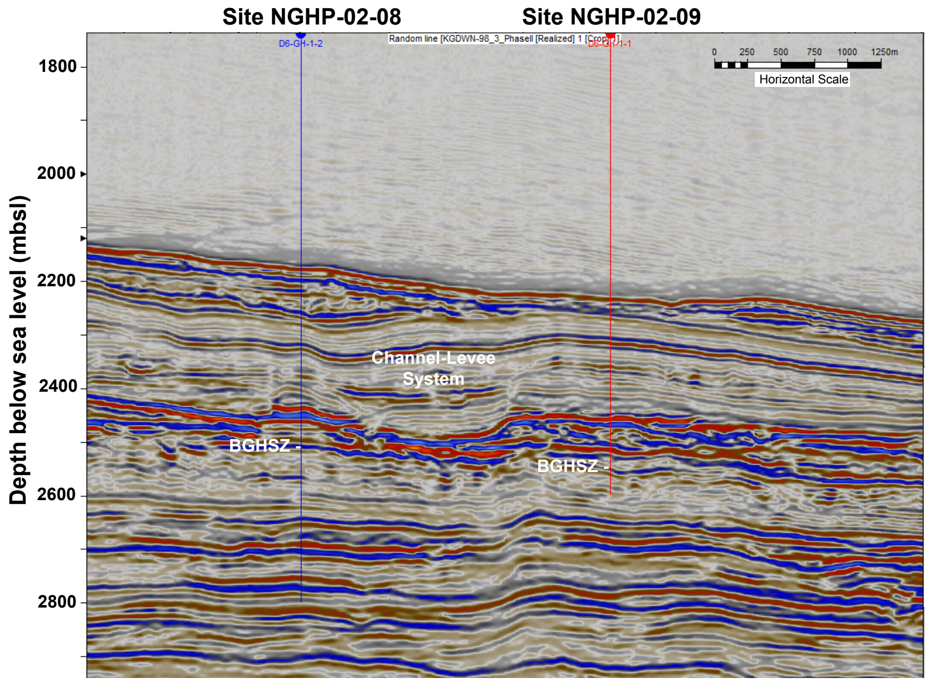
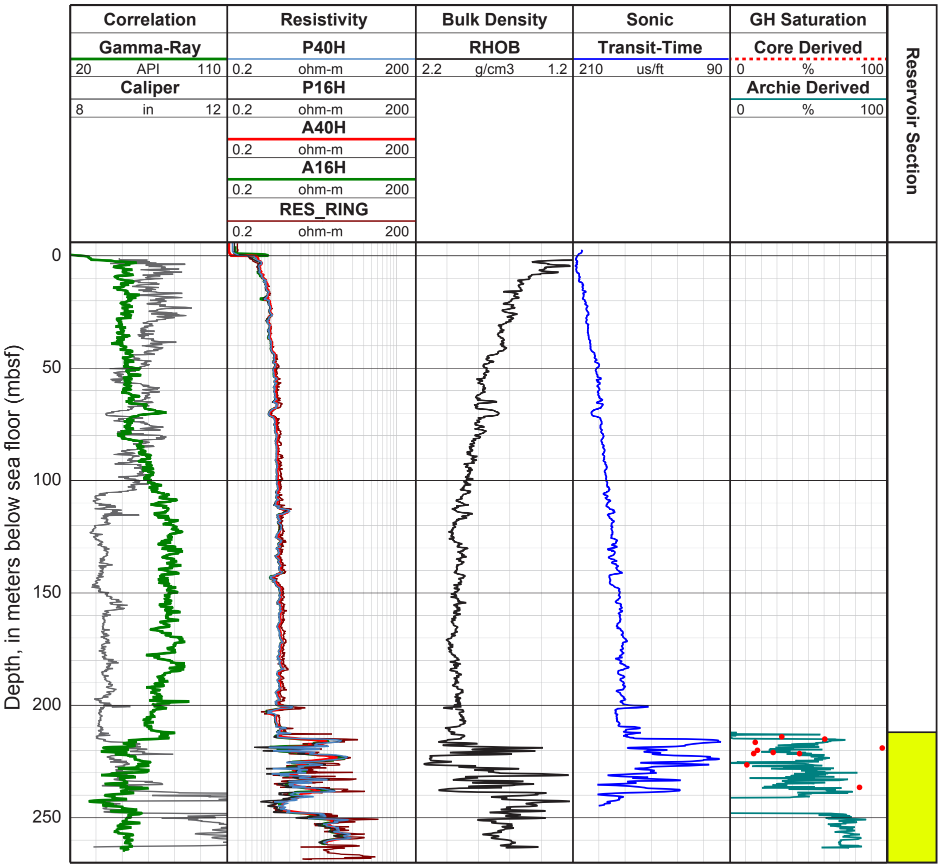


Figure 9. Hole NGHP-02-09-A in Area-C penetrated a 50-m-thick interval of what appears to be a sand-rich channel-levee deposit with high gas hydrate saturations.



THE POTENTIAL FOR ABIOTIC METHANE IN ARCTIC GAS HYDRATES

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Most methane enclosed in gas hydrates is biotic in origin, formed by microbial degradation of sedimentary organic matter. Increasingly, there is evidence that substantial gas hydrate may also be sourced from thermogenic decomposition of organic matter and subsequent migration of this gas into the gas hydrate stability zone. In addition, there is a third potential source of methane that does not involve organic matter at all—abiotic methane, which can be generated by magmatic processes or gas-water-rock reactions in the crust and upper mantle.

Abiotic Methane in Slow and Ultraslow Spreading Environments

The Earth produces abiotic methane in a variety of geologic settings and at a range of temperatures and pressures from chemical reactions that do not directly involve organic matter. Experimental studies and field observations in modern slow and ultraslow spreading mid-ocean ridge environments have shown that serpentinization reactions occur during the high temperature (>200 °C) hydrothermal alteration of ultramafic rocks, resulting in significant hydrogen production. The hydrogen produced during serpentinization can react with CO or CO_2, via Fischer-Tropsch Type Reactions, to produce abiotic methane.

During the last 25 years, studies at modern ultramafic-hosted seafloor hydrothermal vents along the Mid-Atlantic Ridge provide clear evidence for high hydrogen and methane concentrations. Serpentinization in slow and ultraslow spreading ridge environments is focused along large detachment faults that can exhume deeper crustal and upper mantle rocks and accommodate a significant portion of the extension along magma-limited ridge segments. Such detachments are often well developed at the inside corners of ridge-transform intersections and are believed to be active for 1 to 4 million years, limiting active serpentinization and abiotic methane venting to the youngest crust near the ridge axis.

In the north Atlantic and Arctic ocean basins, spreading ridge rates are transitional from slow to ultraslow spreading (Figure 1). As spreading rates decrease, extension is accommodated mainly by detachment faulting, with minimal volcanism. Low-angle detachment faults and exhumed serpentinized peridotites have been observed and sampled on Gakkel Ridge; serpentinite and peridotite have been sampled on Lena Trough and Molloy Ridge; and black smokers and vent fauna have been observed at the junction of the Mohns and Knipovich Ridges, near exhumed detachment surfaces. Bottom simulating reflectors (BSRs), identified in seismic sections above interpreted serpentinized ultramafic diapirs, also exist on the sediment-covered eastern flank of Knipovich Ridge. These

