

Fire in the Ice

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CONCENTRATED GAS HYDRATE DEPOSITS IN THE KUMANO FOREARC BASIN, NANKAI TROUGH, JAPAN

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While it has been proven that natural gas can be produced from hydrate reservoirs using current technology, it is essential that the highest quality reservoirs be identified to ensure that production is economically viable. The current consensus is that deeply buried, sand-rich turbidite deposits are the best geologic targets for offshore gas hydrate exploration,

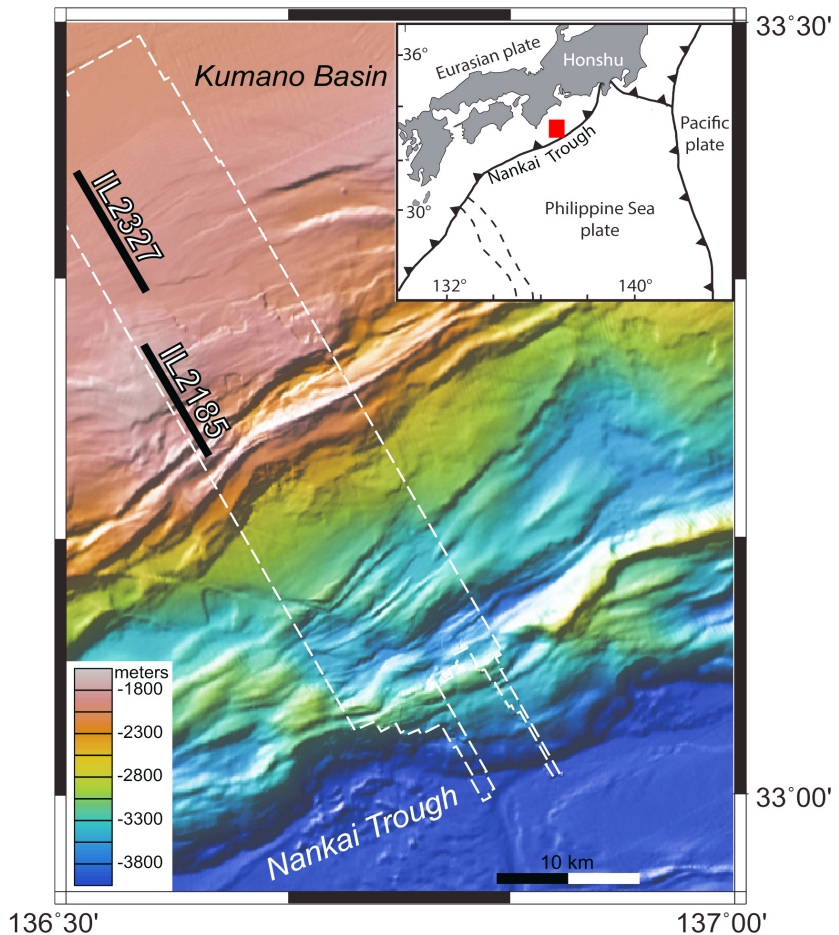


Figure 1. Bathymetric map showing the Kumano Basin, Nankai Trough, 2006 3D seismic volume (white dashed area), and seismic lines IL2327 and IL2185 (black lines). Location of main map with respect to Japan and regional plate boundaries is indicated by the red rectangle in the small inset map.

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drilling, and production trials. Our analysis of 3D seismic data from turbidite deposits in the Nankai Trough has led to the identification of two large gas hydrate-concentrated zones within the Kumano Forearc Basin.

Kumano Basin Geology and Seismic Evidence of Gas Hydrates

The Kumano Basin is the largest forearc basin in the Nankai Trough and lies at about 2000 m water depth. Sediment is delivered into the basin via a submarine turbidite system. High resolution 3D seismic data used for this study was collected in 2006 by Petroleum GeoService over an area of 11 x 57 km, as shown in Figure 1, and was later processed by Compagnie de Geophysique and Japan Agency for Marine Earth Science and Technology.

Paradigm Geophysical's 3D seismic interpretation software was used to analyze the pre-stack depth migrated volume. Examples of the seismic volume are shown in Figures 2 and 3. The data reveal a complex fault pattern, with tilted beds indicating tectonic uplift along the basin's seaward margin and numerous examples of mass wasting. Prominent hydrate-related Bottom Simulating Reflections (BSRs) of characteristic reversed polarity with respect to the seafloor occur between 330-480 meters below seafloor. These BSRs are assumed to be the base of Structure I methane hydrate accumulations. A number of positive polarity, double BSRs (DBSRs) occurring 30-100 meters below the main BSR are widely distributed in the region closest to the outer arc ridge (Figure 3). We interpret these DBSRs to be active features representing a Structure II hydrate layer composed of methane and ethane. Note that ethane has been found to increase with depth in the adjacent NanTroSEIZE International Ocean Drilling transect.

Tectonic events have affected the geometry and subsurface distribution of free gas and gas hydrate in the Kumano Basin, as evidenced by (1) the complex distribution of BSRs; (2) variable BSR reflection strengths; and (3) patches of localized High Amplitude Reflections (HARs) above and below the BSR. Amplitude analysis of the Kumano Basin, from the landward edge of the survey area up to the Splay Fault boundary, was aided by tracking the signal envelope attribute. This attribute helped define the boundary between hydrate concentration zones and underlying free gas.

Hydrate-Concentrated Zones

Packages of HARs associated with sand units occur above the BSRs in two distinct regions of the basin. Zone 1 (Figure 2) contains an anticlinal, buried thrust feature and is likely associated with significant accumulations of gas hydrates above the BSR. A gas hydrate-saturated horizon beneath a water-saturated horizon would result in a strong, positive amplitude reflection. Similar zones of high amplitude reflections have been observed in the Nankai Prism, Gulf of Mexico, and KG Basin offshore India, and they were found to be highly gas hydrate-saturated based on core analysis. High amplitude anomalies above the BSR in Zone 1 are 35-70 m thick and extend 10 x 6 km aerially. These HARs terminate against normal faults, indicating structural compartmentalization of hydrate reservoirs in this area.

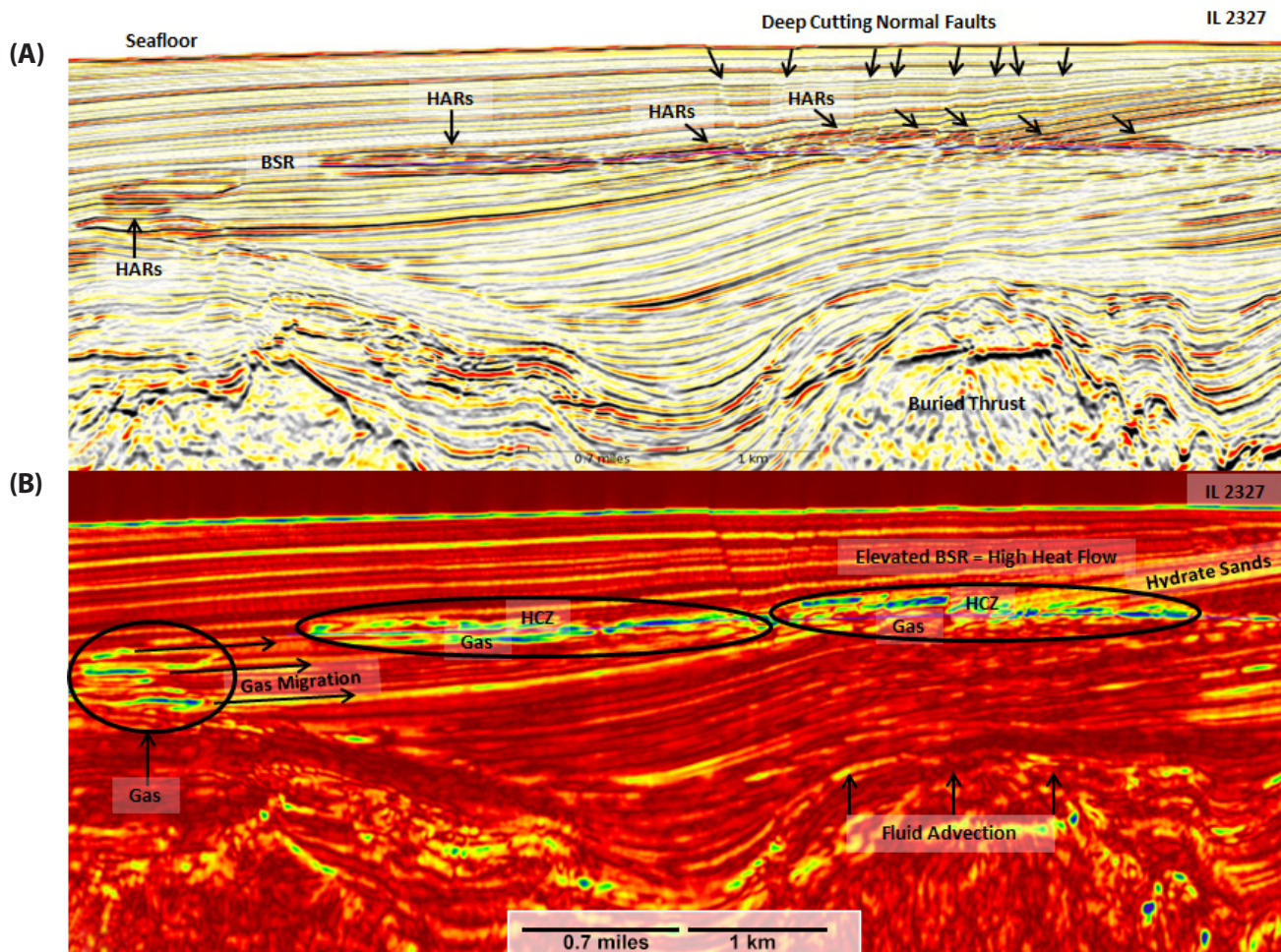


Figure 2. Representative seismic line through Zone 1. (A) Seismic amplitude display of inline 2327. Seafloor depth is ~2000 m. BSR over the syncline is 420 mbsf, while the BSR over the anticline is 370 mbsf, suggesting higher heat flow over the buried thrust, with possible fluid advection from depth along the fault network. (B) Signal envelope display of inline 2327. HARs characteristic of gas-charged sediments in the lower left corner suggest a gas source from depth. High amplitudes confined to bedding indicate gas migration updip along the permeable sand layers into the GHSZ. We interpret the package of high-amplitude horizons above the Hydrate Concentration Zone (HCZ) to the top right of this figure to be hydrate-saturated sand layers.

