the ENERGY lab

Fire in the Ice

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Methane Hydrate Newsletter

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GAS HYDRATES IN NEW ZEALAND – A LARGE RESOURCE FOR A SMALL COUNTRY?

By Ingo A. Pecher (GNS Science, Lower Hutt, New Zealand & Heriot-Watt University, Edinburgh, UK) and the GHR Working Group[1]

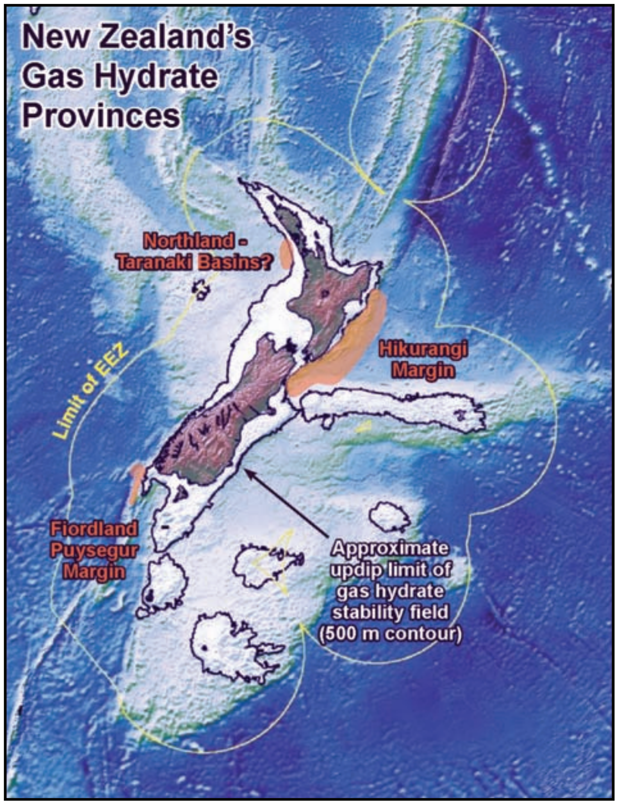

Figure 1: New Zealand's gas hydrates provinces

Background

Gas hydrates have attracted steady interest in New Zealand for over 30 years. The Hikurangi margin, east of the North Island, was among the first regions globally for which the presence of gas hydrates was inferred from bottom simulating reflections (BSRs) (Katz, 1981). BSRs were later also discovered on the Fiordland-Puysegur margin to the southwest of the South Island (Townend, 1997). Recently observed evidence for gas pockets within the hydrate stability field also suggests presence of gas hydrates in the deep-water Taranaki and Northland basins to the west of the North Island (Ogebule and Pecher, *in press*) and it is considered likely that further data analysis will lead to the discovery of gas hydrates elsewhere in New Zealand's vast economic zone (Figure 1).

Research into New Zealand's gas hydrates is largely motivated by the possibility that hydrates may constitute a future source of natural gas. Funding for gas hydrates research since the mid-1990s was provided under the umbrella of various petroleum-related programs. In 2010 the New Zealand Foundation for Research, Science, and Technology (FRST), for the first time awarded funding for a dedicated gas hydrates program (Gas Hydrates Resources, GHR). Most research is focusing on the Hikurangi

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[1] *GHR Working Group*: R. Archer, P. Barnes, D. Bowden, A. Gorman, M. Fohrmann, D. Fraser, G. Lamarche, J. Mountjoy, A. Rowden, R. Srinivasan Navalpakam, S. Toulmin.

margin, largely because its large area and proximity to New Zealand's major population centers make it economically most attractive for potential gas production.

Because of New Zealand's isolation and small population base, the economics of gas production is different from most countries. A single giant gas field, the ~4 tcf Maui Field, has provided the backbone for domestic gas supply since the 1970s. The field is being depleted and it is possible that New Zealand may need to rely on relatively expensive LNG imports.

New Zealand's annual gas consumption between 2005 and 2009 has been ~160 PJ, i.e., roughly 0.16 tcf (MED, 2010). For the Eastern Nankai trough, resource assessments suggest ~20 tcf of gas may be present in the form of concentrated gas hydrates (Fujii *et al.*, 2008). Gas hydrate deposits offshore New Zealand may be of a similar size (Pecher and Henrys, 2003). Even if only a small part of this volume is economically recoverable, hydrates could provide the main source of gas for New Zealand for several decades.

Key Observations

The collection of high-quality industry-style 2-D seismic data on the Hikurangi margin in 2005 (05CM) and in 2009 (PEGASUS) has significantly improved our knowledge on gas hydrates within the region. Three research cruises in 2006 and 2007 (R/V *Tangaroa* TAN 0607, TAN 0616, R/V *Sonne* SO-191) also involved geochemical analyses and seafloor sampling, including recovery of gas hydrates during TAN 0616 and SO-191 (Figure 2), together with controlled-source electromagnetic during SO-191. Results from these campaigns are summarized in *Marine Geology* Special Issue 272/1-4 (2010).

Several key features of the gas hydrate system on the Hikurangi margin include:

- The source of gas for hydrate formation is likely to be biogenic based on geochemical analyses of seafloor cores and water samples (e.g., Faure *et al.*, 2010) and because a significant part of the gas hydrates province is located seaward of inferred thermogenic source rocks.
- A strong link between BSRs and features that promote fluid flow suggests that much of the gas for hydrate formation is supplied from beneath the BSR (Pecher and Henrys, 2003).
- The Hikurangi margin has relatively low heat flow (Townend, 1997). Subsequently, BSRs are quite deep, often around 700 mbsf.
- BSRs are often relatively weak – at a few locations however, high-amplitude patches are present at BSRs similar to segmented BSRs in the Gulf of Mexico (Shedd *et al.*, 2009) (Figure 3).

Future Plans

The quality of reservoir rocks and characterization of individual reservoirs, including a better understanding on how they have formed, have been identified as the key questions for better assessing potential gas hydrate resources. The current program, awarded for two years, will focus on regional analysis of seismic data to improve our understanding of reservoir rocks and on characterization of specific deposits to investigate gas hydrate formation. It is also planned to conduct initial production modeling as well as a first assessment of the potential impact of production on seafloor communities. Analysis of existing data should further corroborate evidence for gas hydrates in the Taranaki and Northland basins as well as in the Rienga basin further to the northwest.

A survey by the R/V *Sonne* is planned for March and April, 2011 (New Zealand Methane Seep Systems, NEMESYS, led by IFM-Geomar, Kiel,

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This newsletter now reaches more than 1000 scientists and other individuals interested in hydrates in sixteen countries. If you would like to submit an article about the progress of your methane hydrates research project, please contact Jennifer Presley at 281-494-2560.

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Germany; J. Bialas and C. Berndt). It is planned to acquire several high-resolution 3-D seismic cubes with the P-Cable seismic system to investigate the sub-seafloor plumbing system of vents identified during the SO-191 cruise. Furthermore, controlled-source electromagnetic transects to investigate gas hydrate saturations beneath the seafloor are planned as well as seafloor sampling for chemical and biological studies. These studies should significantly improve our understanding of the gas hydrate system on the Hikurangi margin and allow us to better gauge the potential of what might become the largest known gas resource in New Zealand.

Figure 2: Gas hydrate veins in sediment cores recovered during SO-191. Courtesy R. Martin, University of Washington

Suggested Reading

Faure, K., J. Greinert, J. S. von Deimling, D. F. McGinnes, R. Kipfer, and P. Linke, 2010. Methane seepage along the Hikurangi margin of New Zealand: geochemical and physical properties of the water column. *Mar. Geol.*, *272*, 170-188.

Fujii, T., T. Saeki, T. Kobayashi, T. Inamori, M. Hayashi, O. Takano, T. akayama, T. Kawasaki, S. Nagakubo, M. Nakamizu, and K. Yokoi, 2008. Resource Assessment of Methane Hydrate in the Eastern Nankai Trough, Japan. In *Proc. 38th Offshore Technology Conference*, edited, pp. 19310-MS.

Katz, H. R., 1981. Probable gas hydrate in continental slope east of the North Island, New Zealand. *J. Petrol. Geol.*, *3*, 315-324.

MED, 2010. Table E.5b:Natural Gas Consumption by Sector (Gross PJ), http://www.med.govt.nz/upload/37595/Table%205a%20-%20Gas%20Supply%20and%20Consumption%20(Gross%20PJ).xls, Last accessed 23 Nov. 2010, Ministry of Economic Development.

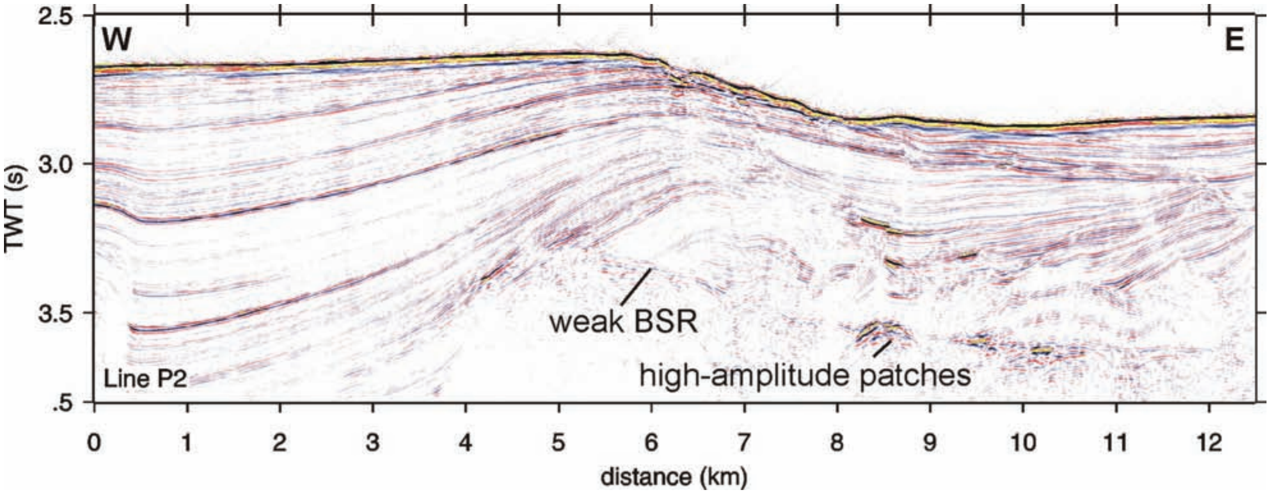
Ogebule, O. Y., and I. A. Pecher, in press. Possible gas hydrates in the Northland and northern Taranaki basins – indirect evidence from seismic data. *N. Z. J. Geol. Geophys.*

Pecher, I. A., and S. A. Henrys, 2003. Potential gas reserves in gas hydrate sweet spots on the Hikurangi margin, New Zealand, Science Report. 32 pp, Institute of Geological and Nuclear Sciences, Lower Hutt.

Shedd, W., M. Frye, P. Godfriaux, R. Boswell, and D. R. Hutchinson, 2009. Occurrence and variety in expression of the base of gas hydrate stability in the Gulf of Mexico, USA, *Fire in the Ice*, *Winter 2009*, 11-14.

Townend, J., 1997. Estimates of conductive heat flow through bottom-simulating reflectors on the Hikurangi margin and southwest Fiordland, New Zealand. *Mar. Geol.*, *141*, 209-220.

Figure 3: Segmented BSR on the Hikurangi margin.



ENVIRONMENTAL IMPACT ASSESSMENT STUDY ON JAPAN'S METHANE HYDRATE R&D PROGRAM

By Sadao Nagakubo[1,3], Nao Arata[1,3], Itsuka Yabe[1,3], Hideo Kobayashi[2,3], and Koji Yamamoto[1,3]

Japan's Methane Hydrate R&D Program was established by the Ministry of Economy, Trade and Industry (METI) in July of 2001 with the prime goal of developing the science and technology necessary to produce energy from methane hydrates (MH). One of the primary research objectives in this program was the "Establishment of a development system that fully complies with environmental protection." In Phase 1 of the program (FY2001-2008), the MH21 Research Consortium (MH21) conducted fundamental research to determine the most promising scenario for MH development and to develop tools and approaches for conducting the Environmental Impact Assessment (EIA). In Phase 2 (FY2009-2015), MH21 plans a wide range of research, including the execution of two production tests within the eastern Nankai Trough (see Masuda *et al.*, FITI). As part of this program, the MH21 EIA Team, including representatives from JOGMEC and AIST, has set the following objectives for Phase 2.

(1) Conduct environmental risk analysis and investigate countermeasures;

(2) Develop and field test environmental impact measurement technology;

(3) Conduct Environmental Impact Assessments tailored to the specific conditions for of the planned offshore production tests, and

(4) Utilize these findings to develop a comprehensive environmental assessment and to develop optimal approaches for future MH development.

To estimate the environmental risk factors for MH development, the 'Development Scenario' must be fixed. Based on the results of Phase 1, the MH21 EIA Team focused on the following scenario (1) production from pore-filling MH deposits in sandy sediments buried up to 350 m below the seafloor (MH concentrated zone), and (2) Production to be obtained through wells installed using drilling and completion technologies analogous to those used in conventional natural gas development, and (3) Production obtained via reservoir depressurization.