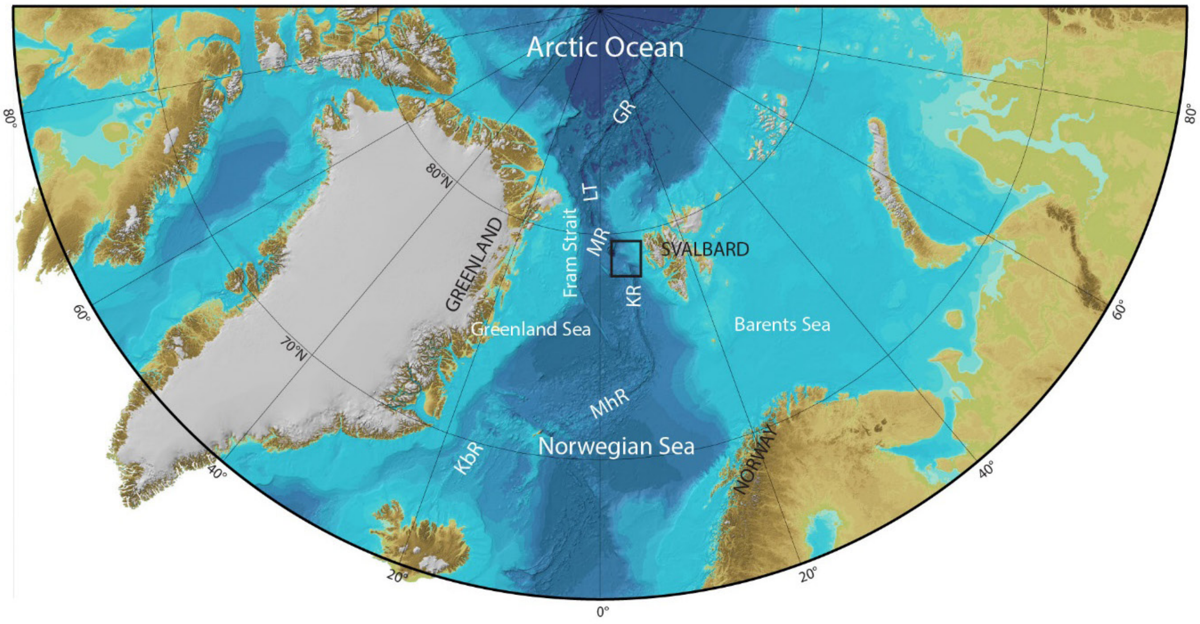

Figure 1. Arctic Ocean Bathymetry (IBCAO Version 3.0). Labels identify the slow to ultraslow spreading ridges that extend northward from Iceland; KbR-Kolbeinsey Ridge, MhR-Mohns Ridge, KR-Knipovich Ridge, MR-Molloy Ridge, LT-Lena Trough, and GR-Gakkel Ridge. Black box outlines the study area near the Vestnesa Ridge, described below and in Figures 2 and 3.

observations establish the possibility of methane delivery for gas hydrates from an abiotic, serpentinized mantle source throughout sediment-covered portions of the Arctic Ocean ultraslow spreading ridge system.

Sediment-Covered Ultraslow Ridges in Fram Strait

The potential for gas hydrate systems to be charged by serpentinized mantle sources of methane is high in Fram Strait, where young portions of ultraslow spreading ridge flanks are sediment covered and lie within the gas hydrate stability zone. Water mass transport through Fram Strait since the early Miocene created an environment for the formation of sediment drifts. These drift deposits grow during northern hemisphere glaciations and are sustained throughout the ultraslow separation of Greenland and Svalbard.

The most well known gas hydrate-bearing drift in the Fram Strait is the Vestnesa Ridge. It is a >100-km-long and 50-km wide sediment drift between the northwest Svalbard margin and the Molloy Transform fault (Figure 1). It contains a gas hydrate reservoir and active free gas system that creates vents that release gas through the seafloor and into the ocean. Isotope measurements of gas from hydrates at this location are indicative of biotic sources (thermogenic methane). Abiotic sources are not present, likely due to the old age (10-20 million years old) of the crust beneath the drift.

Just south of the Molloy Transform fault, however, on significantly younger crust (0-10 million years old), an offset portion of the Vestnesa drift shows an equally well-established gas hydrate system. Its underlying crustal structure suggests that, in addition to biotic gases, abiotic gases formed by

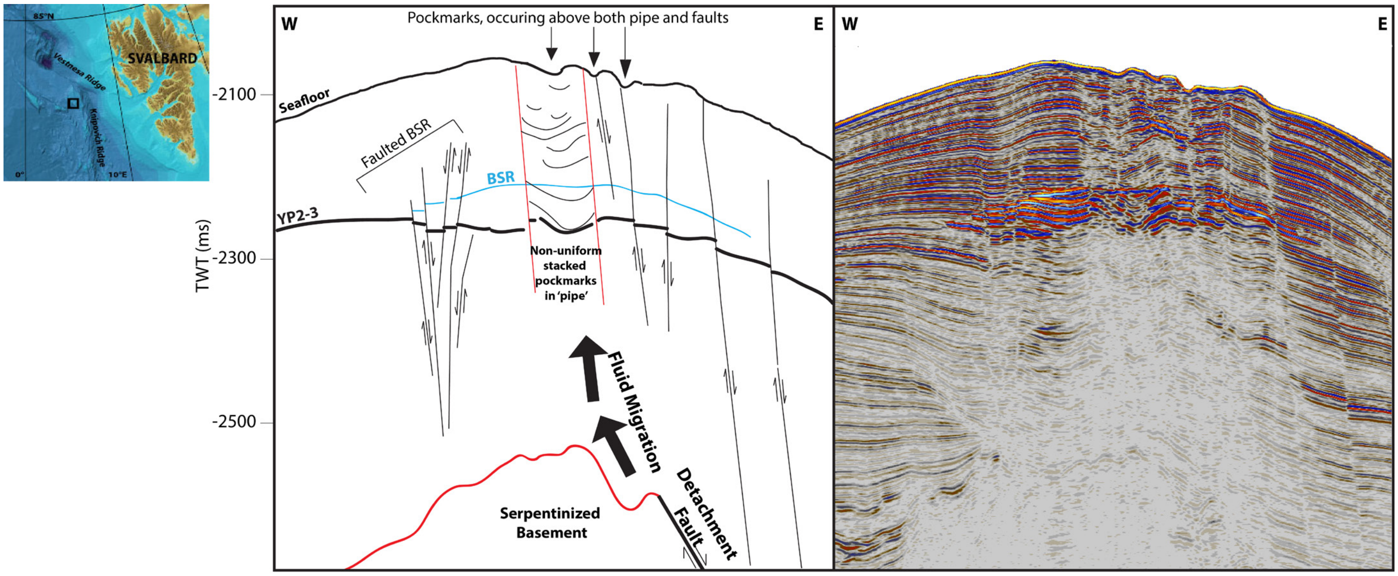

Figure 2. Location map (left) and interpreted seismic section (middle) of the gas hydrate system, including (from bottom to top) gas migration blank areas, the BSR, faults, and depressions at the seabed, across the crest of the offset Vestnesa drift south of the Molloy transform fault.

serpentinization also charge this gas hydrate system (Figures 2 and 3).

Abiotic Methane Window

In a 2015 paper, we presented the concept of an abiotic methane window for ocean basins characterized by ultraslow spreading. The extent of the abiotic methane window depends on the age of the oceanic crust, typical activity along detachment faults, and the optimum temperature range for serpentinization reactions (Figure 3).

Active detachment faults that accommodate the majority of plate motion in ultraslow spreading environments are a key component of this conceptual model. Such faults exhume ultramafic mantle rocks and

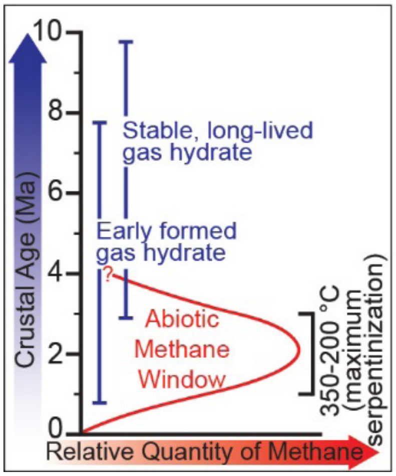

Figure 3. Conceptual diagram of an abiotic methane window for serpentinized ocean crust in a sediment-covered ultraslow spreading ridge environment (modified after Johnson et al., 2015). Abiotic charged gas hydrate is most likely to form in sediments that cover ultraslow spreading ridges early, near the ridge axis, when detachment faults are active, and the temperature regime is optimized for serpentinization. Progressive translation of gas hydrated drifts into deeper water with continued ultraslow spreading, increases the stability of the gas hydrate system, contributing to its potential longevity.

SOURCES AND SUGGESTED READING

Bünz, S., Polyanov, S., Vadakkepuliyambatta, S., Consolaro, C., and Mienert, J., 2012. Active gas venting through hydrate-bearing sediments on the Vestnesa Ridge, offshore W-Svalbard: Marine Geology, v. 332–334, p. 189–197, doi: 10.1016 / j. margeo.2012.09.012.

Dick, J.B.H., Lin, J., and Schouten, H., 2003. An ultraslow-spreading class of ocean ridge: Nature, v. 426, p. 405–412, doi:10.1038/nature02128.

Etiope, G. and Sherwood Lollar, B., 2013. Abiotic methane on Earth. Reviews of Geophysics 51(2): 276-299. doi:10/1002/rog.20011.

M. Jakobsson, J. Backman, B. Rudels, J. Nycander, M. Frank, L. Mayer, W. Jokat, F. Sangiorgi, M. O'Regan, H. Brinkhuis, J. King, K. Moran, 2007. The Early Miocene onset of a ventilated circulation regime in the Arctic Ocean. Nature, 447 (2007), pp. 986–990 doi: 10.1038/nature05924.