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- Zone 2 (Figure 3) is closer to the deformation front along the outer arc ridge. Strong positive amplitudes change polarity as they cross below the BSR, which is consistent with a shift in pore fill from gas hydrate to free gas. Interestingly, the seismic profiles reveal DBSRs beneath the main BSR that are positive polarity and correspond to a second change in reflection polarity. The DBSRs are superimposed across tilted strata, indicating that they formed after tilting ceased, about 1 million years ago.

- A horizontal reflection, characteristic of a free gas accumulation, is present in the downdip sediments on the left side of Figures 2 and 3, with HARs occurring in adjacent, updip strata. This geometry suggests delivery of thermogenic gas from depth into the hydrate stability zone via permeable sand layers. The HARs terminate against the DBSRs, which we believe are Structure II gas hydrate-saturated zones. A break in the BSR is observed near the outer arc ridge, suggesting fluid migration from depth. The high amplitude anomalies in the tilted strata within the Gas Hydrate Stability Zone (GHSZ) are interpreted to be a zone of highly concentrated gas hydrates.

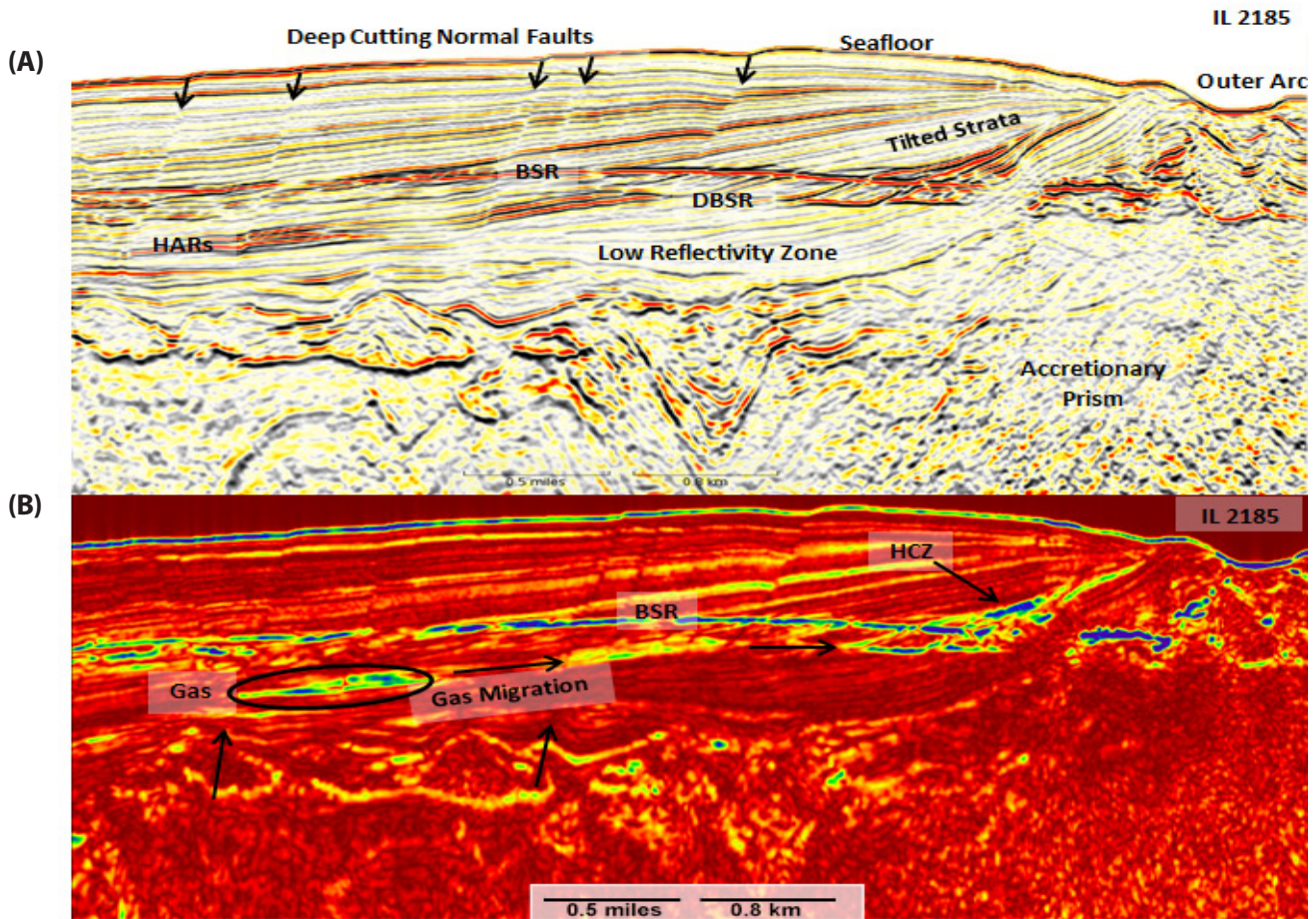


Figure 3. Representative seismic line through Zone 2. (A) Seismic amplitude display of inline 2185. Shown is the main BSR with negative polarity, the DBSR with positive polarity, and a large low-reflectivity shadow zone. High-amplitude reflections above and below the BSRs are interpreted to be gas and hydrate. Tilted strata related to accretionary tectonics and deep-cutting normal faults that may serve as conduits for thermogenic gas migration are also shown. (B) Signal envelope display of inline 2185. Display clearly draws out changes in physical properties. High values below the BSR are likely to correspond to gas migrating from depth, updip via permeable sand beds. Gas fractionation may result in Type II hydrate boundary 70 m below the main BSR. High signal envelope values above the BSR are interpreted as evidence for a zone of high gas hydrate concentration. Note the phase change across the BSR.

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Conclusions

- Based primarily on seismic evidence, we have identified two highly prospective, gas hydrate-rich reservoirs in the Kumano Forearc Basin: Zone 1 and Zone 2. We have also interpreted likely gas migration pathways from a deeper, thermogenic source upwards into the GHSZ.

- Amplitude analysis in complex regions containing gas hydrates can be difficult because of interference from faults, fractures, and the multiple fluids present at the three-phase boundary. However, this study has shown that amplitude analysis combined with the signal envelope attribute analysis is a powerful and effective tool in these complex settings. Continued improvements in these exploration techniques may help identify hydrate concentration zones and quantify methane hydrate resource volumes, particularly near the base of hydrate stability in deep water environments.
- Continued application of these methane hydrate exploration tools should improve the likelihood of success in future methane hydrate production efforts.

Acknowledgments

- We are grateful to Paradigm Geophysical and Landmark Graphics, a subsidiary of Halliburton, for providing the software that made this work possible.

RECENT ADVANCES IN NETL'S LABORATORY STUDIES OF HYDRATE-BEARING SEDIMENTS

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Introduction

The physical properties of hydrate-bearing sediments are influenced not only by hydrate saturation, but also by its growth habit and distribution in pore spaces. In fact, for sediments containing the same amount of hydrate, physical properties may vary considerably depending on the growth habit of the hydrate. For this reason, knowledge of hydrate growth patterns, including identification of cementing vs non-cementing growth, is helpful for understanding the physical and mechanical properties of samples measured in the laboratory and in the field.

The Gas Hydrate Research Laboratory at NETL supports the U.S. DOE National Gas Hydrate R&D program by providing enhanced understanding of pore-scale and core-scale phenomena in hydrate-bearing sediments. To this end, we have developed new techniques to: 1) synthesize non-cementing methane hydrate in laboratory sediments; 2) image hydrate growth habits using micro-focus X-ray computed tomography (μ XCT); and 3) characterize physical properties of sediments containing methane and carbon dioxide hydrates.

Laboratory Formation of Non-cementing Hydrate

Hydrate growth habits in laboratory specimens are influenced by pressure, temperature, and the availability of water and gas during hydrate formation. Expedient techniques synthesize methane hydrate in water-limited systems, in which hydrate preferentially nucleates at gas-water interfaces—at grain contacts (in samples with low water saturation) or on the surfaces of gas bubbles (in samples with high water saturation). This type of growth results in a hydrate cement that bonds adjacent grains together.

In nature, methane hydrate is most commonly formed from dissolved-phase methane, and it tends to form non-cementing hydrate. Laboratory synthesis of this type of hydrate is limited, because it requires preparing and injecting methane-supersaturated water for extended time periods to provide sufficient methane molecules to grow hydrate in the sediment's pore spaces.

We have developed new laboratory techniques to form non-cementing hydrate in sediments in a more timely fashion. We start by making cementing hydrate in a water-limited specimen; follow this with slow saline water injection at controlled pressure-temperature conditions; and finally implement a series of warming/cooling cycles in a closed, water-saturated system.