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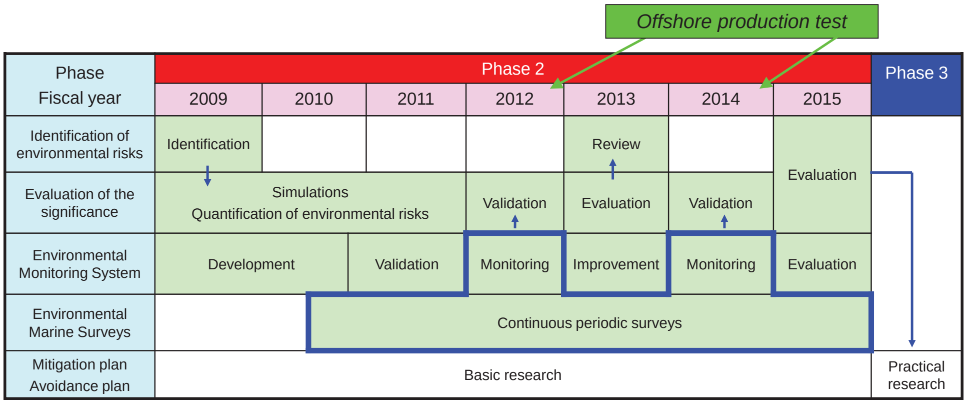
1 Japan Oil, Gas and Metals National Corporation
2 National Institute of Advanced Industrial Science and Technology
3 MH21 Research Consortium (MH21)



Phase	Phase 2							Phase 3
Fiscal year	2009	2010	2011	2012	2013	2014	2015	
Identification of environmental risks	Identification				Review		Evaluation	
Evaluation of the significance	Simulations Quantification of environmental risks			Validation	Evaluation	Validation		
Environmental Monitoring System	Development		Validation	Monitoring	Improvement	Monitoring	Evaluation	
Environmental Marine Surveys		Continuous periodic surveys						
Mitigation plan Avoidance plan	Basic research							Practical research

Figure 1: Strategy of the EIA Studies in Phase 2

Given this development scenario, we identify the following as the primary potential environmental risk factors for MH development: (1) methane leakages from the seafloor around the production wells, (2) discharge of treated production water into the ocean, (3) seafloor subsidence, and (4) submarine landslides. However, due to the lack of experience with methane hydrate production, it is difficult to evaluate these risks, as we do not know whether they will occur, or if they do occur, whether their magnitudes are likely to be significant. Therefore, to better understand the potential nature of each environmental risk factor, we will conduct marine surveys and environmental monitoring before, during, and after two offshore production tests to be conducted in the eastern Nankai Trough by MH21 in FY2012 and FY2014. Additionally we are developing numerical models to predict severities of those environmental risks.

Environmental Risk Assessment

At present, we are conducting the "problem formulation" stage of the Environmental Risk Assessment (Figure 2) based on the environmental risk factors for the MH development. We are currently in the stage of problem formulation, which includes identification of the desired "endpoints (environmental values to be protected)" associated with each of the environmental risk factors.

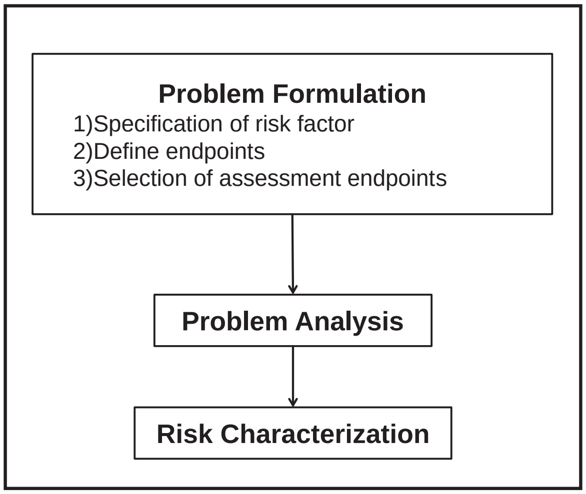


Figure 2: Process of environmental risk assessment

To update the Conceptual Model and to define the endpoints, we have interviewed specialists involved in several fields such as conventional oil and gas development, fishery, marine environment, marine geology, and others. We are currently constructing a primary Conceptual Model for future MH development reflecting this input. At present, we speculate that the environmental risk factors and their impacts are very similar to those of conventional oil and gas development as our past research has shown that very similar approaches, including well drilling and completion, can be used in MH production. However, there are uncertainties about the significance of each risk and some differences to conventional oil and gas development. These uncertainties and differences will be clarified through EIA studies prior to the beginning of commercial-scale MH development.

We will begin to work with various stakeholders in order to further define the key issues, better understand public perceptions, and improve the collective understanding of the nature and impacts of MH development. Key to this process will be the improvement of the Conceptual Model for commercial MH development through data obtained during the two offshore production tests planned for Phase 2.

EIA Methodology

Because MH is an unprecedented resource, it is necessary to establish an appropriate EIA methodology from scratch that is based upon the EIA methods of conventional oil and gas development. As the first step to identify potential environmental impacts and establish the EIA methods for future MH development, we are planning to implement a semi-quantitative EIA method through two offshore production tests as case studies.

In general, the basic components of the EIA process as applied in the oil and gas industry are: (1) Scoping (identify and prioritize potential impacts) (2) Baseline study (existing data collection and new surveys to determine environmental conditions prior to any development), (3) Assessment (predict the magnitude of impacts, evaluate their significance, investigate options for mitigation, and reassess residual impact), and (4) Management plan including environmental monitoring.

The scoping component of the environmental risk assessment is discussed above. Regarding the baseline study, MH21 has conducted environmental *baseline surveys* in the whole area of a model field, eastern Nankai trough, in Phase 1 to understand natural characteristics and variation of water quality, surface sediment characteristics and composition of biological communities. With respect to assessment prediction for magnitude of environmental impacts, MH21 continues to develop the numerical models to predict the behavior of leaked methane gas and discharged production water derived from MH dissociation in seawater. MH21 has also developed a simulator to predict the seafloor displacement accompanied with MH production based on the geomechanical and other test data (Masui *et al.*, 2008; Miyazaki *et al.*, 2010a & b). For evaluation of the significance of the environmental risks, MH21 has been designing two monitoring systems discussed in the following section. Similarly, MH21 is planning to implement detailed environmental marine surveys around production test wells before and after the tests periodically to monitor the changes in affected environment. Additionally we are currently attempting ecotoxicity tests of marine organisms for hazard assessment to support the construction of an ecosystem model of the eastern Nankai trough.

Based on all data (Figure 3), we will propose the necessary management plan for safe commercial MH production prior to onset of any full field development in Japan.

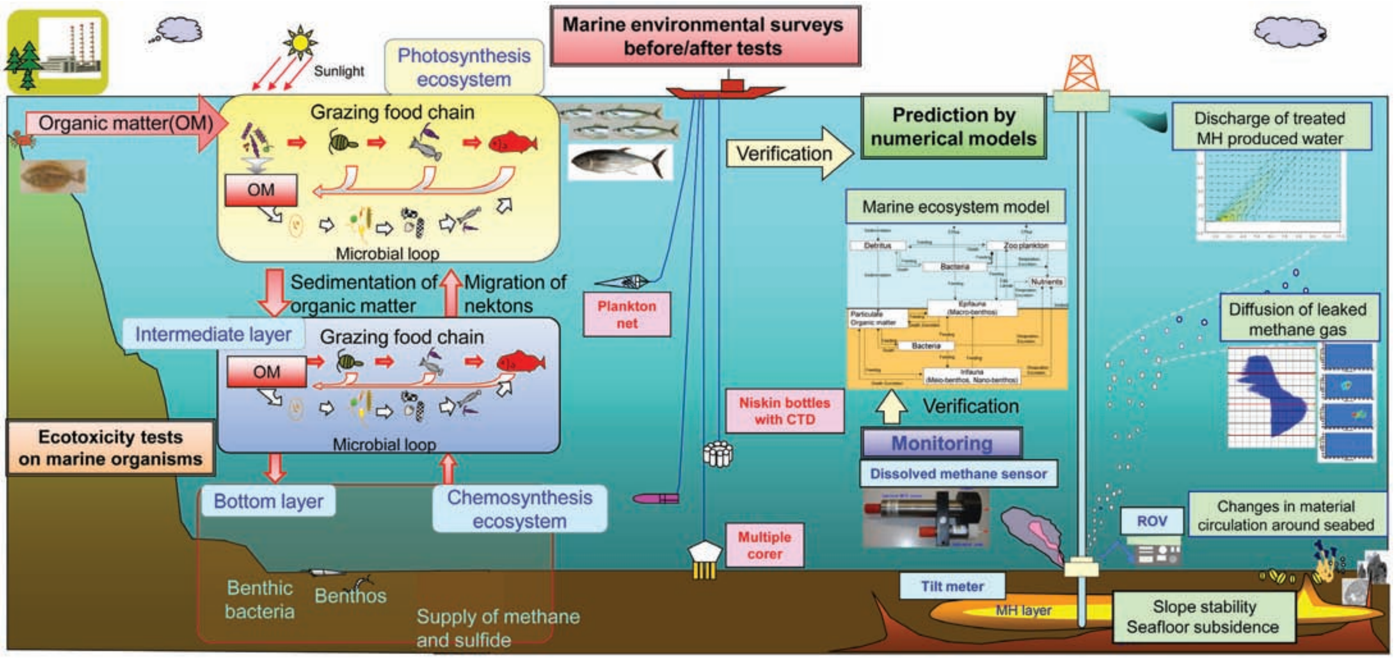


Figure 3: Schematic diagram of EIA methodology from Phase 2

Monitoring Systems for Offshore Production Tests

To obtain an initial measure of the potential significance of each risk factor, MH21 will conduct environmental monitoring before, during, and after the offshore production tests planned in FY2012 and FY2014. In particular, methane leakage from the seafloor and seafloor deformation (subsidence and/or landslide) must be monitored near or on deep seafloor. Considering the scale of the production tests, it is expected that the scale of these risks is not significant. However, we will monitor them as fundamental research to investigate environmental risk factors on future commercial MH development. MH21 is now developing two new monitoring systems that will be placed on the seafloor to detect methane leakage and seafloor deformation. For the first production test (expected testing period of one week to one month), both systems are designed to collect data for six months, including one month of monitoring before the production test (to assist in establishing the baseline condition) and for at least three months after the production test. Based on the data acquired by the first production test, we will improve the monitoring systems to be deployed for the second production test scheduled in FY2014.

Methane Leakage Monitoring System (MLMS) - Because MH-bearing deposits exist in relatively shallow zones (100-350 m at the likely locations for the upcoming production tests) below the seafloor, leakage of produced methane (gas or dissolved) from the seafloor is a concern. The goal of the MLMS is to detect any increase of dissolved methane concentration during/after the production tests which would accompany with released methane bubbles. The MLMS mounts an ‘Improved METS Sensor (dissolved methane sensor)’ developed by MH21 during in Phase 1, along with a temperature sensor, salinity sensor, and current meter (Figure 4). The function of a prototype MLMS will be tested in the deep ocean beginning in 2011.

Seafloor Deformation Monitoring System (SDMS) - The SDMS (Figure 5) mounts two sensors (tilt meter and pressure sensor) to detect seafloor deformation (subsidence). MH21 began the testing of the SDMS in the ocean in 2010.

Seafloor Stability

Seafloor instability is recognized as a possible marine MH-related hazard not only by scientists but also by the public. In the vicinity of the MH resource fields in the eastern Nankai Trough, several seafloor landslide scars have been mapped (Figure 6), but the scale of those slides is relatively small, (not comparable to the mega slides in the Atlantic continental margin), and there is no evidence that the slides were related to MH dissociation because the slide surface occurs well above the MH concentrated zones. Possible reasons of the instability are erosion of the seafloor by submarine valleys, upheaval of the seafloor due to tectonic activities, and triggering by Magnitude 8 and greater earthquakes that have happened periodically in the region. However, even though the observed slides are not large-scale phenomena and are very likely not related to MH, they are hazards to subsea production facilities and must be assessed.

In our study, we adopt a three-stage approach for the investigation. In the first stage, purely natural instability risks are assessed using bathymetry data, seismic survey records, geotechnical information obtained in past drilling activities, and model of seismic activities and ground motion. The effects of the induced MH dissociation are taken into account in the second stage through the reduction of strength and other mechanical condition changes. In the third stage, the risk of possible consequences, such as tsunami that may be generated by slides, are evaluated. These studies are being conducted in collaboration with experts at the Norwegian Geotechnics Institute (NGI), who also conducted risk assessments related to the Storegga mega slide (Kvalstad et al., 2005).

Is Methane Hydrate Development Dangerous?

“MH development is dangerous,” some people say. Is it true or not? MH21 wishes to inform this discussion with the best scientific information obtainable on the true nature of hydrate-bearing sediments in the context of the actual ‘Development Scenario.’