Johnson, J.E., Mienert, J., Plaza-Faverola, A., Vadakkepuliyambatta, S., Knies, J., Bünz, S., Andreassen, K., and Ferré, B., 2015. Abiotic methane from ultraslow-spreading ridges can charge Arctic gas hydrates. Geology, v. 43, no.5, p. 371-374, doi:10.1130/G36440.1.

Kelley, D.S., J.A. Karson, D.K. Blackman, G.L. Früh-Green, D.A. Butterfield, M.D. Lilley, E.J. Olson, M.O. Schrenk, K.K. Roe, G.T. Lebon, P. Rivizzigno, and the AT3-60 Shipboard Party, 2001. An off-axis hydrothermal vent field near the Mid-Atlantic Ridge at 30°N, Nature, 412, 145-149.

Konn, C., Charlou, J. L., Holm, N. G., & Mousis, O., 2015. The Production of Methane, Hydrogen, and Organic Compounds in Ultramafic-Hosted Hydrothermal Vents of the Mid-Atlantic Ridge. Astrobiology, 15(5), 381–399. http://doi.org/10.1089/ast.2014.1198.

Plaza-Faverola, A., Bünz, S. Johnson, J.E., Chand, S., Knies, J., Mienert, J. and Franek, P., 2015. Role of tectonic stress in seepage evolution along the gas hydrate-charged Vestnesa Ridge, Fram Strait, Geophysical Research Letters, v. 42, p. 733-742. doi.org/10.1002/2014GL062474.

Proskurowski, G., Lilley, M.D., Seewald, J.S., Früh-Green, G.L., Olson, E.J., Lupton, J.E., Sylva, S.P., and Kelley, D.S., 2008. Abiogenic hydrocarbon production at Lost City hydrothermal field. Science 319:604–607.

Rajan, A., Mienert, J., Bünz, S., and Chand, S, 2012. Potential serpentinization, degassing, and gas hydrate formation at a young (<20 Ma) sedimented ocean crust of the Arctic Ocean ridge system, J. Geophys. Res., 117, B03102, doi:10.1029/2011JB008537.

Smith, A.J., Mienert, J., Bünz, S., and Greinert, J., 2014. Thermogenic methane injection via bubble transport into the upper Arctic Ocean from the hydrate-charged Vestnesa Ridge, Svalbard: Geochemistry Geophysics Geosystems, v. 15, p. 1945–1959, doi:10.1002/2013GC005179.

provide conduits for seawater, thereby promoting serpentinization. With continued seafloor spreading, these faults become less active and more mineralized—and therefore less permeable—as new detachments form closer to the ridge. Typical activity along spreading ridge detachments ranges from 1-4 million years, restricting the most effective serpentinization to the youngest and warmest crust closest to the ridge axis. In the case where sediment drifts in Fram Strait offset along mid-ocean ridge transform faults, early abiotic gas charge could contribute to early gas hydrate formation.

Future Directions

Realizing the proportion of abiotic and biotic gases stored as gas and gas hydrate on sedimented, ultraslow spreading ridge flanks throughout the Arctic will require: (1) seismic reflection reconnaissance surveys to map the gas hydrate and free gas systems that likely exist within the largely underexplored Arctic and subarctic seafloor environments; and (2) future scientific drilling to directly sample, quantify, and isotopically characterize the gases in these likely mixed biotic and abiotic gas hydrate systems.

Acknowledgments

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COUPLED THERMO-HYDRO-CHEMO-MECHANICAL (THCM) MODELS FOR HYDRATE-BEARING SEDIMENTS

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Introduction

In hydrate-bearing sediments, hydrate stability conditions combine with sediment behavior to produce a strongly coupled and complex Thermo-Hydro-Chemo-Mechanical (THCM) response during dissociation. Methane production from gas hydrate accumulations in permafrost carries additional challenges. Complex stress paths in Pressure-Temperature (P-T) space with two phase boundaries (i.e., ice-liquid and gas-hydrate phase lines) are anticipated during gas production and may include secondary ice and hydrate formation. Owing to these complexities, sequential, explicit computational schemes that resolve the hydrate state separate from the sediment state at every time step are not adequate. Instead, truly coupled THCM numerical approaches are needed for robust analysis of hydrate formation and dissociation in hydrate-bearing sediments.

We have updated our THCM formulation and code for hydrate-bearing sediments to incorporate augmented, constitutive models. We have developed bounding, closed-form analytical solutions that highlight the interplay among governing parameters in the context of gas production and corroborate the numerical code with these closed-form end-member situations. We have also used the enhanced code to analyze in detail existing data available from field programs and laboratory experiments.

Methodology

The dominant THCM phenomena that occur in hydrate-bearing sediments include: (1) heat transport through conduction and liquid- and gas-phase advection; (2) heat of hydrate formation/dissociation; (3) water flux in the liquid phase; (4) methane flux in the gas phase and as dissolved methane in the liquid phase; (5) heat of ice formation/thaw; (6) fluid transport of chemical species; and (7) mechanical behavior related to changes in effective stress and hydrate concentration. All of these coupled phenomena are represented in the CODE_BRIGHT framework, a numerical platform originally developed by Olivella *et al*. (1996).

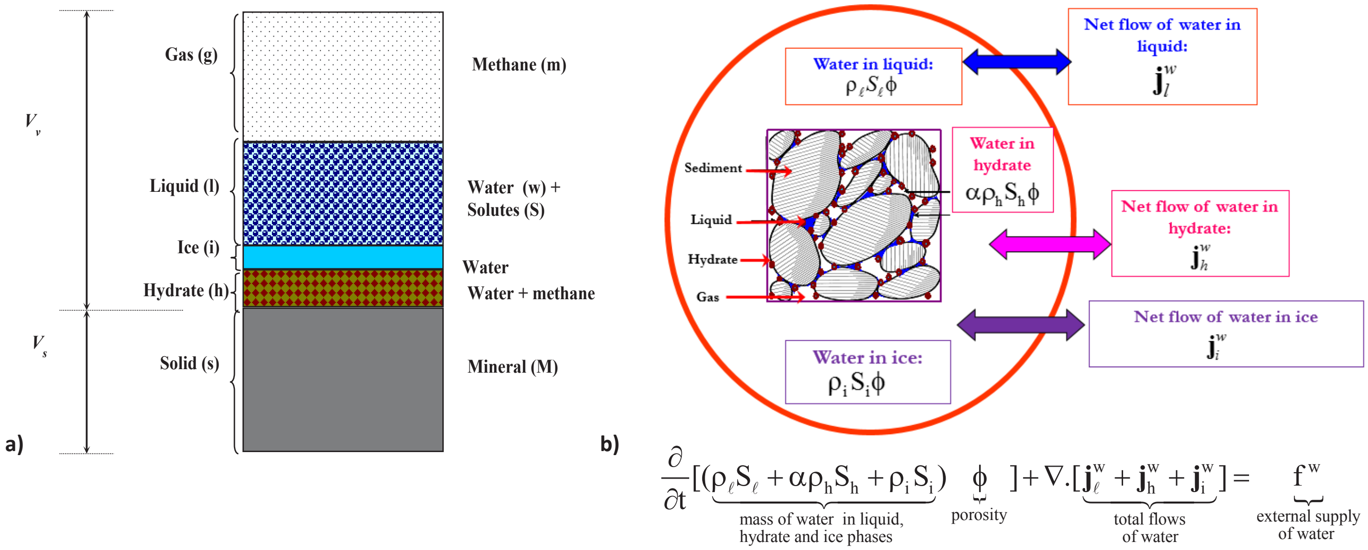
Hydrate-bearing sediments consist of a granular skeleton, containing pore spaces filled with gas, hydrate, water, or ice. The three main species (i.e., mineral, water, and methane) are found in five phases: solid mineral particles, liquid, gas, hydrate, and ice (Figure 1a). To simulate change for production scenarios based on chemical stimulation, we include an additional species. The proposed approach encompasses balance equations (i.e., species-mass, internal energy, and momentum balance equations); constitutive equations; and equilibrium restrictions. Phase boundaries and reaction kinetics equations are also included in the numerical approach. Figure 1b presents an example of the different terms involved in the water/mass balance equation.

Geomechanical Behavior of Hydrate-Bearing Sediments

Geomechanics is a key component in the numerical modeling of engineering problems involving hydrate-bearing sediments. An advanced elasto-plastic framework, based on a critical state model for soils, has been developed to describe the mechanical behavior of the sediments. The proposed framework has been widely validated against recently published experiments involving both synthetic and natural hydrate-bearing sediments , under different confining conditions, hydrate saturations (S_h), and morphologies. Particular attention was paid to evaluating the behavior of hydrate-bearing sediments during dissociation under different stress levels.