Figure 1 illustrates the Pressure-Temperature history during hydrate formation, along with the distributions of gas, water, and hydrate phases in pores at a few critical steps. Hydrate-bearing sediments synthesized in

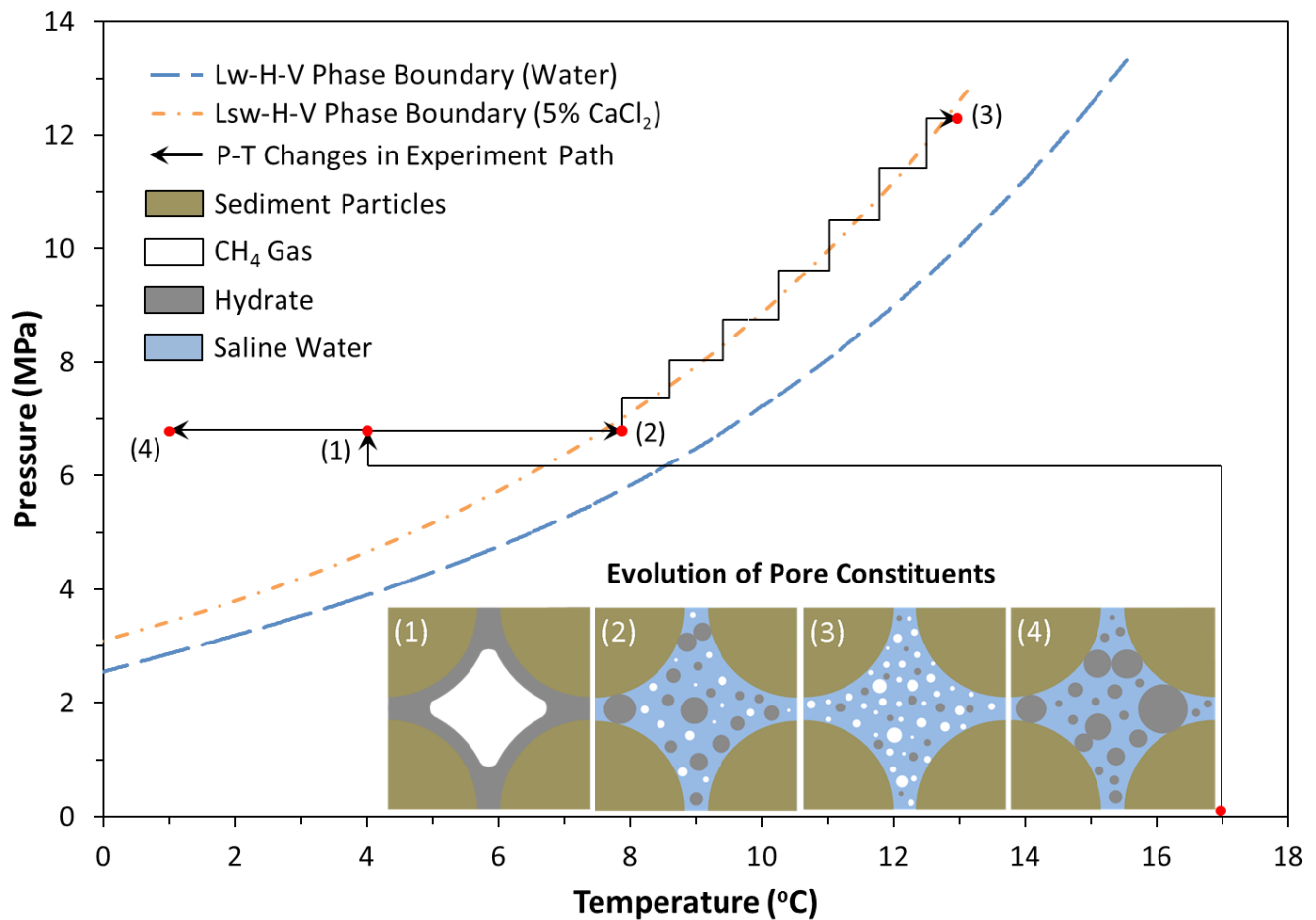


Figure 1. Evolution profile of pressure and temperature during hydrate formation, and subset illustrations of pore constituents at each critical step. (1) hydrate-bearing sample formed under the water-limited condition; (2) completion of saline water injection under controlled P-T, resulting in hydrate bearing sample saturated with saline water or minimal CH₄ gas; (3) completion of warming, resulting in CH₄ bubbles/residual hydrate in saline water-filled sample; (4) formed non-cementing hydrate-bearing sediments after cooling cycle. More details of current non-cementing hydrate formation method can be found in Choi et al. (2014).

- this way have a much lower stiffness than samples containing the same amount of hydrate but in a cementing habit. This technique can achieve 60% hydrate saturation within a week.
- **Pore-Scale Imaging and Flow Simulation**
- We have also developed techniques to image the hydrate growth habits at each step of sample synthesis using μ XCT. Most difficulties associated with μ XCT imaging of hydrate crystals in sediment are caused by the need to maintain high pressure and low temperature conditions during computed tomography (CT) scanning. High pressure core holders made out of metals, typically stainless steel and aluminum for hydrate studies, attenuate the X-ray beams drastically and filter out a majority of the low-energy beams. This is a problem for hydrate-bearing samples, because their constituents (gas, water, hydrate, and sediment grains) show much better contrasts at lower energy levels.
- To address this problem, we use a core holder made of beryllium (Figure 2a), which has high strength and stiffness, comparable to stainless steel,
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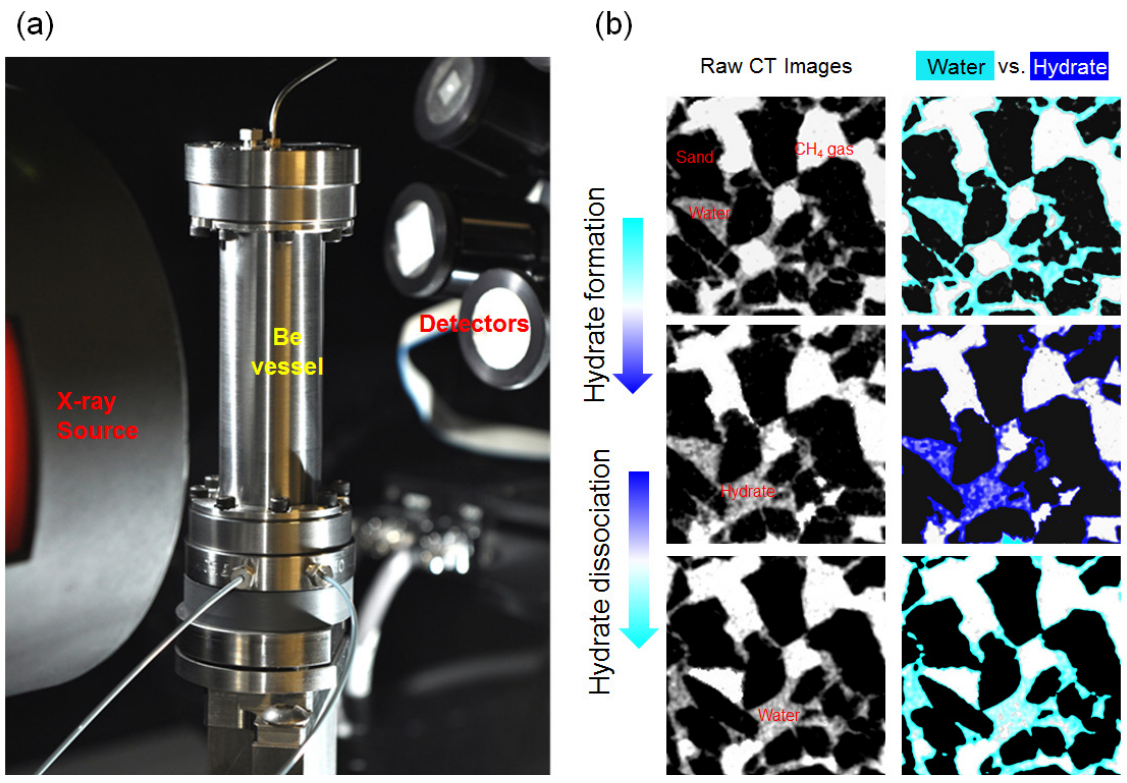


Figure 2. Imaging of hydrate pore habits using μ XCT. (a) The Beryllium vessel stands on the μ XCT station. (b) Distributions of pore constituents (i.e., water, methane gas, and methane hydrate) in sediments before and after hydrate formation and dissociation. The specimen is made of pure silica sands (mean grain diameter $\sim 100\mu\text{m}$) mixed with 20 weight% deionized water and consolidated under 3MPa effective stress. Hydrate formation is then triggered by pressurization followed by cooling. The scanning is conducted at 7°C when the specimen is subject to 10MPa gas pressure and 13MPa confining stress (i.e., 3MPa effective stress).

- but is also extremely low in density and has a small atomic number.
- These properties make beryllium almost transparent to X-rays, and thus it is an ideal material for high-pressure vessels used in CT studies.
- The image quality required to distinguish subtle differences in phase densities can be achieved by scanning the specimen at dual energy levels. Figure 2b shows a sequence of μ XCT images of water and hydrate distribution in a sample formed in a water-limited system within the Be vessel. The Be vessel is now being equipped with controlled vertical stress and acoustic velocity measurement capabilities.
- Figure 3a is a 3D CT image showing a volume of a scanned hydrate-bearing sediment specimen. Such images can be used to quantify the geometric and morphological properties of the solid particles and interstitial pore spaces; to illustrate the relationship of pore size and pore connectivity; and to show the distribution of water, gas, and hydrate phases in the pore spaces. They can also be utilized for geomechanical constitutive modeling and pore flow simulations, as illustrated in Figures 3b (a model of the pore network based on the original CT image), 3c (simulated gas percolation through the extracted pore network), and 3d (simulated relative gas permeability for this sample).