“MH dissociates easily.” This sentence is used often to imply great hazards with methane hydrate production, and tends to imply that MH is particularly unstable, and that once the dissociation reaction is started, it cannot be controlled. However, this is not the case. In fact, MH dissociation is an endothermic reaction, which means that MH dissociation in the sediments cools the temperature of surrounding sediments – just as ice melting in water cools the water. MH dissociation therefore, is naturally self-limiting, and instead of proceeding or accelerating on its own, actually needs continual energy input to continue. In other words a chain reaction

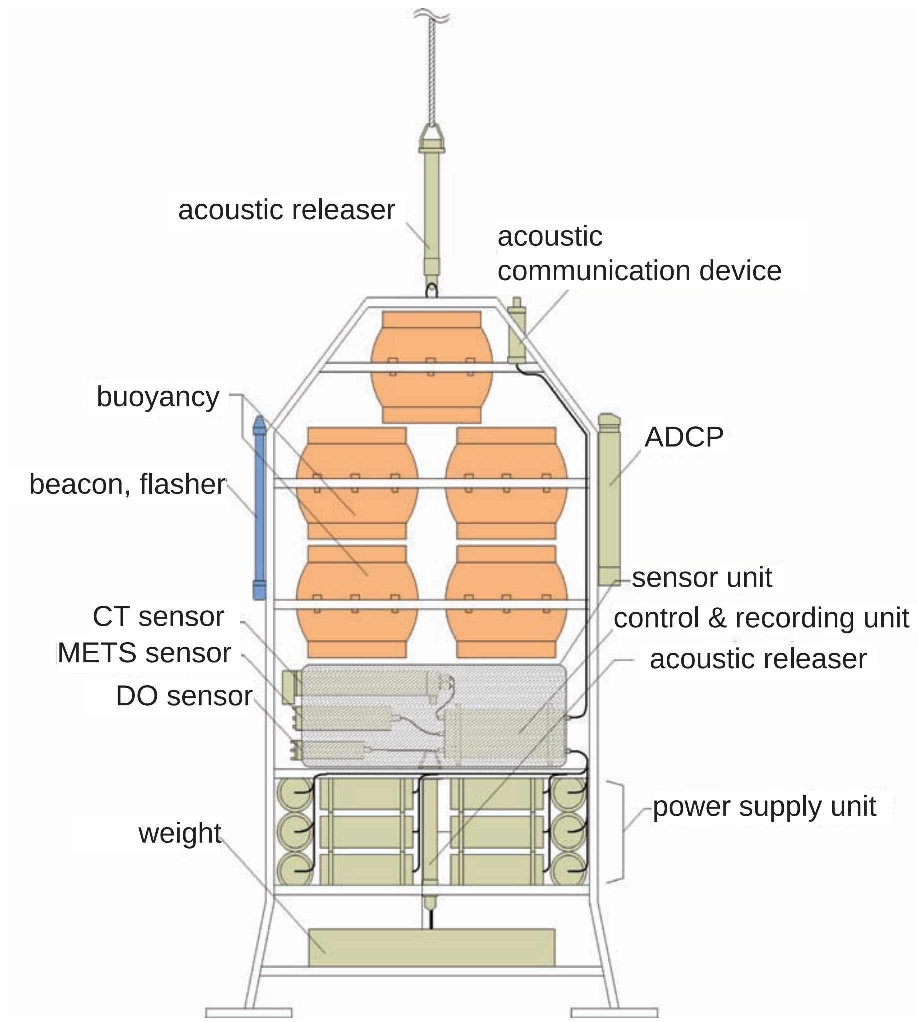


Figure 4: Basic Design of Methane Leakage Monitoring System (designed by IHI Marine United Inc.)

of the dissociation will not occur. If MH did dissociate easily, commercial development already might be underway because perhaps the major challenge faced by commercial development is ‘how to realize the efficient dissociation of the MH at in-situ conditions’.

“MH development may influence Global Climate Change.” This is also said. Some academic papers are discussing that marine MH dissociation by some natural events (sea level change and global warming etc.) through geological time might influence the ecosystem. This is very likely the case. However the issue needs to be discussed in the context of the time and spatial scales of MH development and global environmental change. For example, the area of the eastern Nankai trough where Japan has been studying is approximately 12,000km^2. MH-concentrated zones are scattered in the area. The area of any particular MH-concentrated zone that may be a target for future production is approximately several km by several km. Furthermore, the time scale of the development activity may

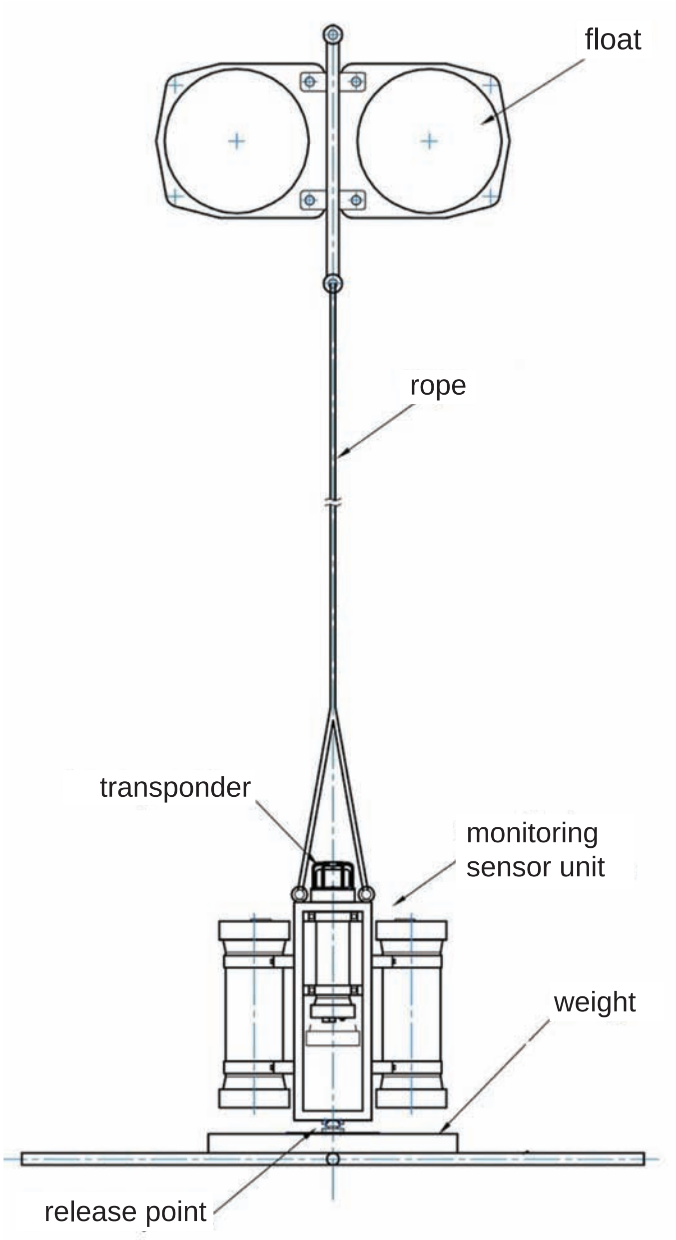


Figure 5: Basic Design of Seafloor Deformation Monitoring System (designed by OYO Corporation)

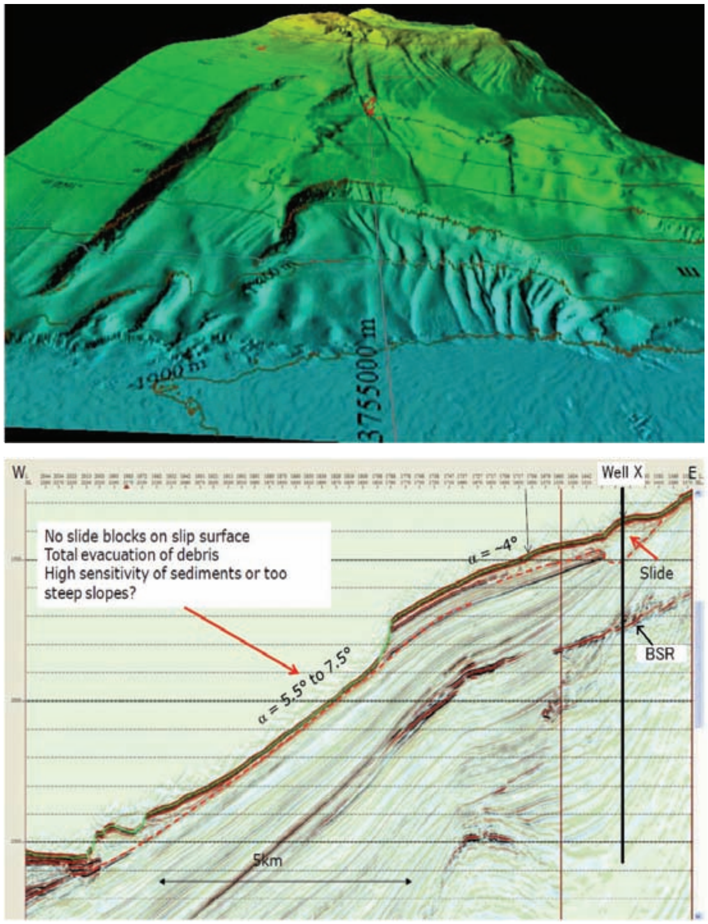


Figure 6: Landslide scars in the eastern Nankai Trough

be 10-30 years duration. On other hand, the spatial scale of natural events is a whole earth-scale. Furthermore the time scale over which the changes occur is hundreds to the tens of thousands of years. We sometimes ask ‘Can you make an easy comparison between MH development and global events? Safety and environmental risks on the MH development should be considered objectively and scientifically within the specific context of the ‘Development Scenario’.

“Submarine landslide and tsunami generation are a concern.” Our approach for seafloor stability as an environmental risk is discussed above. It is to be noted that the spatial scale of a MH reservoir (several km x km) is not comparable to events such as the Storegga mega slide (tens of thousands of square kilometers) – although, commonly described as being associated with MH dissociation. More importantly, MH development will avoid development in locations where landslides could not occur, just as is currently done as part of the geohazard assessment of conventional oil and natural gas developments.

“MH production raises gas blowouts from seafloor.” We believe that the use of the depressurization method for pore-filling MH deposits in sandy sediments fully mitigates this risk. In Figure 7, MH is dissociating by depressurization (lowering water by pumping out) at the production

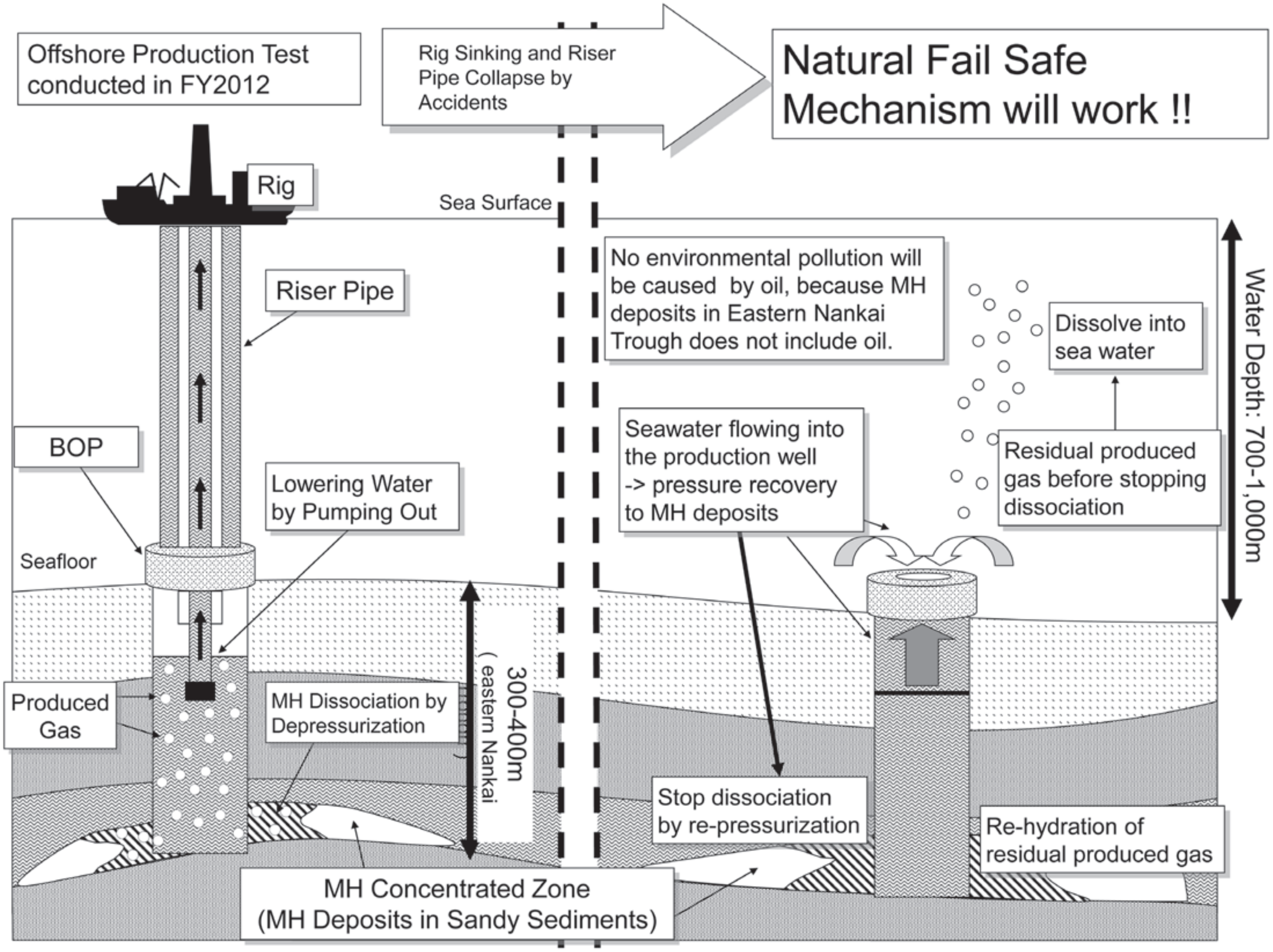


Figure 7: Natural Fail Safe Mechanism (a case of offshore production test conducted in FY2012)

stage. If some accident were to happen with the rig and riser pipes (like the deplorable Gulf of Mexico incident that occurred in April 2010), seawater will flow into the production well. Therefore the pressure of the MH deposit will be recovered and MH dissociation will stop soon. Additionally, residual produced gas in the sediments will be fixed by re-hydration because of pressure recovery. Residual produced gas bubbles leaked from seafloor will be dissolved into the seawater. Fortunately, the MH deposits in the eastern Nankai trough do not include oil and heavy hydrocarbons. Therefore marine pollution by oil will never occur. We call this mechanism 'Natural Fail Safe Mechanism'.