The behavior of hydrate-bearing sediments during hydrate dissociation depends, in part, on stress conditions. When hydrate dissociation takes place at a low deviatoric stress, for example lower than the strength of the already dissociated sediment, the tendency of the sediment after dissociation is to harden (Figure 2a). In contrast, a softening behavior was observed when dissociation occurred at a higher deviatoric stress level (Figure 2b). In other words, a progressive degradation in stiffness of hydrate-bearing sediments is evident.

Hydrate dissociation is also accompanied by profound changes in the sediment structure. Hydrate bonding effects can be damaged during shearing. Figure 2c shows the large volumetric collapse associated with hydrate dissociation under constant effective stress. The proposed model



$$\frac{\partial}{\partial t}[\underbrace{(\rho_\ell S_\ell + \alpha \rho_h S_h + \rho_i S_i)}_{\substack{\text{mass of water in liquid,} \\ \text{hydrate and ice phases}}} \underbrace{\phi}_{\text{porosity}}] + \nabla . [\underbrace{\mathbf{j}_\ell^w + \mathbf{j}_h^w + \mathbf{j}_i^w}_{\substack{\text{total flows} \\ \text{of water}}}] = \underbrace{f^w}_{\substack{\text{external supply} \\ \text{of water}}}$$

Figure 1. a) Diagram illustrating three main species (mineral, water, and methane) in five main phases (solid mineral, hydrate, ice, liquid, and gas) in a hydrate reservoir system. Vs and Vv refer to volume of solids and volume of voids; b) Water mass balance equation and schematic representation showing the water species in its different phases, with fluxes in or out of the system.

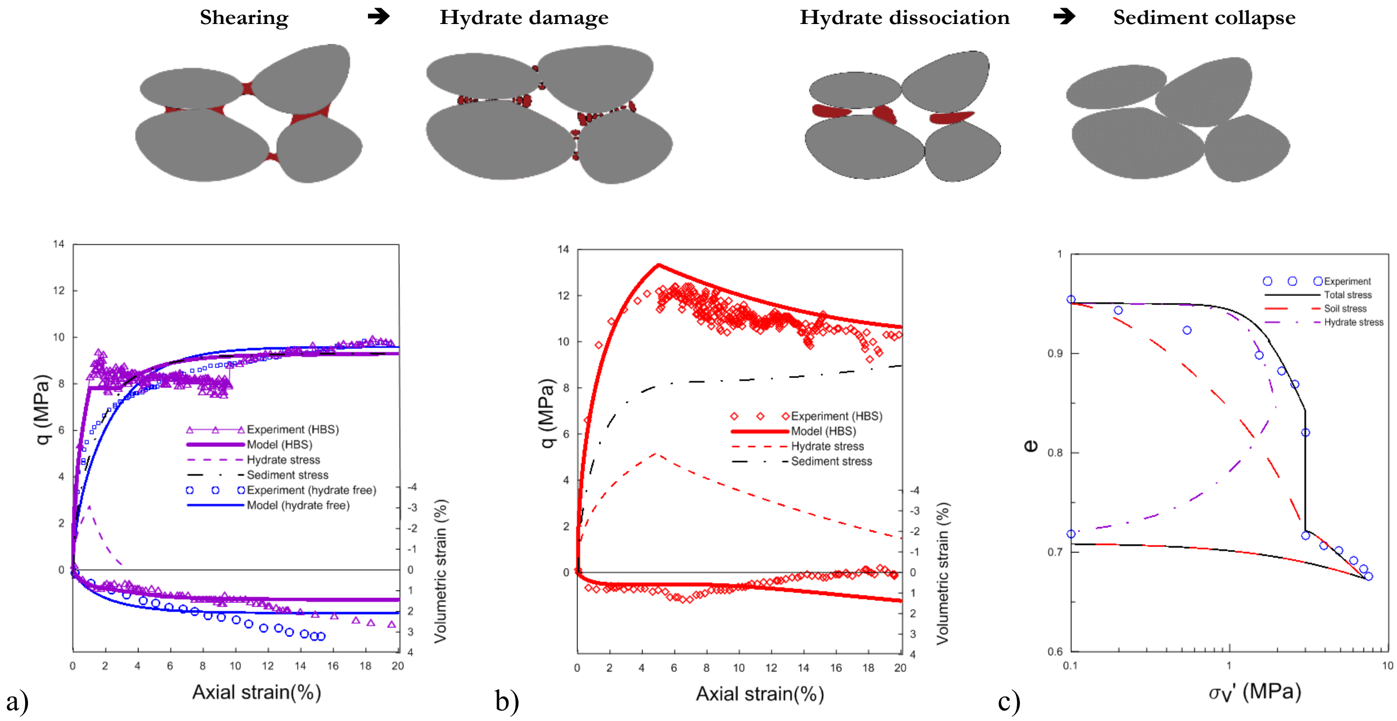


Figure 2. Experimental and modeling results involving hydrate-bearing sediment specimens: a) shear behavior of an already dissociated sediment and one in which dissociation was induced at ε_a=1%; b) shear behavior of a sediment dissociated at ε_a=5%; c) behavior during dissociation of natural hydrate-bearing sediment specimens under oedometric conditions at a constant effective vertical stress. Figures 2a and 2b show experimental data from Hyodo et al. (2014); Figure 2c shows experimental data from Santamarina et al. (2015).

is able to capture the main features of hydrate-bearing sediment behavior observed in these experiments. It can also evaluate the stresses taken by the sediment skeleton and hydrates, as shown in Figure 2. During loading, the stresses increased continuously in the sediment skeleton and hydrate. During dissociation, the stresses in the hydrate decreased progressively and were transferred to the sediment skeleton.

Modeling Hydrate-Bearing Sediment Behavior in the Laboratory

A pressure core recovered from hydrate-bearing sediments in the Krishna-Godavari Basin was depressurized while measuring the internal temperature in the sediment at the center of the core (see Yun *et al.*, 2010). We used our enhanced numerical code to construct a 3D mesh of the core and chamber and to simulate the depressurization experiment. The model accurately predicts the main patterns observed in the test. Experimental measurements and predicted parameters are compared in Figure 3. Endothermic hydrate dissociation lowers the temperature in the core, reaching freezing temperatures and causing ice formation. The temperature recovery at the end of the test results from heat transfer from the surroundings. The simulation also shows the changes in hydrate and ice saturation throughout the test.

Gas Production by Depressurization

Under steady state conditions, the pressure distribution in radial flow is inversely proportional to the logarithm of the radial distance to the well. Therefore, there is a physical limit to the zone around a well that will experience pressure-driven dissociation. We propose a simple yet robust