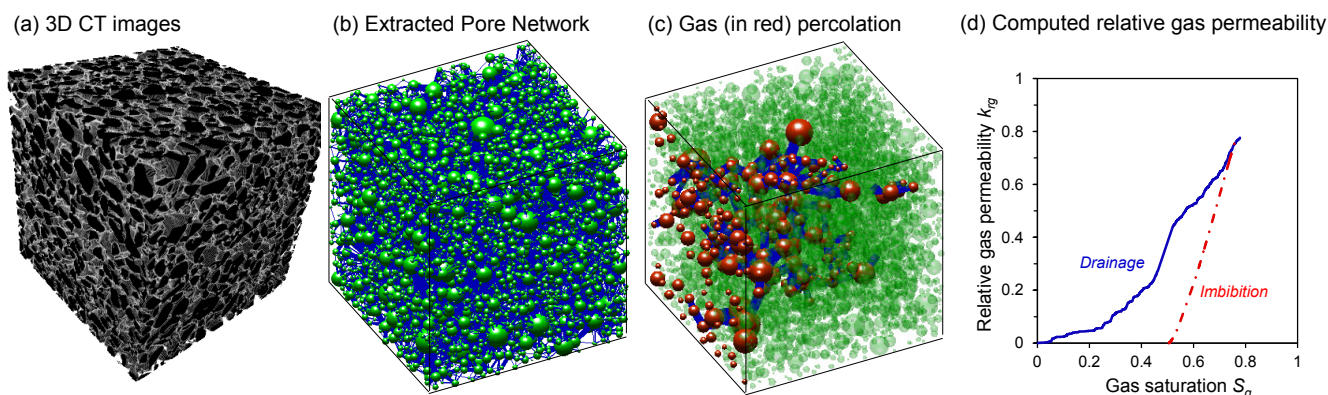


Figure 3. CT-based flow simulation. (a) 3D CT images with submicron resolution. (b) Extracted stick-ball model of pore network based on the CT images. (c) Simulation of gas percolation through the extracted pore network. (d) Computed relative gas permeability during drainage and imbibition processes using the pore network simulation. This work is in collaboration with J. Jang at Arizona State University, and J. Ajo-Franklin and T. Kneafsey at Lawrence Berkeley National Laboratory.

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Core-Scale Geophysical and Geomechanical Characterization

Performing laboratory tests with hydrate-bearing sediment samples is time-consuming and expensive. Our approach is to conduct information-rich tests on fewer samples, rather than an array of simply-instrumented tests on multiple samples. We use a multi-property characterization chamber (MPCC, Figure 4a) to simultaneously measure geophysical and geomechanical properties of hydrate-bearing sediments, including small-strain stiffness (i.e., P- and S-waves), strength, large-strain deformation, stress-volume responses, and permeability. The chamber body is made of aluminum, which is not ideal for resolving pore constituents using μ XCT, but it is sufficient to visualize core-scale hydrate distributions using industry CT instruments.

Current and Future Work

We are currently utilizing the MPCC to investigate geophysical and geomechanical characteristics of sediments containing CH_4 and/or CO_2 hydrate. The tests cover a wide range of hydrate saturations ($S_h =$ up to 50%) and effective stress conditions ($\sigma\sigma' = 0.69, 1.38, \text{ and } 2.76 \text{ MPa}$). We show here the P- and S-waveforms obtained after methane hydrate formation in a water-limited system (Figure 4b), and the stress-strain responses of non-cementing hydrate-bearing sediments (Figure 4c). In future work, we aim to combine the measured physical, mechanical, hydrological, and morphological properties of the samples in order to improve our understanding of how hydrate-bearing sediments behave during the hydrate formation and dissociation processes.

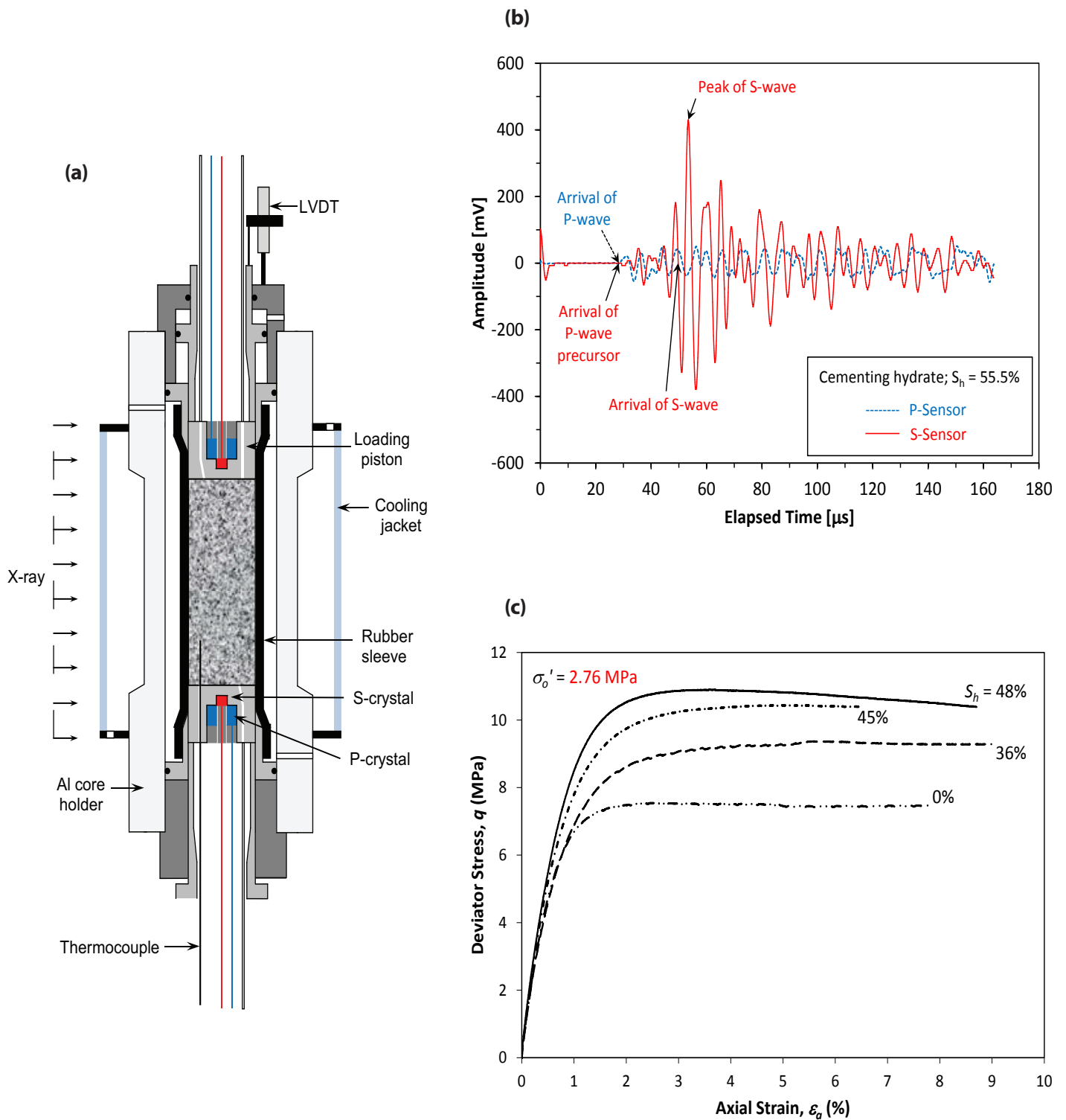


Figure 4. Geophysical/geomechanical characterization of CH_4 hydrate-bearing sediments using the MPCC. (a) Schematic illustration of the MPCC configuration. (b) P- and S-waveforms measured by 250 kHz P- and S- piezoelectric crystals for a cementing CH_4 hydrate-bearing sediments sample. (c) Stress-strain curves of non-cementing CH_4 hydrate-bearing samples obtained at different hydrate saturations (S_h) under the same effective confining stresses ($\sigma_o' = 2.76$ MPa). Details of fabrication and application of MPCC are explained in Seol et al. (2014).

INITIAL INTERPRETATION OF RESULTS FROM THE IĠNIK SIKUMI GAS HYDRATE EXCHANGE FIELD TRIAL

Introduction

In 2011 and 2012, the IĠnik Sikumi Gas Hydrate Exchange Field Trial was conducted in northern Alaska to test the viability of gas injection as a hydrate production strategy and, more specifically, to assess the potential for using N_2 - CO_2 - CH_4 exchange (originally conceived as CO_2 - CH_4 exchange) to produce methane from natural gas hydrate reservoirs. This science-based field trial was carried out by ConocoPhillips in partnership with the U.S. Department of Energy/NETL, the Japan Oil, Gas, and Metals National Corporation, and the U.S. Geological Survey (USGS) at a site within the Prudhoe Bay Unit of the Alaskan North Slope.

The IĠnik Sikumi test represents the first field investigation of gas hydrate response to the injection of a gaseous mixture of N_2 and CO_2 and the longest-duration field test to-date of a gas hydrate reservoir's response to depressurization. Preliminary results derived from the field trial and related modeling studies include important insights about: (1) the nature of gas hydrate occurrences in the western part of the Prudhoe Bay Unit; (2) the requirements for successful gas injection into native gas hydrates; (3) the responsiveness of hydrate reservoirs to changes in depressurization; (4) the presence of free water within hydrate-bearing formations in this region; and (5) thermal, physical, and chemical property changes that take place in hydrate reservoirs during mixed gas injection and subsequent depressurization.

For a more in-depth discussion of the IĠnik Sikumi test, please refer to the project web page ([click here](#)), publications listed there, and prior Fire in the Ice newsletter articles (IĠnik Sikumi Project Team, 2012, FITI Vol. 12, Iss. 1; Schoderbek and Boswell, 2011, FITI Vol. 11, Iss. 1; and Farrell, 2010, FITI, Vol. 10, Iss. 1, all available [here](#)).

The site for the IĠnik Sikumi test well was a temporary ice pad located with the Prudhoe Bay Unit (PBU) on the Alaska North Slope. The site was adjacent to the "L-pad," at a location where prior drilling had confirmed the occurrence of multiple gas hydrate-bearing sands with thickness, depth, temperature, and hydrate saturation favorable for drilling and production testing.

The IĠnik Sikumi field program began in January, 2011, with drilling and completion of the vertical test well; acquisition of mudlogging data and logging-while-drilling data in the top hole and test interval of the well; and running a comprehensive suite of open-hole wireline logs in the target interval, through a thick section of gas hydrate-bearing sandstone reservoirs. The well was temporarily abandoned until the following winter drilling season.