At present, we are speculating that the environmental risks of the MH development in the eastern Nankai trough are not thought to be any more serious than those posed by conventional oil and gas production.

Suggested Reading

Kvalstad, T., Andresen, K., Forsberg, C., Berg, K., Bryn, P., Wange, M., 2005. The Storegga silde: evaluation of triggering sources and slide mechanics, J. Mar. Pet Geol. (22) 245-256.

Masuda Y., Yamamoto K., Shimada T., Ebinuma T. and Nagakubo S., 2009. Japan's Methane Hydrate R&D Program Progresses to Phase 2. *Fire in the Ice*. Volume 9, Issue 4 (Fall)

Masui, A., Miyazaki, K., Haneda, H., Ogata, Y. and Aoki, K., 2008. Mechanical Characteristics of Natural and Artificial Gas Hydrate Bearing Sediments. *Proc. of 6th Int. Conf. on Gas Hydrates* (CD-ROM).

Miyazaki, K., Masui, A., Tenma, N., Ogata, Y., Aoki, K., Yamaguchi, T. and Sakamoto, Y., 2010a. Study on Mechanical Behavior for Methane Hydrate Sediment Based on Constant Strain-Rate Test and Unloading-Reloading Test Under Triaxial Compression. Int. *J. Offshore Polar Eng*., 20, 61-67.

Miyazaki, K., Masui, A., Aoki, K., Sakamoto, Y., Yamaguchi, T. and Okubo, S., 2010b. Strain-Rate Dependence of Triaxial Compressive Strength of Artificial Methane-Hydrate-Bearing Sediment, *Int. J. Offshore Polar Eng*., 20, 256-264.

Nagakubo S., Arata N., Kobayashi H. and Yamamoto K., 2009. Policy for Environmental Impact Assessment Study in the Phase 2 of the Japan's Methane Hydrate R&D Program, OS31A-120, *Abstract of AGU Fall Meeting 2009*.

Yamamoto K. and Nagakubo S., 2009. Environmental risks of the gas hydrate field development in the Eastern Nankai Trough, OS24A-07, *Abstract of AGU Fall Meeting 2009*.

Yamamoto K. and Nagakubo S., 2009. Environmental impacts of methane hydrate field development in the eastern Nankai Trough, *Chikyu*, Vol. 31, No.9, p.476-485. (in Japanese)

MODELING THE THERMAL DISTURBANCE OF GAS HYDRATE RELATED TO OIL AND GAS PRODUCTION

By Suntichai Silpngarmlert, ConocoPhillips

ConocoPhillips, in collaboration with DOE, recently completed numerical modeling efforts aimed at improving understanding of the effects of conventional oil and gas operations (injection and production) on hydrate-bearing sediments. Insights gained from these modeling exercises will assist in the planning of a field trial that seeks to evaluate the viability of exchanging carbon dioxide molecules for methane molecules within a hydrate structure (see "CO_2-CH_4 Exchange in Natural Gas Hydrate Reservoirs: Potential and Challenges" in the March 2010 issue of the Fire in the Ice). The field trial is planned to be conducted on the Alaskan North Slope as early as 2011.

Thousands of wells transect the North Slope gas hydrate stability zone, with nearly all completed in zones significantly deeper than the hydrate-bearing sediments. Many of these wells produce or inject fluids significantly hotter than hydrate stability conditions. Heat transfer from hot oil and gas in the wellbore through well casing can result in gas hydrate dissociation around the well casing leading to potential gas leakage and loss of sediment strength that can degrade casing integrity. Before the bottom hole location of the new test well could be selected, the potential impact of previous hot fluid injection and production in nearby wells on the hydrate stability of the interval to be tested needed to be estimated using a simulation model. This would allow a location to be selected in which the test could be assured of encountering virgin reservoir conditions. Another issue to be investigated was disturbance to the reservoir of the field trial well cementation, that is, the effects from hydration heat of well cementation.

Thermal Impacts from Existing Wells

ConocoPhillips utilized the TOUGH+Hydrate reservoir simulator to model the effects of hot fluid injection and production on near-wellbore hydrate stability. Multiple cases representing injection and production and homogeneous and heterogeneous formations were modeled. Three 2-D models were used based on the configuration and production history of the Prudhoe Bay Unit (PBU) L-106, L-107, and L-213 wells. PBU L-213 has been in operation for over three years as an injection well (Figure 1) and PBU L-106 and L-107 have both been in operation for over eight years as production wells (Figure 2).

In the first case, based on the L-213 injection well, a homogeneous model was constructed and two in-situ permeability settings were used: 1 mD and 5 mD, with 70% hydrate saturation. The temperature of the injected fluid was set at a constant 125° F. The simulation found that heat transfer from the hot fluid in the wells can indeed cause dissociation of near-wellbore hydrates. The simulations showed that the temperature of the formation was affected out to a distance of 80 feet by the injection of warm fluids. However, the hydrate saturation around well L-213 was affected only out to a radial distance of 10 to 15 feet after injection over a period of nearly four years. In the lower in-situ permeability case (1 mD), there was evidence of bands of alternating high and low hydrate saturation. Note that the similar banded structure of hydrate saturation was also predicted in the case with in-situ permeability lower than 1 mD.

Production from wells L-106 and L-107 was also simulated for a homogeneous formation at in-situ permeabilities of 1 mD and also 5 mD, at 70% hydrate saturation. The same fluid temperature and hydrate saturation were assumed. The simulations showed that during 8.2 years of production the formation temperature profiles of both the 1 mD and 5 mD cases are not significantly different; the affected radial distance is about 115 ft. Similar to the L-213 injection well case, the hydrate saturations around the producing wells for the 1 mD and 5 mD cases are significantly different, with a "banded" structure of low and high hydrate saturation in the 1 mD case. The affected radial distances in the 1 mD and 5 mD cases were 10 ft and 26 ft, respectively.

For the third case, a model of the vertical heterogeneity of hydrate saturation (resulting in vertical heterogeneity of in-situ permeability) in PBU L-106 was set up to study the effect of in-situ permeability and hydrate saturation variation on hydrate dissociation in the near wellbore region due to production of warm fluids over a 10 year time period. In-situ permeability at various hydrate saturation used in this study were consistent with measured data from the Mt. Elbert #1 well (0.15 mD at $S_H = 75\%$ and 1.5 mD at $S_H = 65\%$). Permeability anisotropy (k_v/k_h) was set at 0.1 for the entire model. In this model, the top seal (above the hydrate zone) was assumed to be permeable, with the top-seal horizontal permeability (k_h) at 0.1 mD and also at 1 mD. The temperature of the fluid in the wellbore was modeled at a constant 125° F, as in the previous simulations, but a case with fluid temperature at 165° F was also examined as a worst case scenario.

The simulation shows that there is not a great deal of difference in the radial extent of formation temperature change (it was about 115 to 125 feet in all cases), or hydrate saturation change (it was about 30 to 45 feet in all cases).

The thermal impact from an inclined borehole case was approximated from the simulation results of the vertical borehole case. The estimations revealed that in the case of a 45-degree inclined producing well with a 30-foot thick hydrate-bearing interval, hydrate dissociation occurred up to a distance of no more than 60 feet from the wellbore (Figure 3).

Thermal Effects from Well Cementation

Researchers modeled the effects of heat released from cement hydration as it sets up in the casing-wellbore annulus during casing operations. The heat-of-hydration effects were modeled in three different cases using the TOUGH+Hydrate reservoir simulator. Each case utilized the same casing diameter (7") and different hole diameters: 8 ¾", 16", and 24" (Figure 4). The larger diameter holes, i.e., 16" and 24", simulated washed out or enlarged

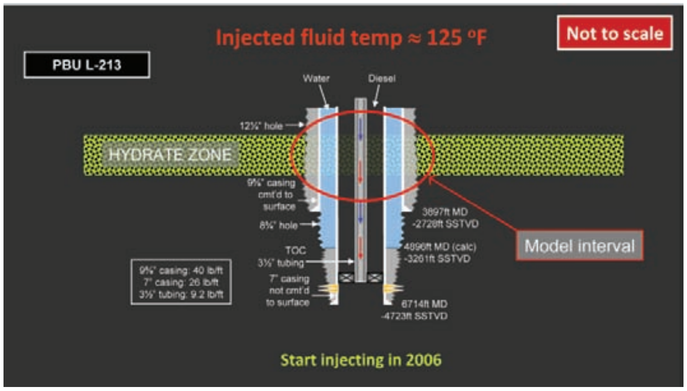


Figure 1: Simplified wellbore schematic of PBU L-213

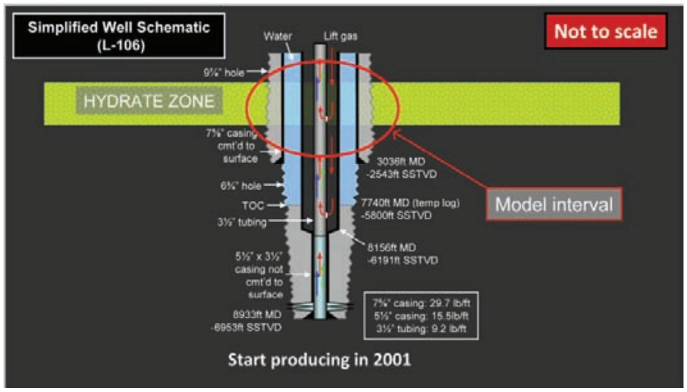


Figure 2: Simplified wellbore schematic of PBU L-106 and L-107

holes. Two potential strategies that were examined for mitigating the heat of hydration effects were circulating cold fluid inside the casing while the cement is setting and using colder cement slurry. The modeled assumption in the cold fluid circulation case is that inner-string circulation could keep fluid temperature in the wellbore constant at 26° F. A low heat-of-hydration cement known as LiteCRETE cement was assumed for this study.

Near-wellbore hydrate dissociation was not predicted during the cementing of an 8 ¾″ hole, whereas the models predicted the dissociation in the 16″ and 24″ holes cases. However, the dissociation affects a very small radius (a few inches to less than 1 ft) from the wellbore in these two cases. The simulation also revealed that hydrate reformation occurs very close to the wellbore. The simulation shows that lower in-situ formation permeability results in less hydrate dissociation, since near wellbore pressure increases more rapidly as hydrate dissociates, inhibiting further hydrate dissociation. Cold fluid circulation does not effectively mitigate the dissociation. On the other hand, lowering initial cement slurry temperature from 42.8° F to 35° F effectively mitigates dissociation of near-wellbore hydrate.

For additional information regarding this project, please visit the Gas Hydrate Production Trial Using CO2 / CH4 Exchange project page located on the NETL Methane Hydrates web site. Additional details on the modeling simulations can be found in the 2010 First Half Progress Report provided by ConocoPhillips and found on the NETL Methane Hydrates web site.

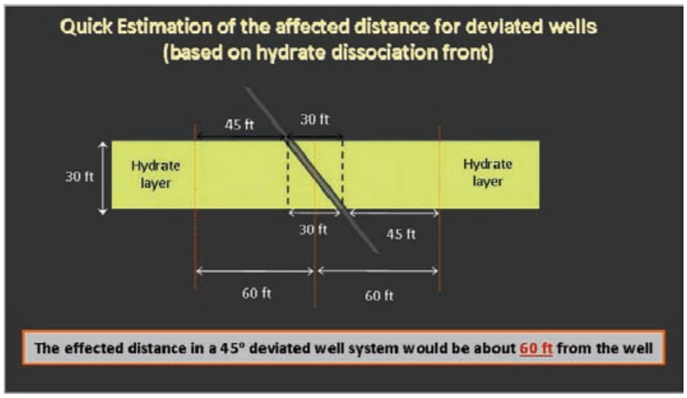


Figure 3: Quick estimation of affected distance in a 45-degree deviated well system

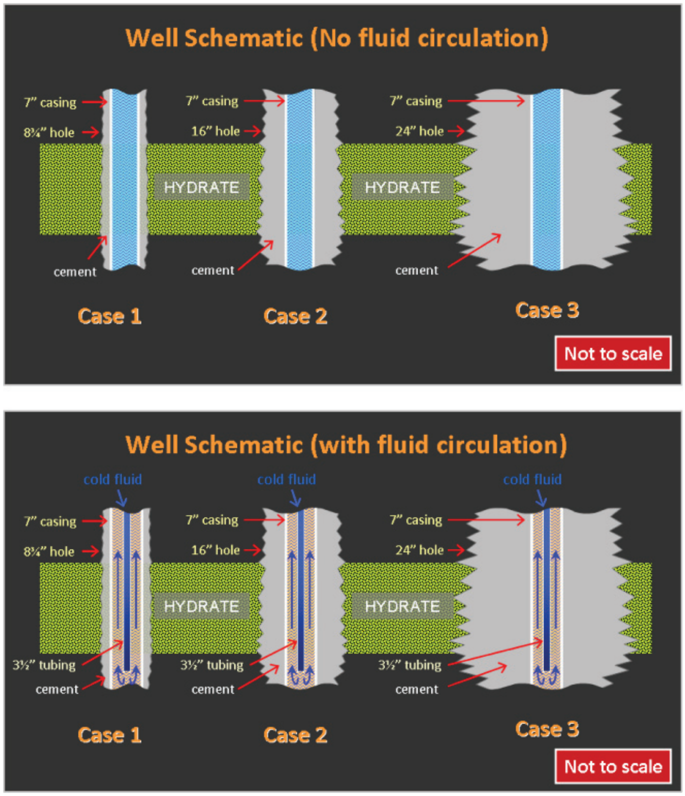


Figure 4: Well schematic of the three simulation cases used to model heat-of-hydrate effects during the casing cementing process.