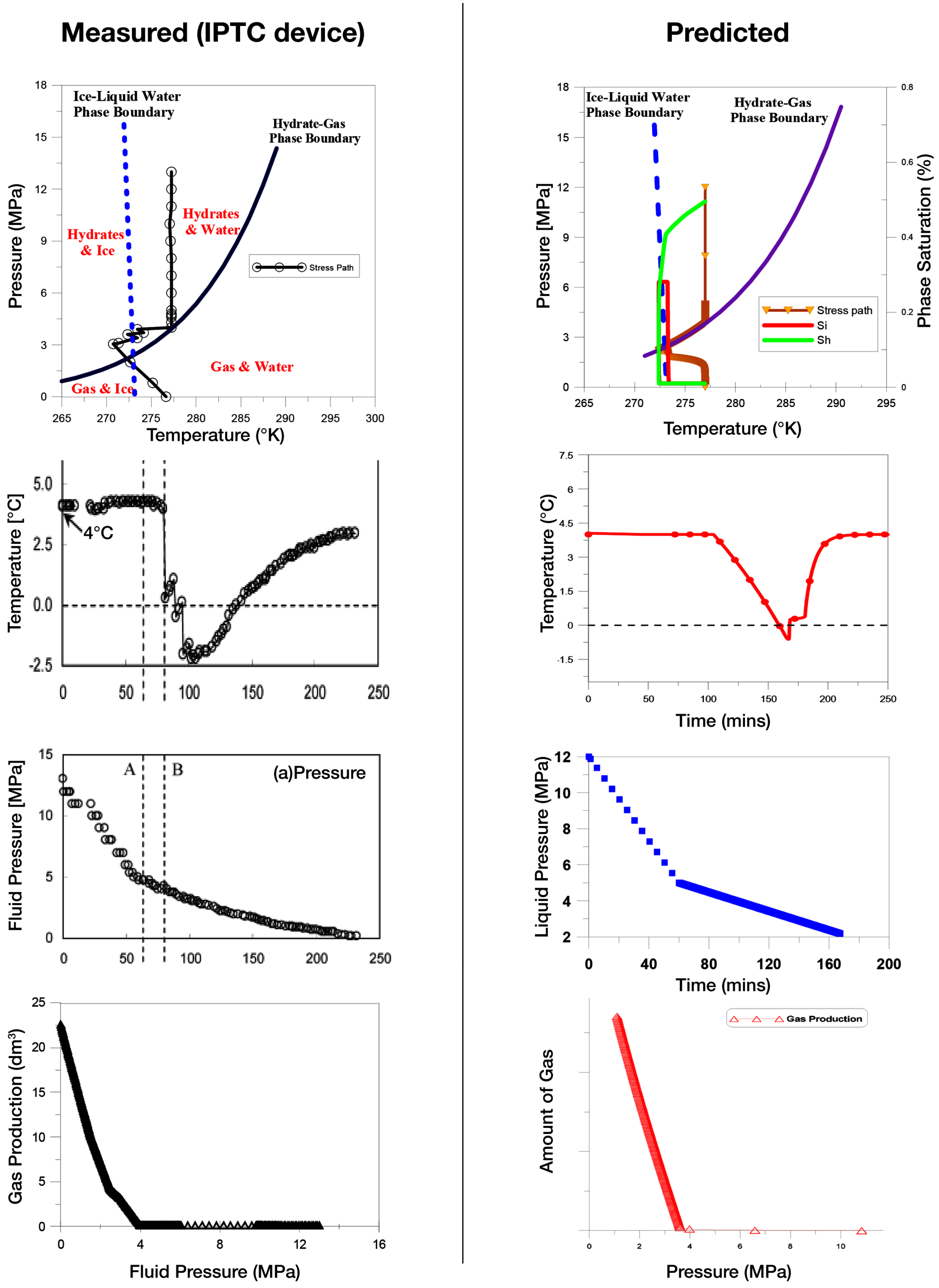


Figure 3. Production monitoring in the IPTC-pressure core from the Krishna-Godavari Basin. Monitored and predicted response (Data in Yun et al. *2010).*

set of equations to estimate limits for gas production from hydrate-bearing sediments using depressurization. This analytical solution is a function of four main parameters (see Figure 4a): (1) the radius of the wellbore area and the wellbore pressure; (2) pressure at the dissociation front (which depends on reservoir temperature through the methane-hydrate phase boundary); (3) pressure at a distant boundary (equal to reservoir initial pressure); and (4) the ratio between the permeability coefficients of the already dissociated hydrate sediment (K_{Sed}) and the hydrate-bearing sediment (K_{HBS}).

Figure 4b presents the results of this analytical solution (dashed lines) for the different cases listed in Table 1, showing the interplay between the relative permeability coefficients (K_{Sed}/K_{HBS}) and the relative dissociation pressure ($(h^* - h_w)/(h_{far} - h^*)$). This solution was also used to verify the coupled THCM numerical code. The numerical results are very satisfactory when compared against the analytic ones for the range of conditions analyzed.

Summary

We have developed a general mathematical formulation to analyze coupled THCM problems involving hydrate-bearing sediments. Our code incorporates advanced constitutive models to capture the complex behavior of hydrates during formation and dissociation. The performance of the proposed framework has been very satisfactory when verified and validated against closed-form analytical solutions and available experimental data, respectively. We have also used the enhanced code to analyze field problems aimed at optimizing strategies for methane production from hydrate-bearing sediments.

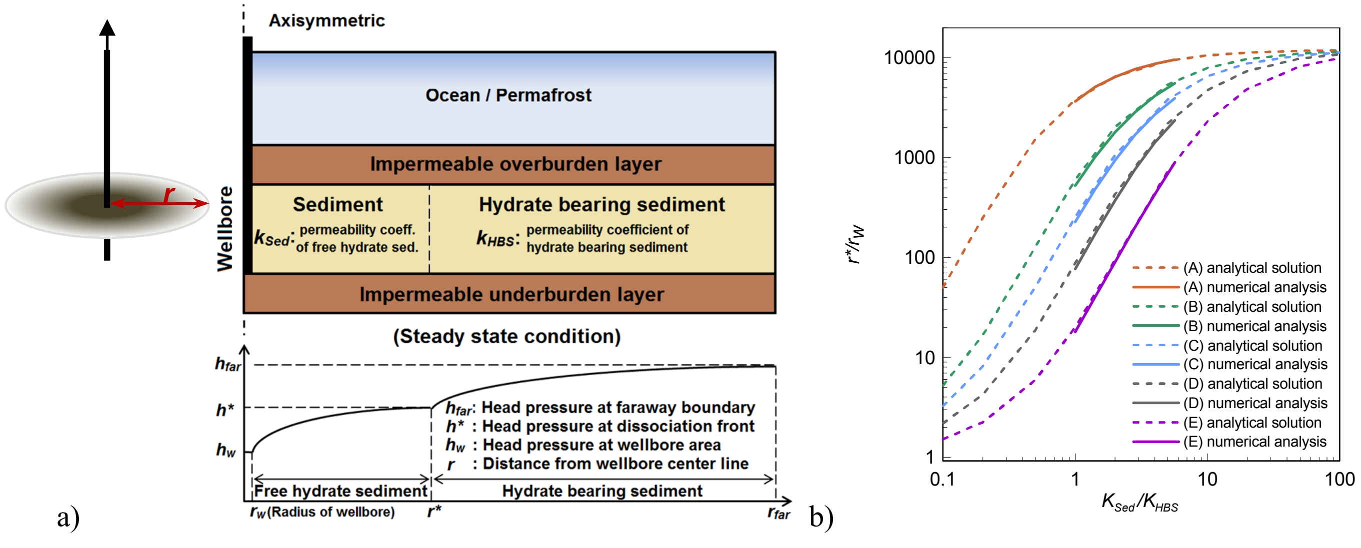


Figure 4. a) Two zones can be identified under steady state conditions when the pressure drop is kept constant and hydrate stops dissociating: an inner zone where hydrate has been depleted and an outer zone where hydrate remains stable; b) results obtained with the analytical solution and numerical model for the different cases listed in Table 1 and for different relative dissociation pressure, in terms of permeability coefficients ratio and radii ratio.

Table 1. Cases considered in the analysis

Case	h_{far} (m)	h_w (m)	T (°C)	$\frac{h^* - h_w}{h_{far} - h^*}$
A	1020	306	12	7.14
B	1224	306	12	2.14
C	1224	510	12	1.44
D	1224	306	10	0.91
E	1224	306	8	0.47

Acknowledgments

The authors would like to acknowledge the financial support from DOE/NETL through Award No: DE-FE0013889.

Sources and Recommended Reading

Hyodo M, Li Y, Yoneda J, Nakata Y, Yoshimoto N, Nishimura A. Effects of dissociation on the shear strength and deformation behavior of methane hydrate-bearing sediments. Marine and Petroleum Geology. 2014;51:52-62

Olivella, S., Gens, A., Carrera, J., Alonso, E.E. Numerical formulation for a simulator (CODE-BRIGHT) for the coupled analysis of saline media. Engineering Computations. 1996, 13(7), 87–112.

Santamarina JC, Dai S, Terzariol M, Jang J, Waite WF, Winters WJ, Nagao J, Yoneda J, Konno Y, Fujii T, Suzuki K. Hydro-bio-geomechanical properties of hydrate-bearing sediments from Nankai Trough. Marine and Petroleum Geology. 2015.

Yun T.S., Fratta D. and Santamarina J.C. Hydrate Bearing Sediments from the Krishna-Godavari Basin: Physical Characterization, Pressure Core Testing and Scaled Production Monitoring. Journal of Energy & Fuels. 2010, 24, 5972 -5983.

EMERGING ISSUES IN THE DEVELOPMENT OF GEOLOGIC MODELS FOR GAS HYDRATE NUMERICAL SIMULATION

Ray Boswell (NETL, Pittsburgh, PA) and Timothy Collett (USGS, Denver, CO)

Introduction

The numerical simulation of gas hydrate reservoirs has evolved greatly in recent years. Scientific and industrial drilling programs have acquired detailed characterization data from gas hydrate systems in Alaska, Japan, India, Korea, China, and the Gulf of Mexico. These data provide invaluable calibration points that serve to ground-truth hydrate reservoir modeling efforts.

At the same time, increasingly complex field testing programs require the best possible prediction of the response of a hydrate reservoir system. Currently, the major emphasis in gas hydrate modeling is on full integration of thermodynamic and hydrologic phenomena with the geomechanical behavior of the hydrate reservoir and its bounding strata. An emerging issue is understanding and predicting hydrate reservoir response to temporary cessation of production activity. Critical to the ultimate success of these efforts is the development of suitable input geologic models, which is the subject of this article.