The well was re-occupied in January, 2012, when the N_2 - CO_2 - CH_4 exchange production test was initiated. The test included: injecting a

(a)

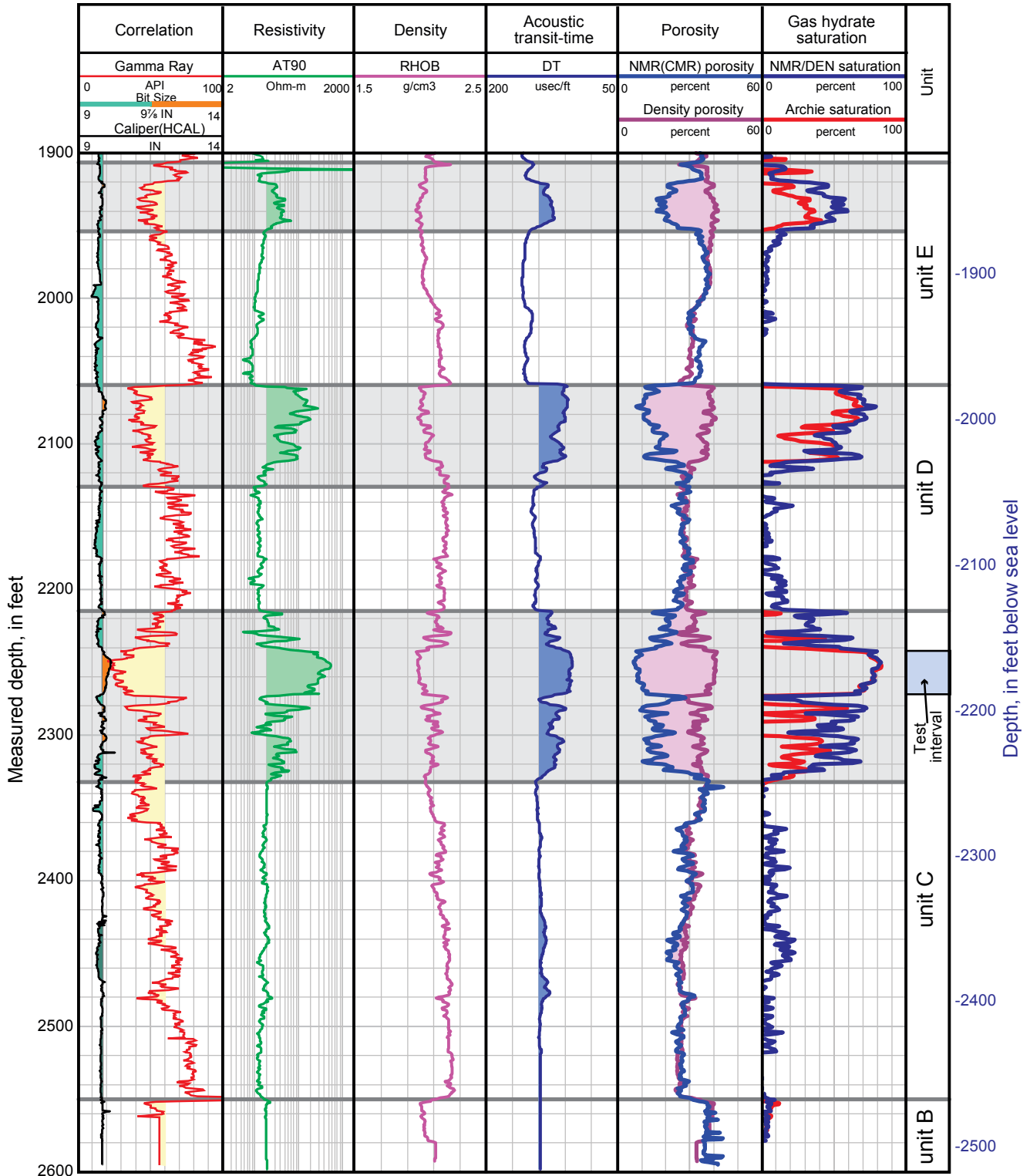


Figure 1a. Well log display for Ignik Sikumi #1 test well depicting the depth of units B, C, D and E. Grey shading showing occurrence of gas hydrate within reservoir-quality sands of units C, D and E. Data shown include the natural gamma-ray, caliper (HCAL), electrical resistivity (AT90), bulk-density (RHOB), acoustic transit-time (DT), neutron porosity (NMR(CMR)) logs; and calculated density porosity, NMR-density porosity derived gas hydrate saturations and Archie calculated gas hydrate saturations.

Figure 1b. Well log enlarged for test interval in unit C. Data shown include the natural gamma-ray, caliper (HCAL), calculated density porosity, NMR-density derived saturations, and Archie-derived saturations. Test interval is noted in blue shading.

gaseous mixture of N₂ and CO₂ and chemical tracers (14 days); flow back conducted at downhole pressures above the stability threshold for pure CH₄ hydrate (1.5 days); and an extended (30-day) jet-pump-assisted flow back at pressures below the stability threshold of pure CH₄-hydrate. At the conclusion of the 30-day production test, the well was permanently abandoned and site remediation was completed. For a comprehensive review of the Iñnik Sikumi test, please see the ConocoPhillips Final Report ([link](#)). Full datasets for the Project can also be accessed through this web site.

Preliminary Results

Extensive and rigorous evaluation of well log and production data have been conducted to assess the reservoir's response to all four phases of the Iñnik Sikumi field trial: well logging, gas injection, unassisted flow-back period, and jet pump-assisted (depressurization) flow back.

Log data acquired in 2011 confirm the occurrence of multiple gas hydrate-bearing sand reservoirs in this part of the PBU. Log results (Figure 1) reveal the co-occurrence of gas hydrate (occupying up to 80% of pore volume), bound water (occupying up to 10% of pore volume), and free water (occupying up to 10% of pore volume) in the "C", "D", and "E" sandstones.

Correlation of the Iñnik Sikumi well with prior wells drilled from the L-pad revealed that these accumulations occur over a large area around the well pad. Further comparison of the Iñnik Sikumi data with data available from the PBU L-106 well indicated that the "D" sand is full of gas hydrate to its base; whereas the "C" sand appears to exhibit a gas-hydrate/water contact that occurs at a common structural level in both wells.

The decision to inject a mixed gas resulted in successful injection and production (Figure 2). Despite complications introduced by gas injection, the subsequent depressurization phase was characterized by production that was highly responsive to changes in bottomhole pressure. While interpretation of the field data is ongoing, the primary scientific findings and implications recognized to-date are as follows:

- N₂-CO₂-CH₄ exchange can be accomplished in naturally occurring gas hydrate reservoirs, although the extent is not yet known;
- free water can greatly limit the success of pure CO₂ injection, but a carefully designed gas mixture, in this case of N₂-CO₂, can be effective;
- wells must be carefully designed to enable rapid remediation of wellbore blockages that may occur during any cessation in operations;
- sand production can be effectively managed through standard engineering controls;
- reservoir heat exchange during depressurization is more favorable than expected—providing insights into the nature of near-wellbore freezing during hydrate production and prompting consideration of a more aggressive pressure reduction plan.