ROCK PHYSICS MODELING OF THE GAS HYDRATE AND FREE GAS MIXED SYSTEM IN GREEN CANYON 955, GULF OF MEXICO, AND IMPLICATIONS FOR GAS HYDRATE PROSPECTING

By Zijian Zhang and Dan McConnell, AOA Geophysics

Gas hydrate deposits were predicted and confirmed through logging-while-drilling (LWD) in Green Canyon (GC) 955 during the 2009 JIP Leg II drilling expedition. Unlike previously studied occurrences of gas hydrate, in which gas hydrate is found in low concentrations in the ~100 m interval above base of gas hydrate stability zone (e.g. ODP 164 drilled at Blake Ridge (Lu and McMechan, 2002) and ODP 204 at Hydrate Ridge (Tréhu *et al*., 2003)), high concentrations of gas hydrate occur within a sand zone in GC 955 near the base of gas hydrate stability (McConnell *et al*., 2009a; Guerin, *et al*., 2009). The hydrocarbon-charged stratigraphic facies in GC 955 have complex amplitude responses in seismic data. For instance, if hydrate layers are thin, tuning effects can occur and make it more difficult to interpret the gas hydrate or determine whether gas hydrates are thin or thick. Therefore, a special approach is required to identify thick high-concentration hydrate layers by integrating rock physics modeling, amplitude analysis, and spectral decomposition.

Reflection Coefficients

The sedimentary section at GC 955, typical of the deep water Gulf of Mexico, is a mostly clay-prone section interspersed with sands (McConnell *et al*., 2009a). Figure 1 shows that clay, water-bearing sand, and hydrate-bearing sand are well separated in the crossplot of *P*-wave velocity versus gamma ray in the GC 955H well. Water-bearing sands have relatively lower velocities than clays, whereas hydrate-bearing sands are characterized by high velocities.

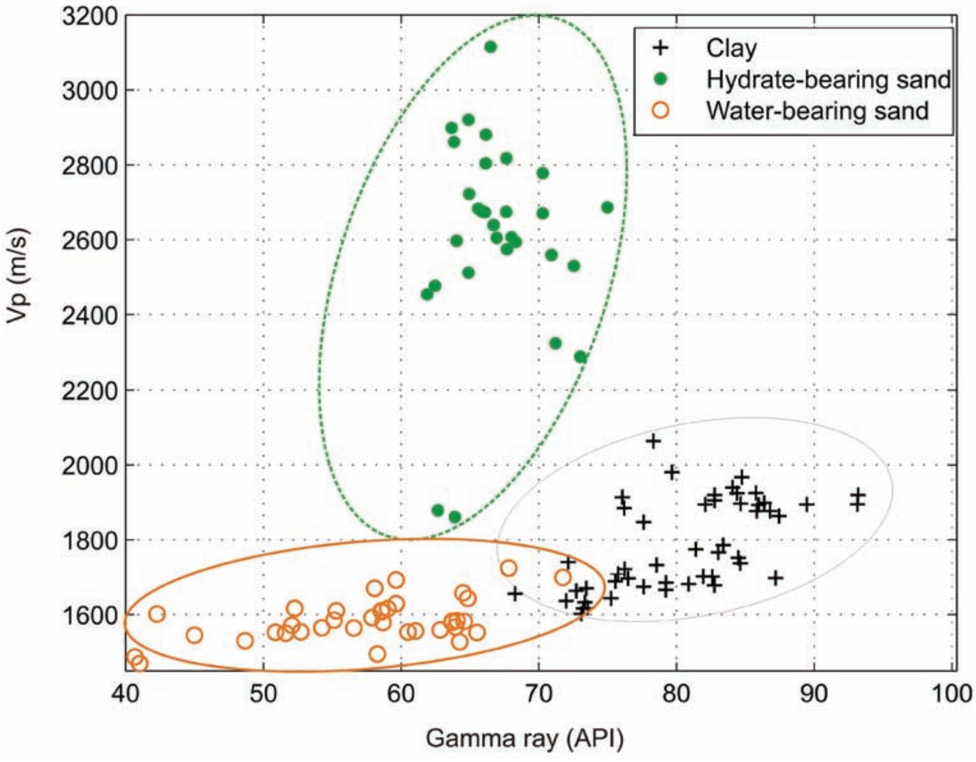


Figure 1: Velocity versus Gamma Ray from well GC 955H, showing clay, water sand and hydrated sand

Figure 2 shows normal incidence reflection coefficients versus gas hydrate and free gas saturation calculated using velocity and density contrasts of the clays and water, gas, and gas hydrate sands. Three cases were assumed: clay over hydrate-bearing sands, clay over free-gas charged sand and hydrate over free-gas charged sand. The velocity and density of clay were extracted from well logs above gas hydrate reservoir, which are 1810 ms and 2.06 g/cc, respectively. The velocities and densities of saturated hydrate-bearing and free-gas charged sands were computed from the well logs and from rock physics models of gas hydrate and free gas using the Hashin-Shtrikman lower bounds and Hertz-Mindlin contact theories (Mavko *et al*., 1998).

The gas hydrate curve in Figure 2 corresponds to a thick layer of gas hydrate sand with laterally variable saturation overlain by clay. The reflection amplitude increases as gas hydrate saturation increases. This positive amplitude change suggests phase reversals can occur in these sands if gas hydrate saturation changes laterally (as was shown by LWD drilling at WR 313, (McConnell *et al*., 2009b)). The reflection amplitude is close to zero and between 20% and 40% gas hydrate saturation in these data, which would correspond with what has been described as a "blanking zone" in other gas hydrate systems

For free-gas charged sands and hydrate-over-free-gas sands, the dominant reflection amplitudes decrease as gas hydrate or free gas saturation increase. Different concentrations of free gas and gas hydrate over free gas can produce the same reflection coefficient. For example, a given reflection amplitude of -0.35 could be caused by 20% free gas, 32% gas hydrate over 20% free gas, or 52% gas hydrate over 10% free gas (Figure 2). So BSR amplitude interpretation is typically ambiguous for a gas hydrate layer.

Complex Trace Analysis

Amplitude analysis with respect to variation of gas hydrate saturation has

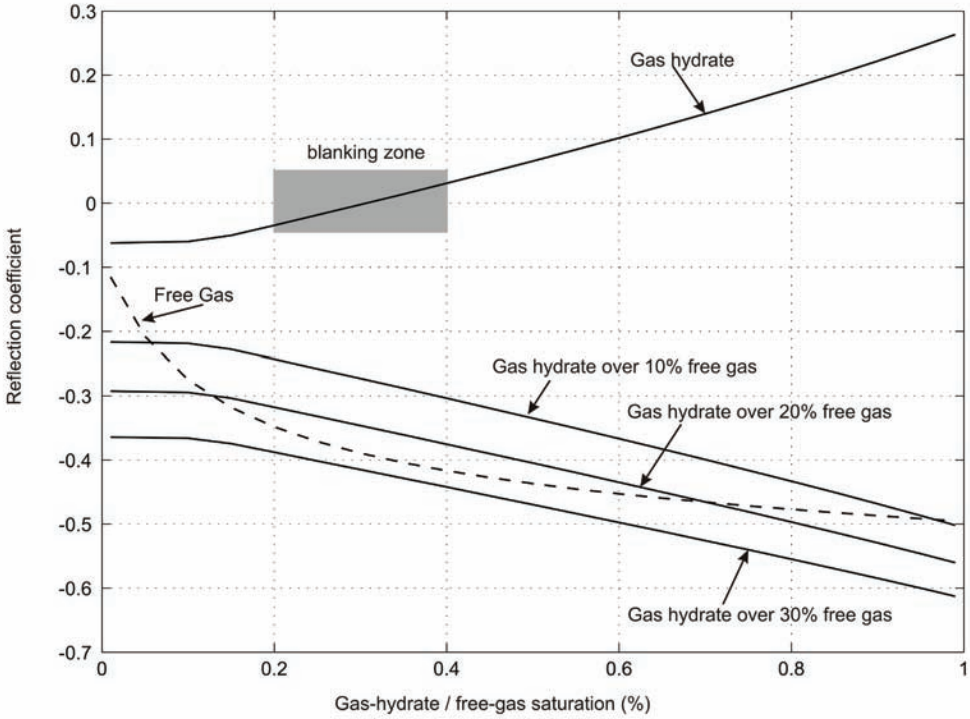


Figure 2: Normal incidence reflection coefficients versus gas hydrate and free gas saturation. The gas hydrate and free gas curves are in sands overlain by clay. The gas hydrate over free gas impedance curves are within a sand.

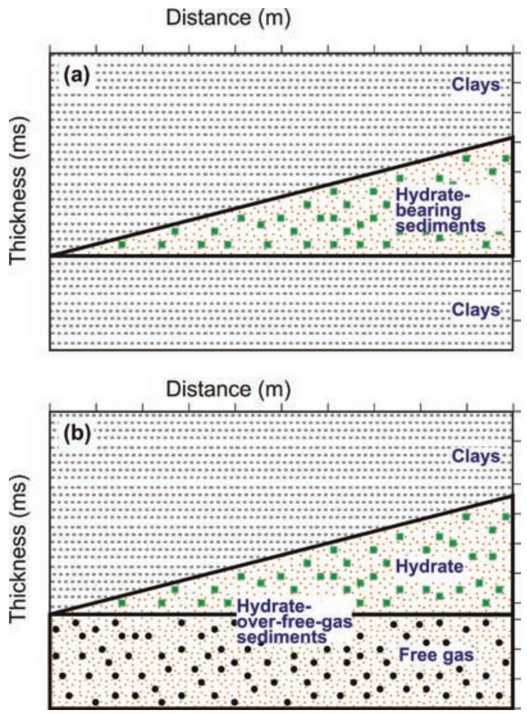


Figure 3: Wedge models for hydrate-bearing sediment (a) and hydrate-over-free-gas sediments (b). (a) is a three-layer model of a gas hydrate layer in clay. (b) is a gas hydrate layer with a clay cap and free gas bottom. The thickness of wedge varies from 0 to 30 ms.

previously been shown by Lee *et al.* (2009), among others, using a modified Biot-Gassman theory. Here, we focus more on interface responses at gas hydrate and gas contacts using rock physics models based on grain contact theories. To observe the effect of amplitude on different thicknesses of gas hydrate, we evaluated two sand wedge models, (a) and (b), with various gas hydrate and free gas saturation levels (Figure 3). In model (a), high amplitude occurs with high hydrate saturation in hydrate-bearing sands with the maximum amplitude occurring at λ/5, where λ is the wavelength. The amplitude starts to decrease at λ/5 and significantly decreases as the layer thins below λ/10 (Figures 4a and 4b). Figures 4c and 4d show the results for a variably thick gas hydrate zone with 30% gas beneath it for model (b). The strong amplitude can be seen at the interface between gas hydrate and free gas, a type of reflection that could form BSRs.

At the tuning thickness (λ/5), the gas hydrate reflection is seen as a strong peak over strong trough at high saturations of gas hydrate (Figure 4b). For model (b) with a gas hydrate zone with 30% gas saturation beneath it, the seismic responses in peak parts of the waveform for gas hydrate are fairly similar to those of the previous example (Figure 4d). However, the trough parts of waveforms are strongly affected by the seismic responses of gas beneath gas hydrate, which shows constant high amplitudes with variation of layer thickness. Thus, peak-to-trough ratio is a good indicator to separate hydrate sand and hydrate over free gas sand.