Background

Initial geologic models, developed by Moridis and Collett, recognized three primary reservoir classes based on the geometric nature of the deposit. Application of these simple models indicated good production potential where gas hydrate occurred in association with underlying free gas; but these models indicated significant challenges where gas hydrate overlay water or was fully confined by bounding shale layers. These challenges included relatively low production rates and long lead times before peak production could be obtained.

A major advance in the geologic input models for reservoir simulation came with the arrival of detailed field data that allowed the introduction of natural vertical heterogeneity in the reservoir depictions. These models showed higher potential production rates with significantly reduced lead times, suggesting that energy potential may exist in all gas hydrate reservoir classes. Application of these complex geologic models raises several emerging issues that may have profound implications for the accurate prediction of production response, including (1) reservoir heterogeneity, (2) interdependency of petrophysical parameters, (3) the nature of reservoir boundaries, and (4) in situ permeability.

Reservoir Heterogeneity: Heterogeneity is a ubiquitous aspect of every natural reservoir, and proper representation of this heterogeneity is vital to the prediction of reservoir behavior. However, heterogeneity is not random, but is instead a function of natural variation in depositional environments in time (vertical variation) and space (lateral variation).

In the vertical direction, variation in reservoir character can be evaluated with core and well log data. However, with core, incomplete recovery and

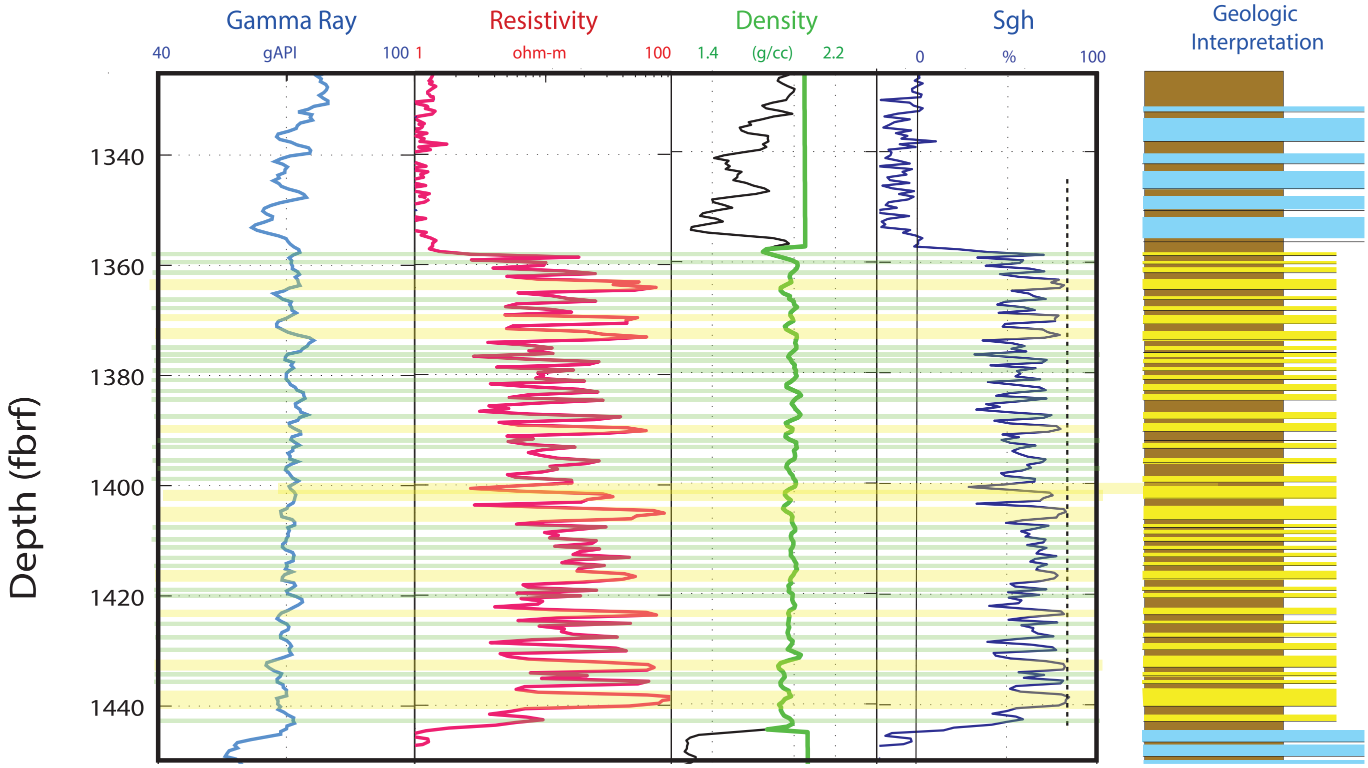


Figure 1: Gas hydrate reservoirs are often thin-bedded, and therefore variations in lithology and key parameters may not be directly measureable in log data. Beds A and B likely have very similar petrographic nature, but the expressed different log response is due to bed thickness variations and log resolution limitations. Example from Green Canyon 955 site in the Gulf of Mexico.

recovery that is biased to select lithologies must be taken into account. With well logs, significant issues arise particularly where reservoirs are thinly-bedded, which is the norm in many deepwater systems.

Each logging tool has a different vertical resolution, and where this resolution cannot resolve individual beds, logging data will not accurately reflect reservoir conditions (Figure 1). This is particularly true with porosity data, but it can also be true of resistivity and lithologic (gamma-ray) data, when bed thicknesses are on the order of 1 ft. or less.

The limited resolution of logging tools affects other key petrophysical measurements that are derived from combined evaluation of different log data. For example, porosity and resistivity data are commonly combined to estimate gas hydrate saturation. Because these logs are measured at very different vertical resolutions, the estimated saturations will yield only bulk average values in a thin-bedded section. This may result in underestimates of saturation in gas hydrate-bearing interbeds and overestimates in non-gas hydrate-bearing interbeds. In such cases, geologic interpretation is required to convert log-based estimates to values most likely to represent nature.

Extrapolation of log data laterally is also complex. Geologic mapping of the reservoir system, where possible, is vital, as it is likely to provide insights about the areal geometry and structural complexity of individual reservoir units. An understanding of geologic environments can also support interpretations of reservoir compartmentalization. Such interpretations

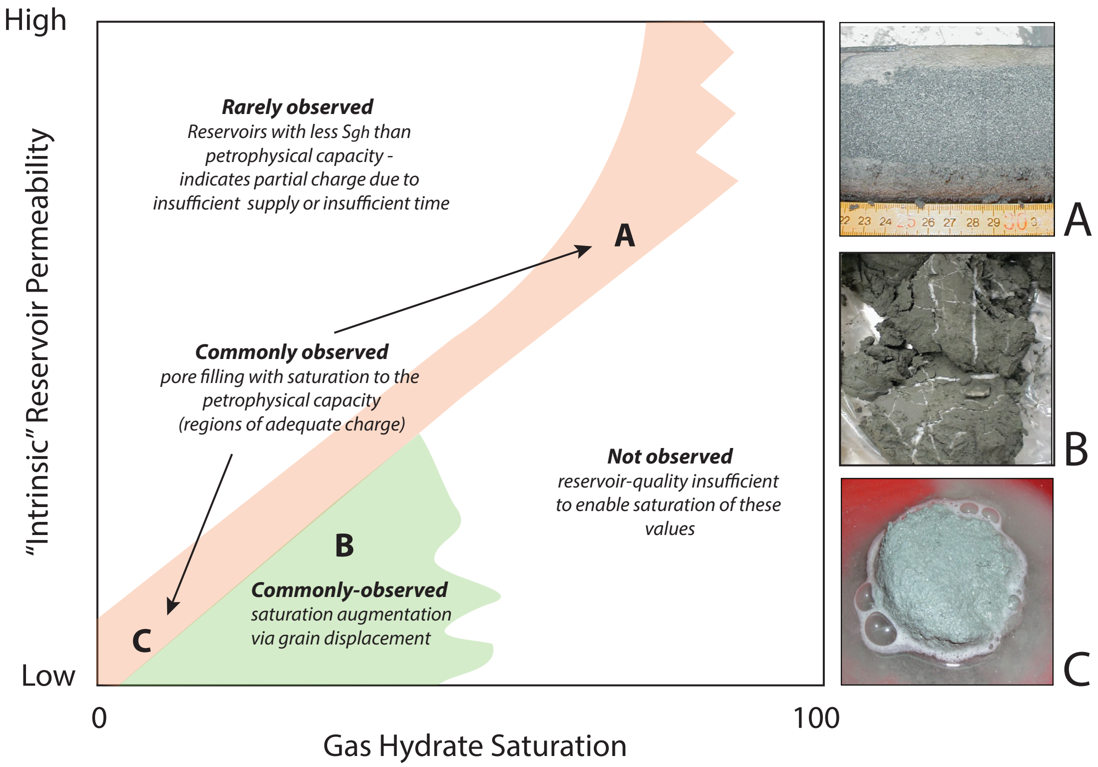


Figure 2: Gas hydrate saturation is closely tied to intrinsic reservoir quality. High saturation in poor reservoirs or low saturation in high-quality reservoirs are rarely observed.

may suggest some units to be highly continuous laterally, whereas others are more prone to lateral heterogeneity.