The test also provided valuable field confirmation that gas hydrate

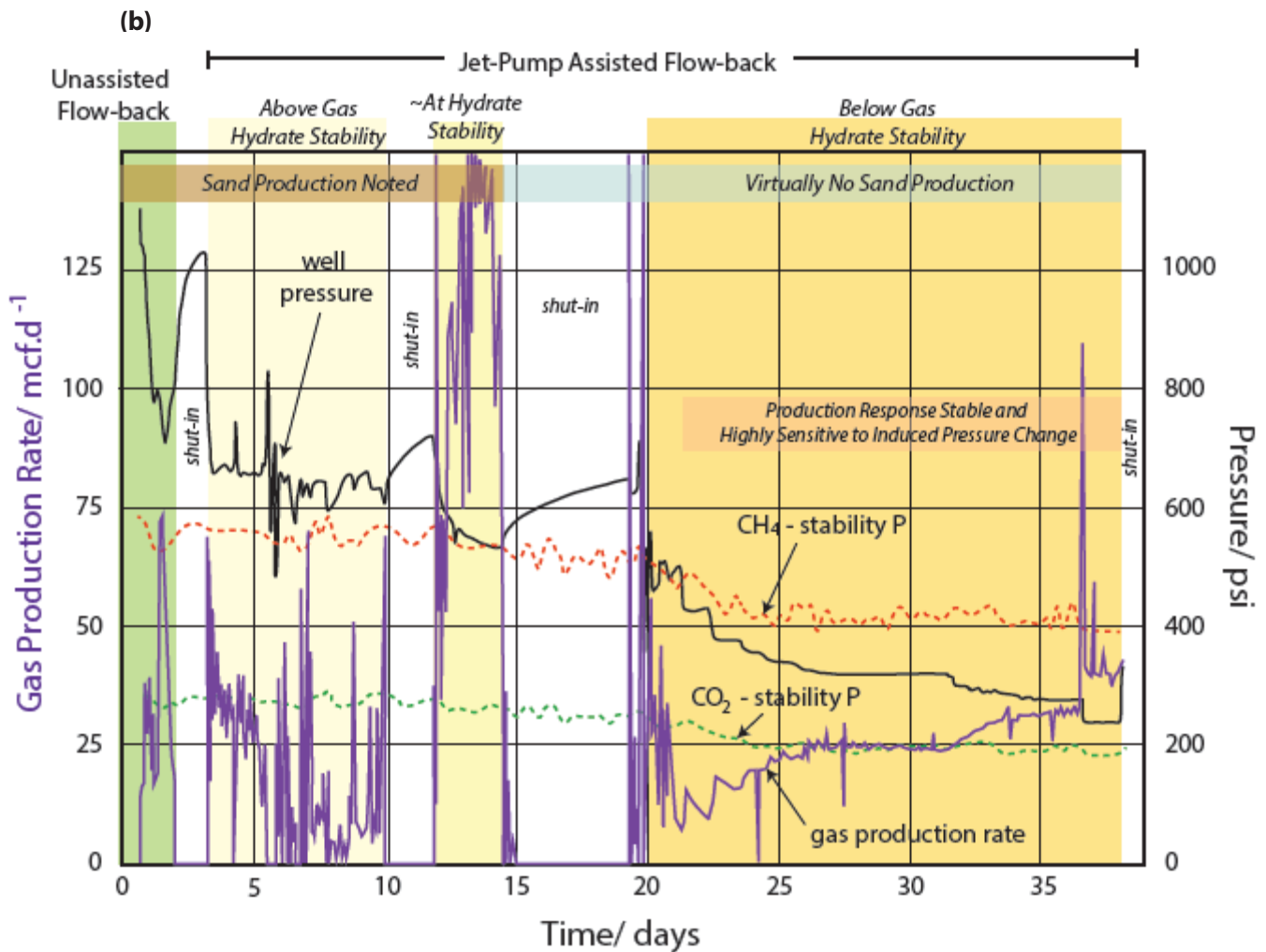


Figure 2. Summary of CO₂-CH₄ exchange production test results, showing well pressure (black line) and gas production rate (purple line) as a function of time. Stages of production are indicated by shading: unassisted flow-back (green shading); jet-pump assisted flowback above gas hydrate stability pressure (tan shading); at hydrate stability pressure (pale yellow shading); and below gas hydrate stability (dark yellow shading). Note that the production was stable after 20 days and clearly responding to induced pressure changes. Sand production, CH₄ stability, and CO₂ stability also shown.

- destabilization is strongly self-limiting (see Moridis and Reagan, FITI 14 (1)), dispelling concerns about uncontrolled destabilization.
- **Discussion And Next Steps**
- The Iġnik Sikumi field test represents a successful first attempt at producing natural gas from a hydrate-bearing reservoir using N₂-CO₂ gas injection and a staged depressurization strategy. Additional field tests, laboratory studies, and modeling efforts will be required to provide a more complete picture of the N₂-CO₂-CH₄ exchange process for a variety of hydrate reservoir systems.
- The complexity of multi-phase chemical processes within the reservoir greatly challenged existing modeling and simulation capabilities. However, the test and subsequent evaluation of results indicate that pure CO₂ injection would have resulted in a failed test due to immediate CO₂-hydrate formation upon injection.
- The Iġnik Sikumi test was conducted using a “huff-and-puff” strategy, with

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a single well for both injection and production operations. The next logical step will be to utilize two wells—an injection well and a producing well. A two-well system will allow CO₂-CH₄ exchange in the injector region during depressurization and/or thermal stimulation in the producer region.

The commercial viability of N₂-CO₂-CH₄ exchange technology will depend on finding the well configuration, injection method, injection gas mixture, and production enhancement strategies that together maximize gas production and hydrate reservoir stability. Based on results of this field test, it is clear that gas injection and exchange will remain a valuable part of gas hydrate production strategies that are based primarily on reservoir depressurization.

Acknowledgment

This short summary is based on the ICGH 2014 paper by Anderson et al. (2014). We would like to thank the original authors—Brian Anderson, Ray Boswell, Tim Collett, Helen Farrell, Satoshi Ohtsuki, Mark White, and Margarita Zyrianova—for making this article possible.

A FRESH LOOK AT THE MEDITERRANEAN AND BLACK SEA BASINS: POTENTIAL FOR HIGH-QUALITY HYDRATE RESERVOIRS

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Hydrate Energy International

Introduction

Turbidite sand-silt systems on continental margins of the world's oceans are regarded as good targets for finding concentrated natural gas hydrates. These turbidite systems are also primary exploration targets for more deeply buried hydrocarbons, and they have been proven to be good reservoirs, with acceptable production rates, for conventional oil and gas.

Turbidite sands are also projected to have acceptable gas hydrate production rates, and this performance potential has been substantiated, at least in part, by a technical production test of gas hydrates in turbidites of the Nankai Trough, off the coast of southeastern Japan.

In this article, we consider the potential for unusually high-quality, non-turbidite sand reservoirs in the Mediterranean and Black Sea basins that may serve as superior gas hydrate production targets.

Mediterranean and Black Sea Basins

The Mediterranean and Black Seas have had a Neogene and younger history that is quite different from that of the world's open oceans, and this unique history has important implications for the presence of reservoir-quality sands containing gas hydrates.

Whereas all but the shallowest portions of the world's open ocean



Figure 1. Shaded relief map showing locations of the Mediterranean and Black Sea basins and related features.

continental slopes have maintained a marine depositional environment throughout the entire Phanerozoic, restricted deep portions of the Mediterranean and Black Seas were cut off from the open ocean for significant periods. During such times, their water levels dropped well below the open-ocean sea level.

This occurred during the latter Messinian part of the Miocene epoch, when a large and complex restricted basin developed, encompassing the present Mediterranean and Black Seas (Figure 1), and went into a cycle of nearly complete desiccation. This episode, known as the Messinian Salinity Crisis, ended in Holocene time with the Zanclean flood, when the Atlantic Ocean reclaimed the basin.

The Zanclean flood began when seawater entered through a spillway from the Atlantic Ocean over what is now the shallow Strait of Gibraltar. The western Mediterranean flooded, until the shallow sill between Sicily and Tunisia was overtopped. The Eastern portion, including the Black Sea and a number of other shallower basins, was flooded when the precursor to the shallow Bosphorus seaway was overtopped.

During the time of abnormally low water levels, a group of potential gas hydrate reservoirs may have formed on the continental slopes of the present Mediterranean and Black Seas (Figure 2). The entire slope region that was then exposed can be expected to have developed subaerial

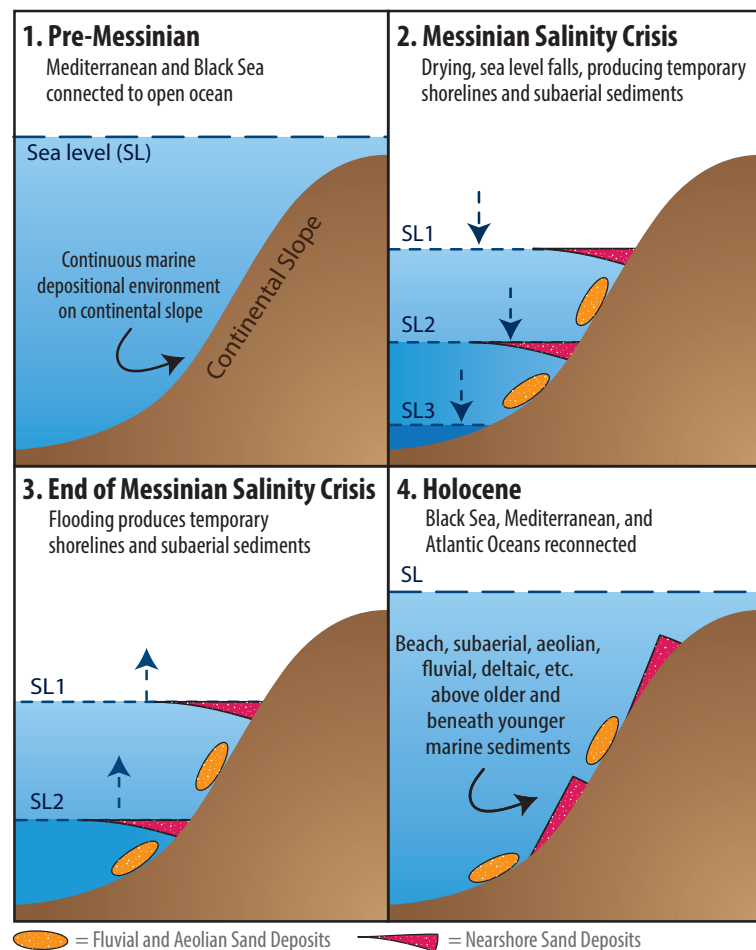
Figure 2. Schematic cartoon, not to scale, illustrating formation of high-quality nearshore and subaerial sand reservoirs in an otherwise marine sequence; nearshore sand deposits, associated with fluctuating sea levels, are shown in red; aeolian and fluvial deposits are shown in yellow.

Stage 1, Pre-Messinian: Mediterranean and Black Seas connected to the open ocean, marine deposition on continental slopes.

Stage 2, Messinian Salinity Crisis: sea level falls, exposing continental slope and producing temporary shorelines and subaerial sediments.

Stage 3, End of Messinian Salinity Crisis: temporary sea levels migrate upward, as flooding is restored.

Stage 4, Holocene: Black Sea, Mediterranean, and Atlantic Oceans reconnected, marine deposition resumes on continental slope.



- sediments. These would have included sand systems related to near-shore
- marine and subaerial longshore beach sediments; deltas; and associated
- highly organic, lagoonal muds. On the slope above temporary shorelines,
- fluvial and aeolian sediments would have formed.

- Such subaerial sediment systems are typically characterized by well-sorted
- sand and possibly gravel bodies that would be coarser-grained than what
- is typically found in marine turbidite systems. Such sands would potentially
- constitute very high-quality reservoirs within an otherwise marine
- depositional environment.

- **Recent Episode as Analog**

- A younger, less extreme drying episode occurred in the Black Sea region
- during the most recent glacial maximum, around 8500 years before
- present. This resulted in deposition of beach sediments, sand dunes, and
- soils—all of which are now found in water depths up to about 100 meters
- below sea level.

- Note that the water level did not fall enough to expose the deeper portions
- of the continental slopes during the recent glacial maximum. Still, this
- recent analog serves to illustrate how high-quality reservoir sands may be
- deposited on temporarily exposed continental slopes, then submerged to
- significant water depths and buried by marine sediments.