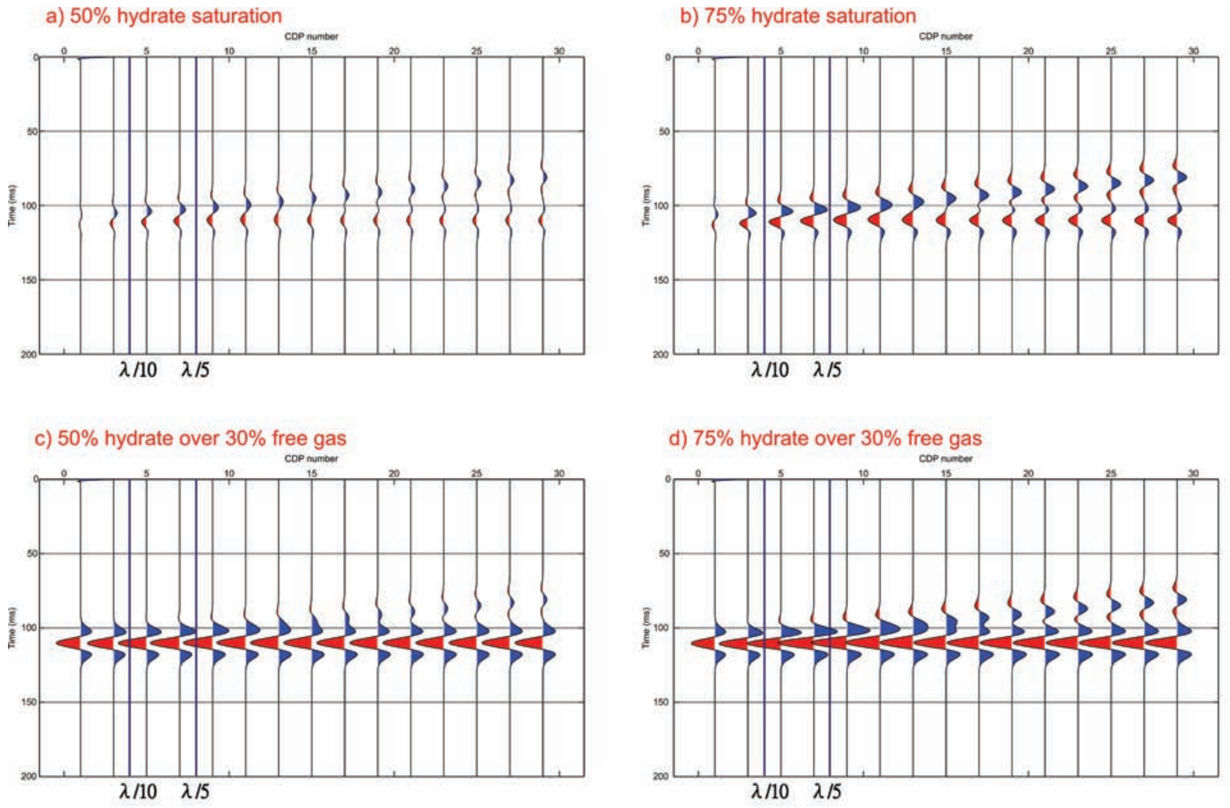


Figure 4: Synthetic seismic from the wedge models for hydrated sediments and hydrate-over-gas sediments. A Ricker wavelet of 50 Hz dominant frequency was chosen to generate zero-offset synthetic seismic data. The P-wave velocity of the clay is 1810 ms and the density is 2.06 g/cc. The properties of wet sand, hydrated sand and gas sand were derived from the well log data and the rock physics model.

In the case of 50% gas hydrate saturation, the amplitude at the top of a thick layer of gas hydrate is significantly weaker than at the bottom of the gas hydrate layer (Figure 4c). The weak amplitude could easily be missed by the interpreter as the top of a thick layer of gas hydrate-saturated sand.

Spectral Decomposition

Conventional thickness analysis by picking horizons cannot be used if the peak-trough time separation is less than the tuning thickness (Partyka, 1999). The spectral decomposition method, however, is a valuable tool with the ability to map thin beds (Partyka *et al.*, 1999, Castagna *et al.*, 2003). Partyka (1999) indicates a robust approach to seismic thickness estimation for thin beds showing that thickness can be derived from amplitudes at appropriately low discrete frequencies. The technique may be especially useful for identifying gas hydrate deposits and determining their thickness.

Figure 5 shows the normalized amplitude at a 12 Hz frequency for the variable gas hydrate saturation model discussed in previous section. The discrete Fourier amplitude increases with increasing layer thickness and hydrate saturation. We consider the amplitude value of 900 as a reference amplitude, with those amplitudes greater interpreted to be a thick layer of highly concentrated gas hydrate. For example, if hydrate saturation is 75%, the thickness of a hydrate layer in the 12 Hz frequency is 16 m (12 ms TWT) at the amplitude. If hydrate saturation is 50%, the thickness is 19 m (16.2 ms TWT) at the amplitude. Fourier amplitudes greater than 1100 at this discrete frequency indicate thick, high saturation gas hydrates.

Conclusions and Future Work

An approach integrating rock physics modeling, amplitude analysis, and spectral decomposition improves the interpretability of gas hydrate and gas in the Green Canyon 955 area. The interaction of varying gas hydrate saturation, reservoir thickness, and free gas generates a complex expression in seismic amplitude. In general, low amplitude peak events occur in the low saturated hydrate sand and high amplitude peak events

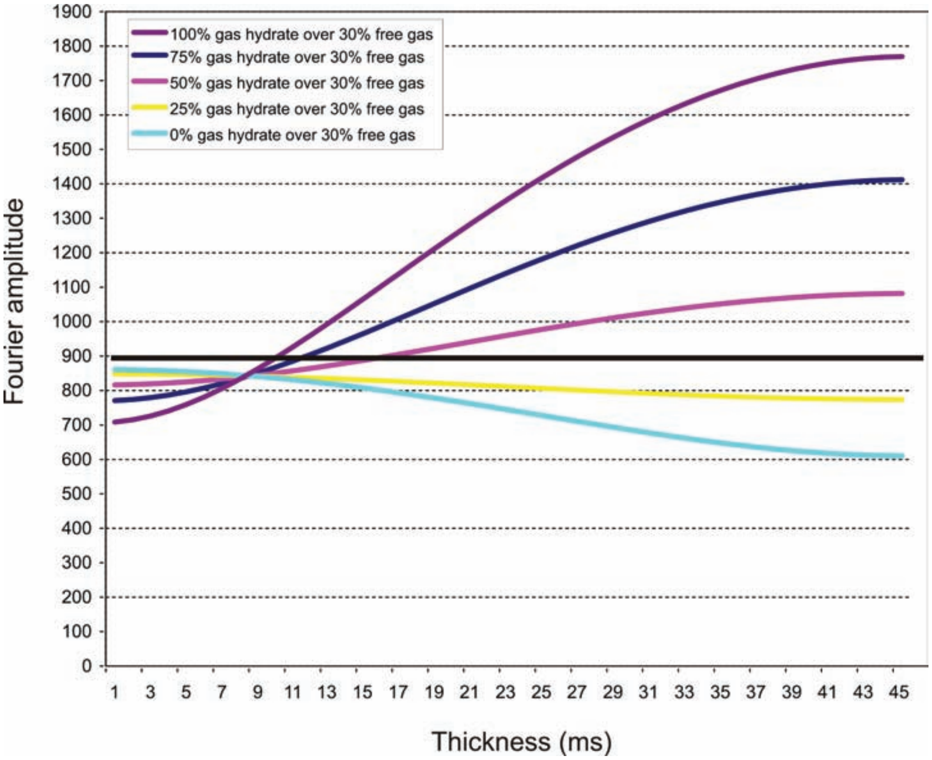


Figure 5: Fourier amplitude plot for the model of the hydrate-over-free-gas sediments

occur in high saturated hydrate sand. The amplitude response, however, is more complicated in a mixed gas hydrate and gas system. Saturated gas hydrate over free gas in sands will drive amplitude lower than for a gas sand with no overlying gas hydrate. Sands with thick gas hydrate deposits underlain by free gas may well have strong trough-dominated waveforms. Furthermore, amplitude is strongly affected by tuning in all cases of thin gas hydrate deposits, but especially so where underlain by free gas. This work suggests the possibility that the high saturation gas hydrate sands drilled in the 2009 campaign may not have been the thickest in this complex system. Finally, this work shows that spectral decomposition of conventional exploration seismic data may be an effective, quantitative, prospecting tool to identify thick, high saturation, gas hydrate sands.

Suggested Reading

Castagna, J. P., S. Sun, and R. W. Siegfried, 2003. Instantaneous spectral analysis: Detection of low-frequency shadows associated with hydrocarbons: The Leading Edge, 22, 120–127.

Guerin, G., A. Cook, S. Mrozewski, T.S. Collett, R. Boswell, 2009. Gulf of Mexico Gas Hydrate Joint Industry Project Leg II — Green Canyon 955 LWD Operations and Results: Proceedings of the Drilling and Scientific Results of the 2009 Gulf of Mexico Gas Hydrate Joint Industry Project Leg II. http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/2009Reports/GC955LWDOps.pdf

Lee, M. W., T. S. Collett, and T. L. Inks, 2009. Seismic-attribute analysis for gas-hydrate and free-gas prospects on the North Slope of Alaska, in T. Collett, A. Johnson, C. Knapp, and R. Boswell, eds., Natural gas hydrates—Energy resource potential and associated geologic hazards: AAPG Memoir 89, p. 541–554.

Lu, S., and G.A. McMechan, 2002. Estimation of gas hydrate and free gas saturation, concentration, and distribution from seismic data: Geophysics, 67, 582–593.

Mavko, G., T. Mukerji, and J. Dvorkin, 1998. The Rock Physics Handbook, Cambridge University Press, Cambridge, UK.

McConnell, D., R. Boswell, T.S. Collett, M. Frye, W. Shedd, G. Guerin, A. Cook, S. Mrozewski, R. Dufrene, and P. Godfriaux, 2009a. Gulf of Mexico Gas Hydrate Joint Industry Project Leg II — Green Canyon 955 Site Summary: Proceedings of the Drilling and Scientific Results of the 2009 Gulf of Mexico Gas Hydrate Joint Industry Project Leg II. http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/2009Reports/GC955SiteSum.pdf

McConnell, D., R. Boswell, T.S. Collett, M. Frye, W. Shedd, G. Guerin, A. Cook, S. Mrozewski, R. Dufrene, and P. Godfriaux, 2009b. Gulf of Mexico Gas Hydrate Joint Industry Project Leg II — Walker Ridge 313 Site Summary: Proceedings of the Drilling and Scientific Results of the 2009 Gulf of Mexico Gas Hydrate Joint Industry Project Leg II. http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/2009Reports/WR313SiteSum.pdf

Partyka, G. A., J. A. Gridley, and J. A. Lopez, 1999. Interpretational aspects of spectral decomposition in reservoir characterization: The Leading Edge, 18, 353–360.

Tréhu, A. M., P. E. Long, M. E. Torres, G. Bohrmann, F. R. Rack, T. S. Collett, D. S. Goldberg, A. V. Milkov, M. Riedel, P. Schultheiss, N. L. Bangs, S. R. Barr,W. S. Borowski, G. E. Claypool, M. E. Delwiche, G. R. Dickens, E. Gracia, G. Guérin, M. Holland, J. E. Johnson, Y.-J. Lee, C.-S. Liu, X. Su, B. Teichert, H. Tomaru, M.Vanneste, M.Watanabe, and J. L.Weinberger, 2004. Three-dimensional distribution of gas hydrate beneath southern Hydrate Ridge: Constraints from ODP Leg 204: Earth and Planetary Science Letters, 222, 845–862.

IDENTIFYING SLOPE FAILURE DEPOSITS FROM A POTENTIALLY MIXED MAGNETIC SUSCEPTIBILITY SIGNAL IN GAS HYDRATE BEARING REGIONS

By Joel E. Johnson (University of New Hampshire), Daniel R. Solway (University of New Hampshire), Corinne Disenhof (University of New Hampshire), Marta E. Torres (Oregon State University), Wei-Li Hong (Oregon State University), and Kelly Rose (DOE-NETL)

Introduction

The marine gas hydrate stability zone (GHSZ) occurs in the slope environment along many active and passive continental margins. In this environment, slope failures are common and can occur near the shelf slope break, within submarine canyons, or on the flanks of bathymetric highs, resulting in a spectrum of slope failure deposits from landslides to turbidites. On the Cascadia margin, the GHSZ occurs within the bathymetric thrust ridges and slope basins of the accretionary wedge. Here, the ridges are composed of uplifted abyssal plain deposits associated with submarine fans and/or paleo-slope basin deposits formed during the evolution of the accretionary wedge (Johnson *et al.*, 2006; Torres *et al.*, 2008). The adjoining slope basins contain the deposits from slope failure of the ridges. Both ridges and slope basins offshore Central Oregon and Vancouver Island were sampled by drilling during ODP Leg 204 and IODP Expedition 311, respectively (Figure 1). The recovered cores document the distribution and abundance of gas hydrate in these regions within a stratigraphy that is dominated by silt and sand turbidites, debris flows, and intervals of silty clay, separated by hemipelagic clay.