Interdependency of Petrophysical Parameters: Many parameters combine to determine the response of a gas hydrate reservoir to an induced change. Key among these are pressure and temperature, as well as reservoir petrophysics-- including porosity, permeability, water saturation, amount of bound- and free-water, and others. Field data collected to-date suggest that gas hydrate reservoirs (particularly those that are candidates for potential production) are most commonly fully-saturated with gas hydrate to the extent that the reservoir quality allows. That is, the degree of hydrate saturation is strongly controlled by reservoir quality, such that a lower-quality reservoir may be maximally-saturated at 50%, whereas higher-quality reservoirs can achieve 80% saturation (Figure 2). Gas hydrate saturations in excess of 80% are likely rare. The remaining pore space appears to be occupied by water (gas is not observed), with some portion of that water being free and some being bound. The ratio of free to bound water is likely also controlled by reservoir quality, with a higher share being free in high-quality reservoirs. Given this insight, it is necessary to recognize that gas hydrate saturation is not independent of other parameters, such as porosity or permeability. While it is well known that high-quality, low-saturation reservoirs may provide the most favorable response to production models, such situations are unlikely nature.

The Nature of Reservoir Boundaries: Significant progress has been made in recent years with regard to geologic characterization of reservoir

RECOMMENDED READING

Anderson, B., et al., 2011. Regional long-term production modeling from a single well test, Mt. Elbert stratigraphic test well, Alaska North Slope. J. Mar. Pet. Geol., 28, 493-501.

Collett, T.S., and Lee, M.W., 2012, Well log characterization of natural gas hydrates: Petrophysics, 53 (5), 348-367.

Collett et al., 2009. Natural gas hydrates – a review. AAPG Memoir 89, 146-220

Boswell, R., et al., 2011. Gas hydrate reservoir types and their application to numerical simulation. Proceedings, ICGH, Edinburgh, Scotland.

Konno, Y., et al., 2015, Permeability of sediment cores from methane hydrate deposit in the Eastern Nankai Trough. J. Mar. Pet. Geol. 66 (2), 487-495.

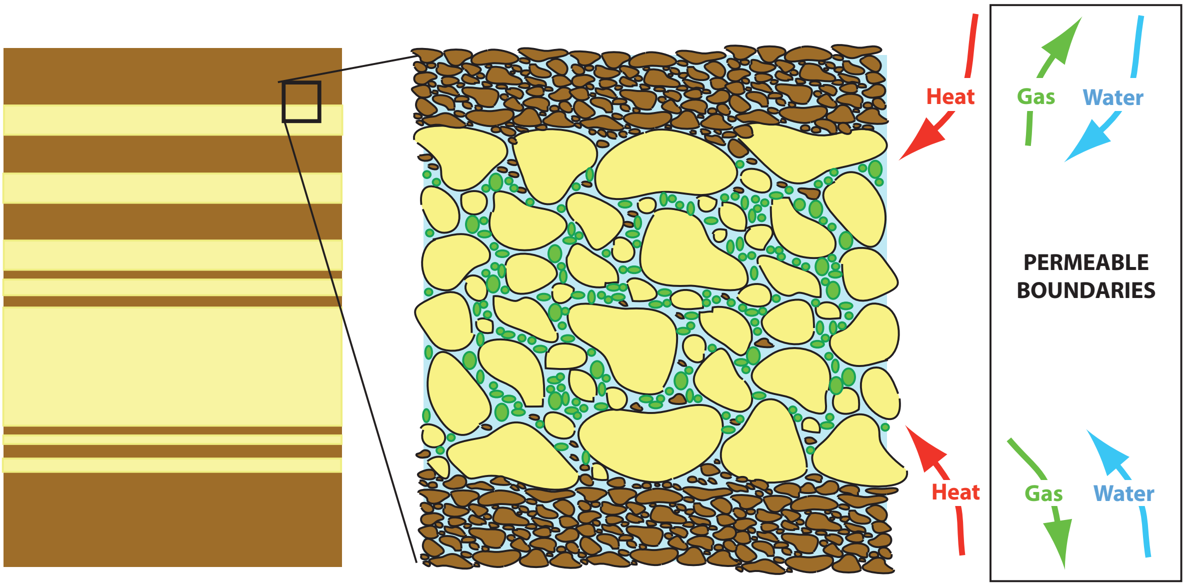


Figure 3: Vertical permeable boundaries enable complex interactions between reservoirs and bounding lithologies.

RECOMMENDED READING CONTINUED

Kurihara, M., et al., 2010. Prediction of production test performances in eastern Nankai Trough methane hydrate reservoirs using 3-D reservoir model, Proceedings, OTC, OTC-19382.

Moridis, G., and Collett, T., 2004. Strategies for gas production from hydrate accumulations under various geologic conditions. Proceedings, Tough Symposium, LBNL-52568.

Moridis, G., et al., 2009. Toward production of gas hydrate; current status, assessment of resources, and simulation-based assessment of technology and potential. SPE Res. Eng. & Eval., 12 (5), 745-771.

boundaries. Initial numerical simulation of gas hydrate reservoirs assumed vertical reservoir confinement and laterally open reservoirs, which generally means no-flow vertical boundaries. Such conditions are clearly optimal for gas hydrate production but are generally not present in nature. In some situations, it is likely that bounding, vertical seals may have greater permeability than the in situ reservoirs when hydrate is present, creating conditions not only favorable for the transfer of heat from seals to reservoirs, but also the movement of fluids (Figure 3). Just as important is the appropriate characterization of lateral boundaries, including the potential for lateral fluid flow and potential communication with high-permeability water-bearing zones that will challenge pressure reduction in the reservoir. Faults may also act to laterally isolate the reservoir thus limiting the extent of the reservoir's lateral pressure drawdown and related production.

In situ Permeability: Finally, a related petrographic issue with critical importance to gas hydrate reservoir simulation is in situ permeability. This refers to the permeability in the presence of gas hydrate. Prior work, based primarily on short-duration borehole pressure-transient testing in Alaska, had generally indicated a low value, such as 0.1 md. However, recent evaluation of pressure cores acquired in Japan suggest in situ permeability of hydrate-bearing sands may range from 1 to 100 md. These values, if they are found to be typical of marine hydrate occurrences, will have profound implications on current concepts of gas hydrate production.

DOE/NETL FY2016 Methane Hydrate Funding Opportunity Announcement

DOE/NETL has released a Methane Hydrate Funding Opportunity Announcement (FOA) for FY2016. The intent of the FOA is to solicit applications that focus on fundamental research assessing the scale, development, and nature of hydrate-bearing geological systems, the role of these systems in the natural environment (including geohazards and potential feedbacks to changing global climate), the potential of these systems for commercial recovery of methane, and the potential environmental implications of methane hydrate resource recovery. Research in these areas is consistent with the program mission and goals and with the Secretary of Energy Advisory Board's 2016 recommendations and represents a critical component of advancing several of the specific mandates previously established for the Methane Hydrate Program.

The FOA is intended to support:

- Fundamental laboratory and numerical simulation studies of gas hydrate reservoir response to potential production activities
- Fundamental field, laboratory and numerical simulation studies of the development and evolution of gas hydrate-bearing systems and their response over various temporal and spatial scales to natural perturbations.

To view the content/description of the FOA please visit the FedConnect website and look for the Documentation section in the upper right hand corner. Click on "Body" to access the full FOA description.

A Synopsis of the FOA is available for viewing on the Grants.gov website. To download the Application Package and Instructions necessary for applying to the FOA, select the "Package" tab from the Grants.gov page accessed by clicking the Synopsis link above, click the "Select Package" link in the bottom right corner then follow the instructions provided via the website.

If you have difficulty accessing the full announcement electronically, please contact:

Bethan Young, Contract Specialist (412-386-4402, Bethan.Young@NETL.DOE.GOV)

Technical or administrative questions regarding the content of the FOA itself must be submitted through the FedConnect system. The ability to submit questions on the FOA is available to you once you have registered in the FedConnect system.