- Similar sandy deposits likely formed during the Messinian period on the
- continental slopes of the Mediterranean and Black Sea basins, and we
- suspect they may be found today sandwiched between older and younger
- marine sediments.

- **Turkish Black Sea Margin**

- One of the necessary conditions for natural gas hydrate accumulation is an
- influx of gas, and the Turkish Black Sea margin appears to have sufficient
- gas migration via sedimentary units and possibly along vertical structures.
- Gas may also migrate into the gas hydrate stability zone (GHSZ) from
- leaking subjacent structural traps.

- Sedimentary influx into this region is also substantial. Anatolian rivers
- appear to deliver more than one-third of the total sediment input into the
- Black Sea. This high sediment load may be related to the proximity of the
- North Anatolian Fault system and associated tectonism in northern Turkey
- and its Black Sea continental slope.

- A similar sediment delivery system probably operated during the
- Messinian sea-level lows, which implies that considerable coarse sediment
- was delivered to the continental slope that could have formed high-quality
- sand deposits. Because of the narrow continental shelves along the Turkish
- Black Sea coast, almost all of the sediment, including the coarser fraction,
- would have reached the continental slope at that time.

- **Persistence of Hydrates**

- Natural gas hydrates can be expected to persist in the GHSZ in continental
- slope sediments, as long as marine conditions are maintained and not

- altered drastically. The Messinian sea level change was drastic and likely
- resulted in dissociation of virtually all older hydrates in the Mediterranean
- and Black Seas.

- In contrast, during the Holocene drop in sea level, which was much less
- extreme, the top of GHSZ would only have lowered, and the thickness
- of the stability zone would have decreased. With substantial gas flux
- and reflooding of the Black Sea, however, former concentrations and
- thicknesses of gas hydrate deposits may have been reestablished relatively
- quickly.

- **Summary**

- Reservoir-quality, sand-rich sediments are likely to have formed on
- Mediterranean and Black Sea continental slopes during an abnormally
- low sea-level trend in Messinian time. Near-shore sand deposits, as well as
- fluvial and aeolian lenses, are likely to have formed as a result of shifting,
- temporary shorelines and are likely to be interleaved with older and
- younger marine sediments.

- We regard the Turkish margin of the Black and Mediterranean Seas as
- prospective for gas hydrates, due to the presence of gas and sediment
- influx, as well as the likelihood of high-quality sand reservoirs formed
- during this Messinian Salinity Crisis.

- **Suggested Reading**

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Announcements



The Frozen Heat report is available online, via [this link](#) on NETL's Methane Hydrate Program website.

• UNITED NATIONS HYDRATE REPORT PUBLISHED ONLINE

• The United Nations Environment Programme (UNEP) has released a new report, "Frozen Heat, A Global Outlook and Methane Gas Hydrates." The report provides a comprehensive review of the science and technology of gas hydrates and a discussion of the potential role of hydrates in the environment and in the future global energy mix.

• "Frozen Heat" was organized by an international steering committee consisting of 25 experts from academia, government, industry, and non-governmental organizations all over the world.

• Frozen Heat is intended for policy makers, the general public, and other stakeholders, and it was developed in large part from the contributions of scientists and engineers throughout the gas hydrate community. The report is organized in three parts: 1) the executive summary; 2) Volume 1, a review of gas hydrates in nature; and 3) Volume 2, the potential significance of gas hydrates as an energy resource.

• Volume 1 presents a brief history of gas hydrate research, describes how and where gas hydrates form, and illustrates how gas hydrates interact with the environment. Environmental interactions are discussed in terms of localized phenomena, including links between gas hydrates and deep marine biological communities; and on the larger scale of global processes, including the global carbon cycle and the interplay between gas hydrates, climate, and the changing environment.

• Volume 2 is focused on the energy resource potential of gas hydrates and includes discussions of the size of the resource and the technologies that will likely be needed to access that resource. This volume also includes a review of the environmental, economic, and societal factors that serve to influence the timing and ultimate role of gas hydrates in the global transition to low-carbon energy systems.



- **Announcements**

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- UNEP's global outlook emphasizes the need for a strong foundation in science, in order to effectively mitigate the potential environmental impacts of energy resource development. The gas hydrate community supports this philosophy and is working to advance our understanding of gas hydrates in nature with past, current, and future collaborative field programs around the world.

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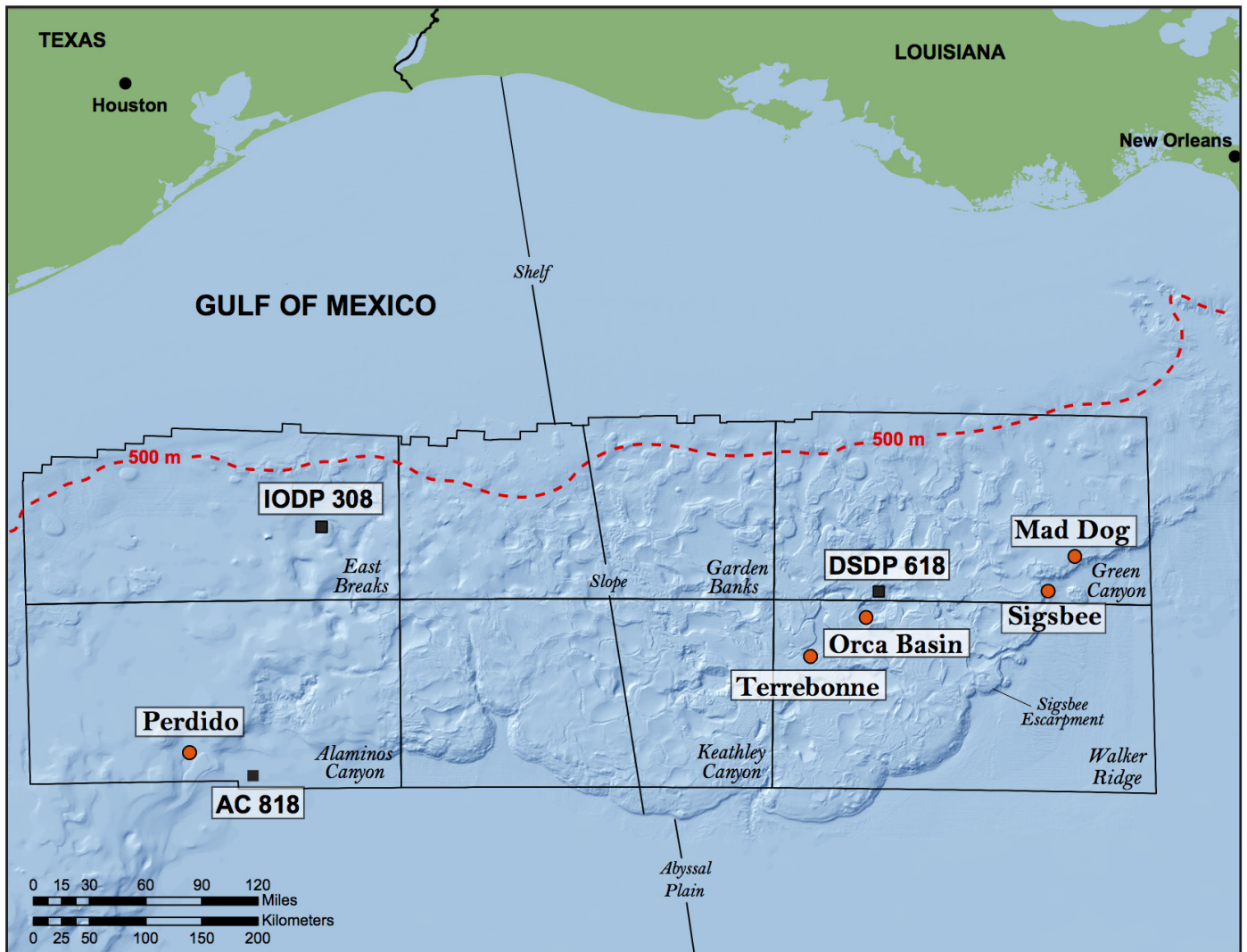
Announcements



NETL LAUNCHES NEW MARINE HYDRATE FIELD PROJECT

NETL has awarded a new project entitled "Deepwater Methane Hydrate Characterization and Scientific Assessment," led by researchers at the University of Texas at Austin, with contributions from scientists at Ohio State University, the Consortium for Ocean Leadership, Columbia University – Lamont Doherty Earth Observatory, and the USGS. The goal of this multidisciplinary effort is to plan and execute a state-of-the-art field program in the Gulf of Mexico to identify and characterize potential high-saturation methane hydrate accumulations.