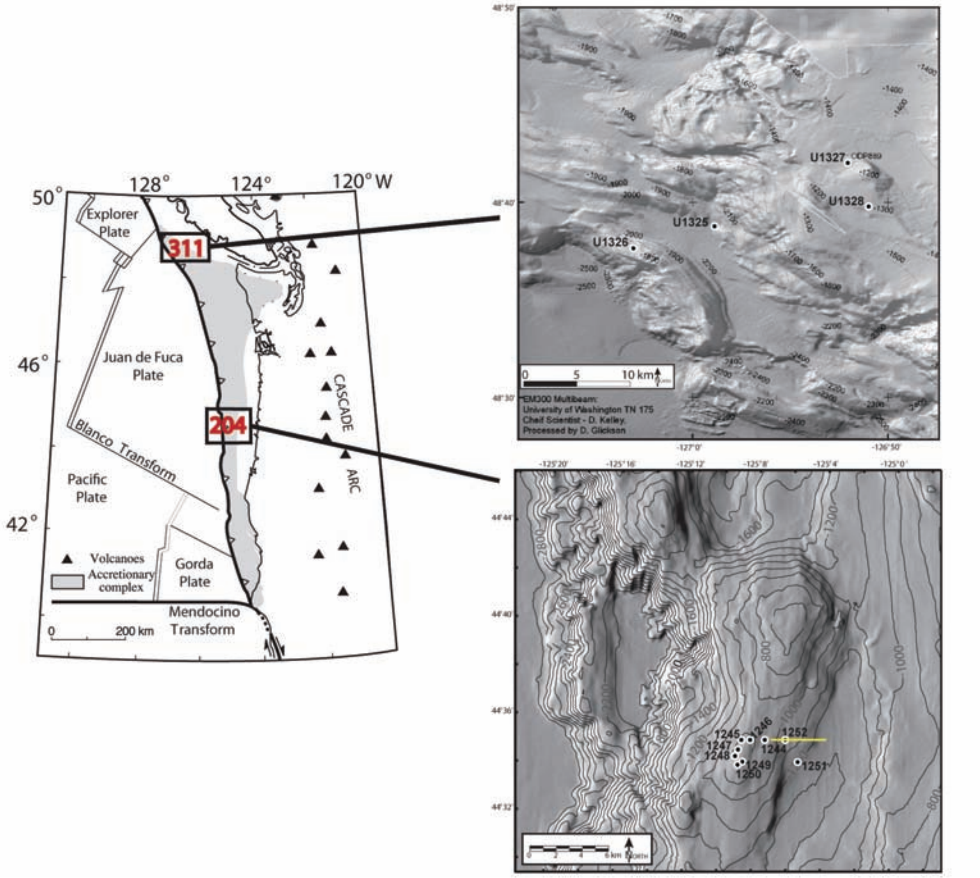


Figure 1: Tectonic setting and bathymetry at IODP Exp. 311 (modified from Expedition 311 Scientists, 2006) and ODP Leg 204 (Hydrate Ridge) core sites. Yellow line shows the location of the seismic reflection profile shown in Figure 2.

The identification of slope failure deposits is most often determined through visual core descriptions coupled with particle size analyses. Discreet measurements of particle size, however, are labor intensive and are often not collected at a sampling interval high enough to capture the range in bed thickness and occurrence observed in slope environments. As an alternative down core magnetic susceptibility (MS) measurements, which are routinely collected at 2.5 cm intervals during ODP and IODP expeditions, can be used to identify slope failure deposits and thus help characterize the host stratigraphy and depositional processes in marine gas hydrate-bearing regions.

Magnetic Susceptibility: A Mixed Signal

MS can be used to identify slope failure deposits by tracking the abundance and composition of detrital magnetic minerals that are transported during slope failure events with other sand and silt sized particles. These deposits are often density sorted, with the magnetic minerals concentrated near the base of each deposit, and are marked by positive excursions in MS from a low baseline MS characteristic of hemipelagic clay. In addition to a MS signal driven by detrital magnetic mineral abundance, Housen and Musgrave (1996) and more recently, Musgrave *et al*. (2006) and Larrasoaña *et al*. (2006 and 2007), have documented the presence of the diagenetic magnetic iron sulfide minerals greigite (Fe_3S_4) and pyrrhotite (Fe_7S_8) in gas hydrate bearing sediments through rock magnetic measurements (e.g. isothermal remnant magnetization, IRM). Precipitates of greigite and pyrrhotite are thought to form within the gas hydrate stability zone by microbially mediated anaerobic methane oxidation (AMO) (Larrasoaña *et al*., 2007 and refs. therein). These precipitates, once formed, may remain in the sediments as a wake of mineralization long after the sulfate methane transition (SMT) migrates up section and may even be left behind as the bottom of the GHSZ migrates upward through time (e.g. Musgrave *et al*., 2006). If large (>0.5 cm), these precipitates can be visually identified in cores as magnetic iron nodules and have been documented in gas hydrate bearing cores from the Indian Ocean (Collett *et al*., 2008) and along the Cascadia margin (Tréhu *et al*., 2003). Given the potential presence of magnetic iron sulfides in gas hydrate bearing sediments, positive excursions in MS could be interpreted as either changes in the detrital or diagenetic magnetic mineralogy or a mixture of both.

Using MS to Identify Slope Failure Deposits on the Cascadia Margin

In this article we focus on the slope failure record at ODP Site 1252, which is located on the eastern flank of Hydrate Ridge, just upslope from an anticline that has served to trap sediments derived from the crest of Hydrate Ridge (Figure 2). Eastward of this fold is a deeper adjoining slope basin, which was cored at ODP Site 1251 and ultimately receives most of the slope failures originating on the crest and eastern flank of Hydrate Ridge (Figure 2). Examination of the 3-D seismic and core data at Site 1252, shows a thick wedge of sediments near the base of the slope basin sequence that is acoustically chaotic and truncated against an uplifted anticline (Figure 2). Sediment from this interval contains some clay clast debris flow deposits within a generally silty clay stratigraphy (Tréhu *et al*., 2003). The MS in this same interval is generally high, compared to the background, baseline MS, and marks the beginning of an apparent cycle of four high MS zones (Figure 3, A-D). Correlation of the uppermost high MS zone (A) with the uppermost seismically defined and cored debris flow and turbidite deposits father down slope at Site 1251 (Johnson *et* *al*., 2010), suggests this and the lowermost MS high (D) or at least 2 of the 4 high magnetic susceptibility zones at Site 1252 are related to slope failures. Absent from all 4 of the high MS zones, are visible sand or silt beds comparable to those observed at IODP Site U1325B offshore Vancouver Island, where visual core descriptions of sand and silt beds of various thickness are well correlated with the positive MS values that deviate from a low baseline MS of hemipelagic clay (Figure 4). This suggests that the origin of the MS highs at ODP Site 1252 may be related in part to the presence of diagenetic magnetic iron sulfides. However, rock magnetic measurements at Site 1252 (Larrasoaña *et al*., 2006) reveal that in the interval that contains the four highs in MS, the magnetic mineralogy is consistent with the presence of magnetite (Figure 3). The increases in MS are thus most likely tracking concentrated zones of detrital magnetite associated with slope failure deposits, rather than concentrations of diagenetic iron sulfides. To investigate this further, we examined the pattern of total organic carbon (TOC) and Sulfur (S) abundance down core at Site 1252 (Figure 3). These data show that the highest concentrations of TOC and S occur in the intervening low MS intervals. The association of high TOC with fine grained clay is consistent with slow settling of particulate organic carbon during fine grained suspension dominated sedimentation. The increases in bulk sulfur concentration are likely tracking

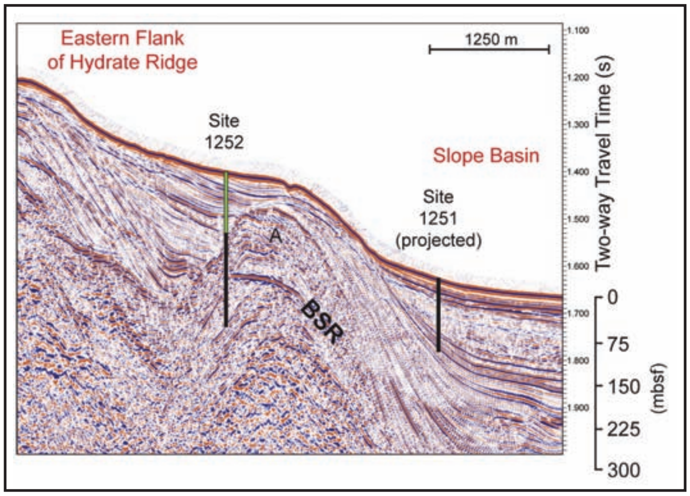


Figure 2: Multichannel seismic reflection data at ODP Site 1252 (with Site 1251 projected). Notice the slope basin sediments at Site 1252 (shown in green) that have accumulated against the uplifted anticline (A) on the eastern flank of Hydrate Ridge.

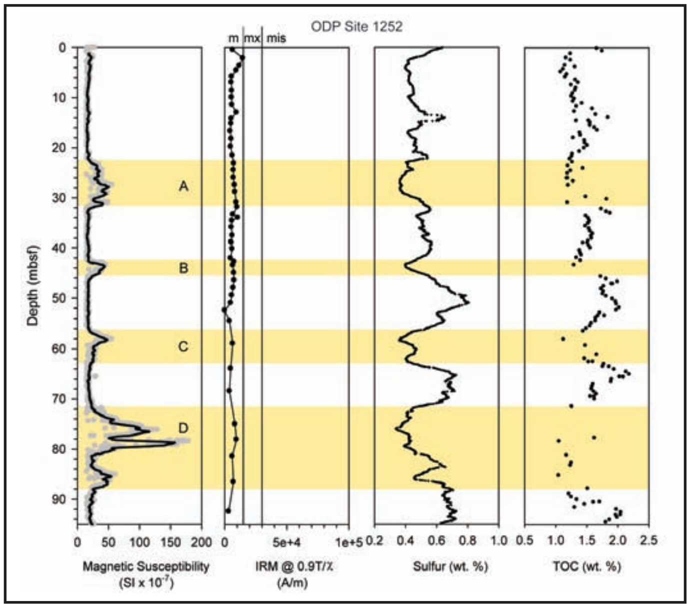


Figure 3: Down core measurements of MS, IRM (isothermal remnant magnetization), bulk Sulfur from XRF (calibrated from unpublished S data courtesy of Ji-Hoon Kim, Oregon State University), and TOC (total organic carbon) for Site 1252 Hole A at Hydrate Ridge, offshore central Oregon. IRM data and interpreted magnetic mineralogy (M = magnetite, MX= mixed magnetite and magnetic iron sulfides, and MIS = magnetic iron sulfides) from Larrasoaña et al. (2006). Notice the lack of MIS or MX mineralogy within the four high MS zones (A-D, marked in yellow) and the corresponding low sulfur and TOC contents. MS zone D is observed on the seismic data (Figure 2) as the chaotic wedge of sediments near the base of the slope basin sequence and contains both debris flow and silty clay deposits. MS zone A is equivalent to the thick, chaotic, seismic wedge cored at Site 1251 (Figure 2), where debris flows and sand and silt turbidites were recovered. MS zones B and C contain non-distinct cores of silty clay and clay, however, the MS, TOC, Sulfur, and magnetic mineralogy characteristics suggest these two zones are slope failure dominated as well.

pyrite abundance, which is greater in the presence of abundant, labile TOC (Berner, 1984). Framboidal pyrite was observed in smear slides examined throughout the record at Site 1252 and black iron sulfide precipitates were visible on the split core surfaces within the fine grained portions of the core (Tréhu *et al*., 2003).

The concentrations of magnetite that result in the four MS highs observed at ODP Site 1252 most likely formed from density sorting associated with an increase in slope failures in these intervals. These episodes of slope failure are separated by lower MS, TOC-rich, and S-rich hemipelagic clays, which formed from the slow vertical accumulation of suspended particles. Bioturbation may have disrupted any original, coarser beds associated with the slope failure episodes or the deposits in these intervals may represent the fine grained, proximal remnant of slope failures that continued to travel down slope, a model consistent with additional seismic data that show all four events may have correlative, deeper, and thicker, seismic equivalents near ODP Site 1251 (Johnson *et al*., 2010).

Conclusions

Characterizing primary and secondary sedimentary processes and products in gas hydrate-bearing stratigraphy is important to accurately reconstruct depositional environments and diagenetic processes associated with carbon cycling and gas hydrate dynamics. Given the potential mixed signal of MS in gas hydrate-bearing stratigraphy, we caution the use of MS as a way to track detrital mineral concentrations associated with slope failure unless independent rock magnetic measurements can rule out the presence of diagenetic magnetic iron sulfides. In our case, without the IRM data at ODP Site 1252, the lack of visible core evidence of slope failure may have led us to speculate that the two middle MS anomalies were diagenetic in origin. In addition, proper tracking of detrital and diagenetic mineral phases in gas hydrate bearing regions may also allow us to examine possible relationships between slope failure and paleo-methane flux in gas hydrate-bearing regions (e.g. Hong *et al*., 2010).

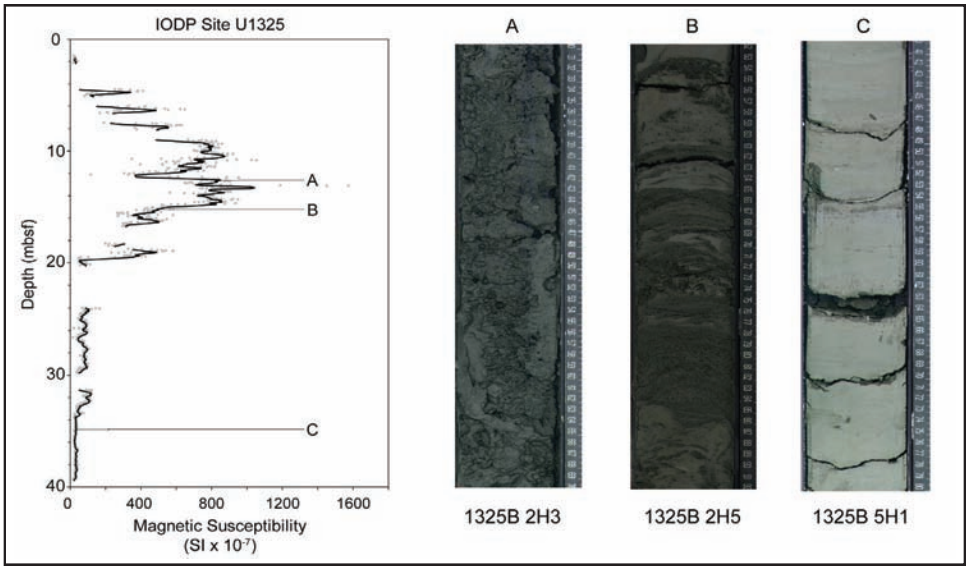


Figure 4: MS record at Site U1325 Hole B, offshore Vancouver Island and selected core photos. (A) Thick, massive sand turbidite and (B) thin turbidite sand beds correlate with high MS values. (C) Hemipelagic clay dominated interval that corresponds with low MS.