Fiery Ice 2016: June 15-17 in Honolulu

Aloha! Check out the website for the 10th International Workshop on Methane Hydrate Research and Development (http://www.hnei.hawaii.edu/focus/alternative-fuels/fiery-ice-2016). The site provides details of the Workshop and a link to online registration. Online registration closes on June 7. The workshop will be held at the Hawaii IMIN International Conference Center (Jefferson Hall) located next to the University of Hawai'i at Mānoa (UHM).

Ninth Int'l. Conference on Gas Hydrates: June 25 - 30, 2017 in Denver

The 9th International Conference on Gas Hydrates (ICGH9) will take place in Denver, Colorado, from June 25 through June 30, 2017. ICGH9 is part of a series of conferences held every three years since 1993 with the aim of bringing together the entire gas hydrate community. For more details, please visit the website: http://icgh9.csmspace.com/. The call for papers will go out May 1, 2016, and the abstract submission deadline will be September 1, 2016.

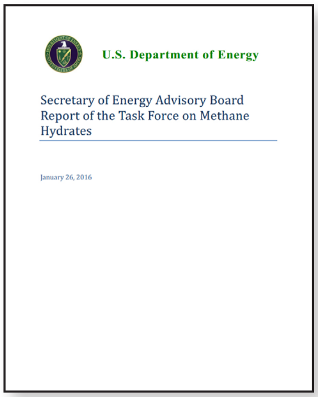
OTC Panel to Discuss Gas Hydrates

At this year's Offshore Technology Conference (OTC), to be held May 2-5 in Houston, there will be a special luncheon discussion panel titled "Gas Hydrate Exploration and Production Testing: Encouraging Results and Future Plans." The panel will meet from 12:15 to 1:45 on Wednesday, May 4. Panelists will include Dan McConnell (Fugro), Norman Carnahan (Carnahan Corp.), Timothy Collett (US Geological Survey), Ray Boswell (U.S. Dept. of Energy), and Pushpendra Kumar (Keshav Dev Malviya Institute of Petroleum Exploration, ONGC). Dr. Collett will give an overview of global activities including the first gas hydrate marine production test in Japan. Dr. Pushpendra Kumar and Dr. Ray Boswell will discuss recent results and plans for gas hydrate deposit delineation and production tests in India, and elsewhere. Details are available at http://2016.otcnet.org/Content/Join-us-for-OTC-2016.

Announcements

SEAB Methane Hydrates Task Force Report Published

On June 17, 2015, U.S. Secretary of Energy, Dr. Ernest Moniz, asked the Secretary of Energy Advisory Board (SEAB) to form a task force to review the U.S. Department of Energy's (DOE's) methane hydrate research program. The charge was to evaluate the program's research activities and progress in (1) understanding the assessment and exploitation of hydrates as an energy resource, and (2) understanding the environmental impact of hydrates. The Task Force's report was published on January 26, 2016 and is available online (http://energy.gov/seab/downloads/report-task-force-methane-hydrates).



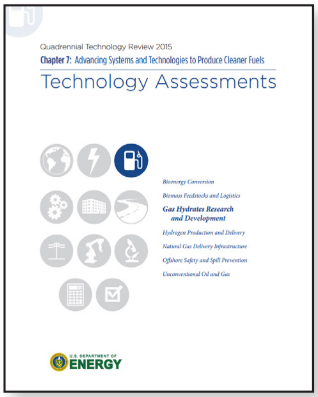
U.S. Department of Energy

Secretary of Energy Advisory Board
Report of the Task Force on Methane
Hydrates

January 26, 2016

Gas Hydrates Science and Technology Assessment Published

As part of its Quadrennial Technology Review carried out in 2015, the Department of Energy published a number of Technology Assessments, including one on Gas Hydrates Research and Development. This document was based on discussions conducted within the Interagency Gas Hydrate Technical Coordination Team (TCT), which includes representatives from the Department of Energy (DOE), the U.S. Geological Survey (USGS), the Bureau of Ocean Energy Management (BOEM), the Bureau of Land Management (BLM), the National Oceanic and Atmospheric Administration (NOAA), the Naval Research Laboratory (NRL), and the National Science Foundation (NSF). The Assessment also drew from the Marine Gas Hydrate Field Research Plan developed for the DOE in coordination with the gas hydrate scientific community and the Consortium for Ocean Leadership. The Assessment is available for download online (http://energy.gov/sites/prod/files/2016/03/f30/QTR2015-7C-Gas-Hydrates-Research-and-Development.pdf).



Quadrennial Technology Review 2015
Chapter 7: Advancing Systems and Technologies to Produce Cleaner Fuels
Technology Assessments

Bioenergy Conversion
Biomass Feedstocks and Logistics
Gas Hydrates Research and Development
Hydrogen Production and Delivery
Natural Gas Delivery Infrastructure
Offshore Safety and Spill Prevention
Unconventional Oil and Gas

U.S. DEPARTMENT OF ENERGY

2016 Hydrates Fellowship Awarded

The U.S. Department of Energy's National Energy Technology Laboratory (NETL) has awarded its latest Methane Hydrates Research Fellowship to Benjamin Phrampus, a post-doctoral researcher at Oregon State University working under the mentorship of Rob Harris and Anne Trehu. Ben graduated in 2011 with a BS in geophysics from Baylor University and finished his PhD at Southern Methodist University in 2015, where he focused on ocean temperature variation and the link to upper slope hydrate stability. He is continuing his work at Oregon State, evaluating hydrate re-equilibration in response to external forcing on mid and low latitude continental margins, initially focusing on Cascadia but with potential applications to Hikurangi, Nankai, and the Chilean margins.

The National Academy of Sciences (NAS) is responsible for administering the program in association with NETL and the ongoing interagency R&D effort in methane hydrates. More details are available at http://sites.nationalacademies.org/PGA/RAP/PGA_050408.

Dr. Ben Phrampus, Oregon State University

K.M. SHUKLA

K.M. Shukla onboard the drilling vessel *Chikyu* during the NGHP Expedition-02

NONLINEAR PATH TO MARINE HYDRATE RESEARCH

Mr. K.M. Shukla was the Lead Geophysicist for India's National Gas Hydrate Program (NGHP) Expedition-02 during March-July 2015 in the deep-water area of the Indian Ocean. He and his team discovered and described the first complete gas hydrate petroleum system in India's deep-water offshore region.

Mr. Shukla's early childhood scientific curiosity was encouraged by his father, who took him on regular visits to the public library in his hometown in central India. Eventually, he completed a Master of Science (M.Sc.) degree in physics in 1983 from Dr. Hari Singh Gaur University in Sagar, Madhya Pradesh, India.

After serving as a lecturer in physics at his university, Mr. Shukla joined India's national oil company (ONGC) as a geophysicist, where he built a successful career, and assumed the task of evaluating conventional hydrocarbon prospects in the Indian Basin in 1994. His ability in this area prompted the head of ONGC's Keshava Deva Malaviya Institute of Petroleum Exploration (KDMIPE) in Dehradun to assign him the task of identifying prospective gas hydrate sites for the NGHP-02 R&D expedition.

Recognizing producible gas hydrate prospects in India's deepwater regions was a challenge, as any seismic data interpretation had to be carried out with minimal subsurface well data available for calibration of the objective sands within shallow sedimentary sections. Most of the available data had been acquired and processed for deeper sediments in the search for conventional oil and natural gas. Moreover, the area of study was spread across the entire eastern offshore of India.

As there was very little published material available regarding procedures and methods for exploration of natural gas hydrate in deep-water marine environments, Mr. Shukla was on his own. His first task was to develop a standardized approach for evaluating India's eastern coast. His geophysical modelling led to the identification of multiple sites which were subsequently accepted by the scientific team. When the sites were drilled in 2015, two areas were found to contain world class gas hydrate accumulations and represented ideal sites for future production testing. One of these has the thickest known gas hydrate-bearing channel-levee sand reservoir system in the world.

Presently, Mr. Shukla is working to identify highly saturated producible gas hydrate in coarser clastic provinces in Indian deep-water. He is also carrying out reservoir characterization and resource estimation work for the gas hydrate prospects established during the expedition, to support future production tests. In addition, he continues to enhance and refine the models which led to the matching of pre-expedition predictions to post-expedition results at almost all of the sites drilled during NGHP-02 in 2015.

According to Mr. Shukla, "The main question associated with methane hydrates for the future will be how to monetize the gas hydrate we find in a sustainable manner, to improve the contribution of clean energy to industrial and domestic development."