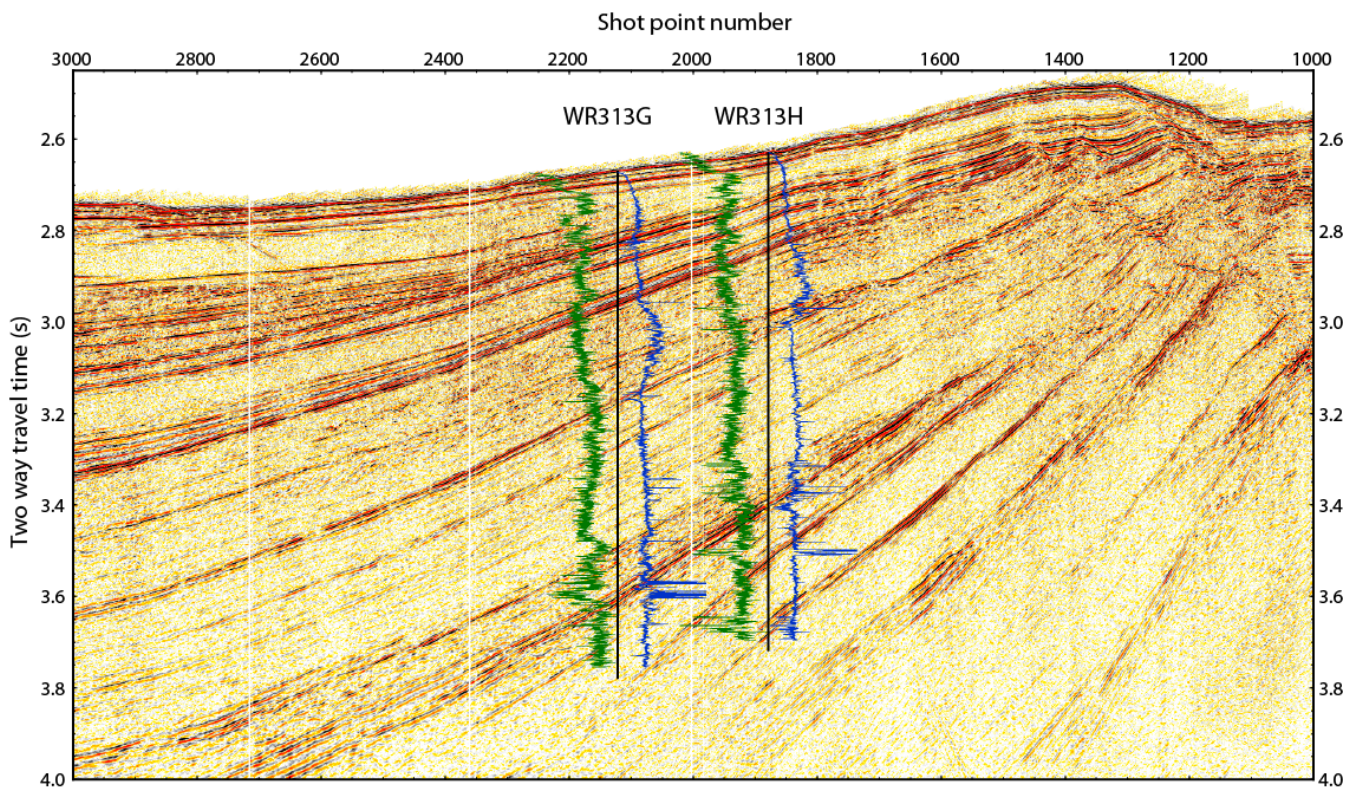
This is a 4-year project, to be carried out in 3 phases. In Phase 1, the project team will identify and rank potential methane hydrate research sites, using geological and geophysical data. One of the highest priority locations



Methane hydrate locations in the northern Gulf of Mexico slope. Black squares indicate locations drilled previously: DSDP Leg 618, IODP 308, and Tiger Shark (AC818) drilled by Chevron. Orange circles are proposed drilling prospects for this study: Terrebonne (formerly WR313), Sigsbee (formerly GC955), Mad Dog, Orca, and Perdido.

• Announcements

- for evaluation and possible drilling is in the Terrebonne minibasin (see below), which has seismic, log, and drilling indications of coarse-grained reservoir sands and high methane hydrate saturations. After sites are selected and ranked, the project team will develop preliminary plans for field research activities, and they will submit a proposal to the International Ocean Drilling Program for access to a scientific drilling and research vessel.
- In Phase 2, the project team will develop detailed operational plans; refine science and logistical plans; prepare and test pressure coring and core analysis tools; complete permitting requirements; and arrange scientific and operational staffing and support needed to carry out the Phase 3 field work. Phase 3 will focus on executing a comprehensive research expedition to characterize gas hydrate reservoirs in the Gulf of Mexico. Activities during Phase 3 will include conventional coring, pressure coring, downhole logging, in situ testing, and subsequent analysis of data and samples collected during that field effort.
- The planned budget for all three phases of the project is \$64 million, with \$41 million of that contributed by the DOE, and \$23 million provided as performer cost share. For more information on this project, please visit the [NETL project web page](#).



Drilling locations in the Terrebonne minibasin-- a type-example of a coarse-grained hydrate reservoir and one of the highest priority research sites. The project team proposes to re-occupy WR313-H and WR313-G, which were logged during JIP Leg II. Terrebonne has a series of phase reversals in high-amplitude dipping reflectors at the base of methane hydrate stability. McConnell and Kendall (2002) interpreted these to represent free gas accumulations beneath methane hydrates. In both holes, JIP Leg II encountered methane hydrate saturations of up to 80% in thick, sand-rich intervals updip of these phase reversals. The new project would core, pressure core, and make in situ measurements through these hydrate-bearing intervals. Seismic data courtesy of USGS.

• Announcements



NETL AND JOGMEC ESTABLISH NEW GAS HYDRATE MOU

NETL and Japan Oil, Gas and Metals National Corporation (JOGMEC) have signed a new Memorandum of Understanding (MOU) to facilitate collaboration leading to field investigations of gas hydrate. This MOU is essentially an update of the previous MOU dated June, 2008. The specific purpose of the new MOU is “to establish a cooperative working agreement... in the areas of gas hydrate production testing on the North Slope of Alaska.” Specific R&D elements of the agreement include: 1) geologic review of gas hydrate occurrences on the North Slope of Alaska, for the purpose of selecting potential sites for gas hydrate production testing; 2) determination of operational logistics and permitting requirements on Alaska State Lands; 3) local and regional outreach to inform local and regional communities in Alaska about the nature of scientific activities to be carried out; and 4) gas hydrate production testing, including analysis of data derived from controlled depressurization of a gas hydrate reservoir over extended time periods.

The agreement was signed in November and will be effective for 5 years, concluding in October 2019. Technical contacts for the MOU are NETL’s Gas Hydrate Program Technology Manager, Ray Boswell (email: ray.boswell@netl.doe.gov) and JOGMEC’s Methane Hydrate R&D Group Leader, Koji Yamamoto (email: yamamoto-koji@jogmec.go.jp).

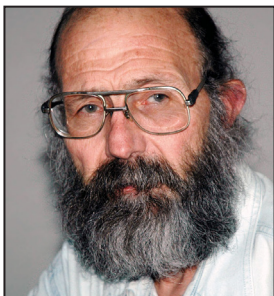


photo credit: Penny Colton

IN MEMORY OF MIKE BATZLE

Dr. Mike Batzle, the fiercely honest and humble Professor of Geophysics at Colorado School of Mines, died January 10th from complications of esophageal cancer. He is remembered fondly by colleagues and students who had the good fortune to work with him in his Center for Rock Abuse, a lab he started at CSM in 1994. When asked what his laboratory work was all about, he was apt to reply: “we squeeze rocks.” In more technical terms, his experimental work was focused on measuring rock and fluid properties and relating them to seismic attributes and hydrocarbon indicators like AVO. Batzle was famous for his part in development of the Batzle-Wang equations, which are used for estimating elastic properties of pore-fluid saturations and remain an integral part of AVO analysis and interpretation today. In recent years, he led a project to relate seismic velocities of sedimentary rocks to hydrate saturation and texture.

Mike was known as a very generous and good-humored scientist and mentor, and he will be sorely missed by colleagues and friends.



• Spotlight on Research



GERALD R. DICKENS

Rice University

Many of us know Jerry Dickens as a methane hydrate expert and professor at Rice University, but most of us do not know that he worked previously as an apple picker, sheep herder, and blackjack dealer. Asked how he went from dealing cards to modeling hydrate stability, Jerry replies, "I ended up in the world of gas hydrates by complete accident."

NONLINEAR PATH TO MARINE HYDRATE RESEARCH

Jerry Dickens grew up in the sixties and seventies on the campus of Stanford University, where his father ran the computer lab. He was interested in science from a young age but put little effort into school. He graduated from high school in 1982, attended Whitman College for a few semesters, then took a break from school to travel and work in New Zealand. He hitch-hiked all over the islands and found work picking fruit and doing other seasonal jobs there, including herding sheep from the seat of a Farmbyke motorcycle.

In 1986, Jerry returned to California and began working in earnest on a chemistry degree at UC Davis. To pay the bills, he worked as a blackjack dealer at Harrah's Club in Lake Tahoe. He was good at dealing cards, but he did not see himself as a future pit boss. He was also good at chemistry, so after graduation, he embarked on a graduate program at the University of Michigan that combined chemistry, marine geology, and maritime adventures.

In the summer of 1994, Jerry stumbled into the world of methane hydrate research, during an internship with Mary Quinby-Hunt, at LBL. Quinby-Hunt had a new project, studying methane hydrate phase boundaries, and, within a few weeks, Jerry was making hydrate samples in the lab from various solutions, including filtered seawater from Monterey Bay. Quinby-Hunt and Dickens wrote up the results, which included the first experimentally-derived methane hydrate phase diagram for seawater.

When Jerry returned to Michigan, he had hydrates on his mind. He began talking with Professor Jim O'Neil about the Paleocene-Eocene Thermal Maximum. The two developed a conceptual model for how climatic warming at the end of the Paleocene may have driven dissociation of methane hydrate and release of free gas from seafloor sediments. They thought this might explain anomalous carbon isotope changes that took place at that time.

In the summer of 1995, Jerry received a call from Charlie Paull, inviting him to join an expedition to collect gas and water samples from the Blake Ridge, off the coast of South Carolina. Jerry joined the science team and became a key player in this important ODP hydrate research expedition, collecting and analyzing the first in-situ measurements of methane concentrations obtained using a pressure coring device.

Jerry is understated about his achievements and professional aspirations. He says he wants to "use scientific observations to fix the holes in the way we view the global carbon cycle." He is currently generating carbon isotope records across key intervals of time to constrain inputs and outputs of methane from the seafloor; and collecting pore-water data from around the world to constrain processes of hydrate formation and dissociation. He believes the results will show that methane hydrates in nature are dynamic, and that we cannot continue to ignore the very large amounts of carbon that are continually cycling in and out of hydrates.

In his spare time, Jerry enjoys travelling and cooking with his family. He is also passionate about motorcycles and enjoys riding a 2008 Harley Davidson Road King on the open roads of Texas.