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Suggested Reading

Berner, R.A., 1984. Sedimentary pyrite formation; an update. *Geochimica et Cosmochimica Acta*, v. 48, no. 4, pp. 605-615.

Collett, T.S., Riedel, M., Cochran, J., Boswell, R., Presley, J., Kumar, P., Sathe, A., Sethi, A., Lall, M., Sibal, V., and the NGHP Expedition-01 Scientists, 2008. *National Gas Hydrate Program Expedition 01 Initial Reports*, *Vol. I and II on DVD*.

Expedition 311 Scientists, 2005. Cascadia margin gas hydrates. *IODP Prel. Rept.,* 311. doi:10.2204/iodp.pr.311.2005

Expedition 311 Scientists, 2006. Expedition 311 summary. *In* Riedel, M., Collett, T.S., Malone, M.J., and the Expedition 311 Scientists, *Proc. IODP,* 311: Washington, DC (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.311.101.2006

Housen, B.A., and Musgrave, R.J., 1996. Rock-magnetic signature of gas hydrates in accretionary prism sediments. *Earth Planet. Sci. Lett.*, v. 139, pp. 509-519.

Hong, W., Torres, M.E., Johnson, J.E., Pinero, E., and Rose, K., 2010. Quantifying Long-term Methane Flux Change by Coupling Authigenic Mineral Distribution and Kinetic Modeling at Southern Hydrate Ridge, Oregon. Abstract OS51D-08 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec.

Johnson, J.E., Goldfinger, C., Tréhu, A.M., Bangs, N.L.B., Torres, M.E., and Chevallier, J., 2006. North-south variability in the history of deformation and fluid venting across Hydrate Ridge, Cascadia margin. *In* Tréhu, A.M., Bohrmann, G., Torres, M.E., and Colwell, F.S. (Eds.), *Proc. ODP, Sci. Results,* 204: College Station, TX (Ocean Drilling Program), 1–16. doi:10.2973/odp.proc.sr.204.125.2006

Johnson, J.E., Torres, M.E., Hong, W., Disenhof, C., Miranda, E., and Rose, K., 2010. Slope failure records in gas hydrate bearing regions of the Cascadia margin. Abstract OS53A-1370 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec.

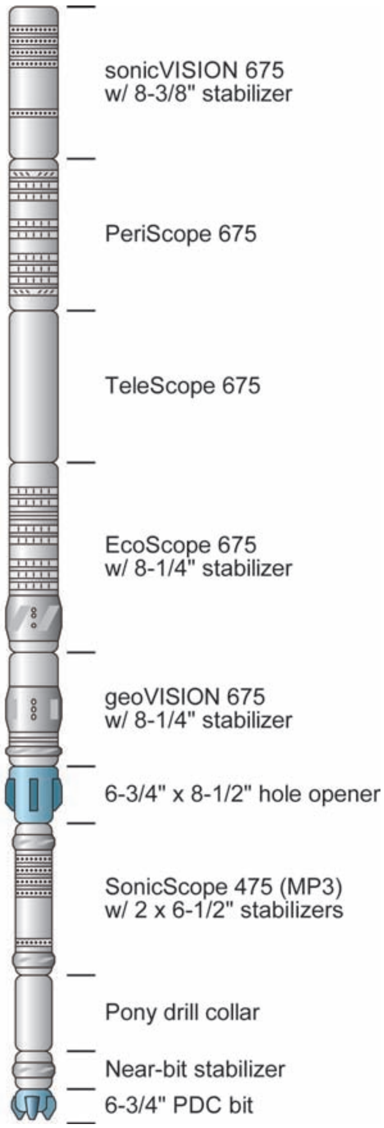
Larrasoaña, J.C., Gràcia, E., Garcés, M., Musgrave, R.J., Piñero, E., Martínez-Ruiz, F., and Vega, M.E., 2006. Rock magnetic identification of magnetic iron sulfides and its bearing on the occurrence of gas hydrates, ODP Leg 204 (Hydrate Ridge), *In* Tréhu, A.M., Bohrmann, G., Torres, M.E., and Colwell, F.S., eds., Proc. ODP, Sci. Results*,* 204: College Station, TX (Ocean Drilling Program), 1–33. doi:10.2973/odp.proc.sr.204.111.2006

Larrasoaña, J.C., Roberts, A.P., Musgrave, R.J., Gràcia, E., Piñero, E., Vega, M., and Martínez-Ruiz, F., 2007. Diagenetic formation of greigite and pyrrhotite in gas hydrate marine sedimentary systems. *Earth Planet. Sci. Lett.,* v. 261(3–4), pp. 350–366. doi:10.1016/j.epsl.2007.06.032

Musgrave, R.J., Bangs, N.L., Larrasoaña, J.C., Gracia, E., Hollamby, J.A., and Vega, M.E., 2006. Rise of the base of the gas hydrate zone since the last glacial recorded by rock magnetism. *Geology*, v. 34, no. 2, pp. 117-120. doi:10.1130/G22008.1

Torres, M.E., Tréhu, A.M., Cespedes, N., Kastner, M., Wortmann, U.G., Kim, J.-H., Long, P., Malinberno, A., Pohlman, J.W., Riedel, M., and Collett, T., 2008. Methane hydrate formation in turbidite sediments of northern Cascadia, IODP Expedition 311. *Earth Planet. Sci. Lett.,* 271(1–4):170–180. doi:10.1016/j.epsl.2008.03.061

Tréhu, A.M, Bohrmann, G., Rack, F.R., Torres, M.E., *et al*., 2003. *Proc. ODP, Init. Repts.,* 204: College Station, TX (Ocean Drilling Program). doi:10.2973/odp.proc.ir.204.2003



Bottom-hole assembly used for LWD operations during Leg II of the Gulf of Mexico Gas Hydrate Joint Industry Project

Logging-While-Drilling Data from Gulf of Mexico JIP Leg II Program Now Available

In April and May, 2009, the Gulf of Mexico Gas Hydrates Joint Industry Program ("JIP") collected extensive logging-while-drilling data from seven wells in the northern Gulf of Mexico (see "Joint Industry Project Leg II Discovers Rich Gas Hydrate Accumulations in Sand Reservoirs in the Gulf of Mexico" in the Summer 2009 issue of *Fire in the Ice*). These data have been processed by the Borehole Research Group at Lamont-Doherty Earth Observatory of Columbia University and reviewed by the JIP science team. The data are now available in digital form to gas hydrate researchers upon request. Interested scientists are asked to review the JIP Leg II log suites that are available at http://brg.ldeo.columbia.edu/ghp/ and then submit a brief research statement and specific data request to John Balczewski at jbalczewski@chevron.com.

7th ICGH Early Bird Registration & Submission of Conference Papers

Early bird registration for the Seventh International Conference on Gas Hydrates will officially open on January 28. The conference, to be held July 17-21 in Edinburgh, Scotland, is also seeking submissions for the conference proceedings volume. The online submission system opens on February 4. Registration and submission information can be found on the ICGH website at www.icgh.org.

Gas Hydrates Session at Upcoming Arctic Technology Conference

Gas hydrates will be the focus of an afternoon session on February 9 of the upcoming Arctic Technology Conference. Held at the George R. Brown Convention Center in Houston, Texas, the session will feature presentations on recent gas hydrate developments. Over the course of three days, the Conference will also offer a varied course program presenting creative solutions to the challenges faced in Arctic exploration. For more information and to register, please visit OTC's Arctic Technology Conference website.

JAPAN-US SYMPOSIUM ON THE MECHANICS OF HYDRATE BEARING SEDIMENTS – RESEARCH NEEDS

A Japanese delegation visited Georgia Tech during December 10 and 11, 2010. Their visit prompted the organization of a symposium on the mechanics of hydrate-bearing sediments, with the participation of other researchers from the USA, UK, Singapore, and South Korea (see photograph and list of participants).

Presentations and discussions addressed: energy demands and resources, thermal and mechanical properties of hydrate-bearing sediments, characterization, natural systems (Mallik, Baikal Lake, Mt. Elbert, and Nankai Trough), reservoir simulation, gas production (thermal stimulation, depressurization and CO_2-CH_4 replacement; recovery efficiency), and potential emergent phenomena in gas production (fines migration and clogging; dissociation-dependent changes in effective stress; deformations and instability).

The symposium concluded with a group exercise designed to identify the most important pending research issues. Suggested research needs were summarized into six categories:

Gas hydrate reservoirs: Further understanding of stratigraphic controls and geo-plumbing constraints on the formation of production-grade reservoirs. Improved reservoir discovery/identification tools leading to enhanced resource estimation. Additional attention to near-surface hydrate accumulations and possible recovery methods.

Properties of hydrate-bearing sediments: Synthesis of available information to link hydrate distribution and pore habit as a function of sediment characteristics and heterogeneity. Identification of the most important set of index properties needed to characterize hydrate-bearing sediments. Further studies on relative permeability and capillary pressure relationships for hydrate bearing sediments. Creep and time-dependent response of hydrate-bearing sediments.

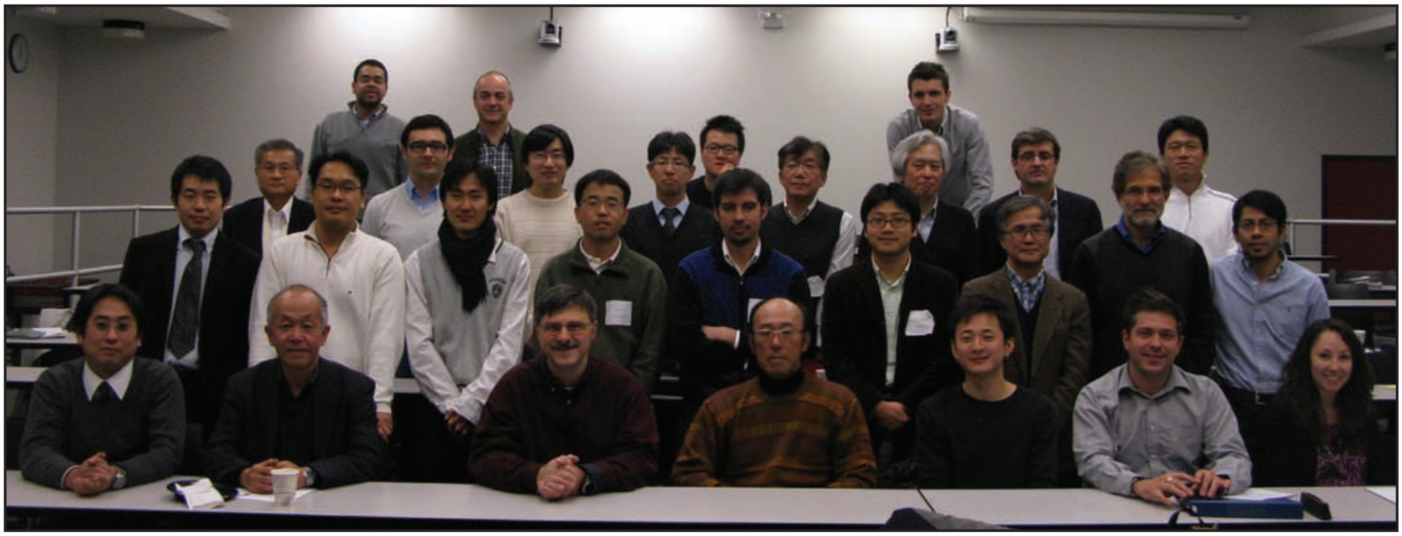
Characterization: Preferred formation techniques for synthetic specimens; evolution of hydrate-bearing sediment specimens prepared using water-limited methods after water saturation: is post water flooding good enough? Pressure core testing: improved tools; recovery effects on hydrate structures. Upscaling properties measured at small laboratory scales (synthetic specimens and pressure cores) to field scale properties needed for simulators. Further developments towards in situ property measurement.

Potential emergent phenomena during production: Enhanced understanding of gas-driven fractures. Response of clayey sediments to changes in salinity during production and the effects of salinity gradients (Manangoni effects). Fines migration and clogging effects, including the formation of skins on screens. Mechanical implications during production: deformations and instabilities.

Numerical modeling – Reservoir simulation: Extend coupled THCM simulators to account for potential emergent phenomena. Proper validation of numerical codes using long-term model/full-scale production data.

Gas production: State of the art, new concepts, and perceived limitations. Alternatives to produce hydrate-bearing clayey sediments. Implications of hydrate distribution and sediment heterogeneity on gas production. Enhanced monitoring techniques during gas production including the use of simulators to establish critical values of monitoring parameters so that real-time feedback can be provided during production. Optimization of production history for optimal recovery. Enhanced deformation analysis associated to gas production. Continue advancing the possibility of CH_4–CO_2 gas replacement taking into consideration mixed fluid and the thermodynamics of mixtures. Establish adequate criteria for gas recovery efficiency.

The second Japan-US Symposium on the Mechanics of Hydrate-Bearing Sediments will take place in Japan later this year.



Symposium participants (listed in no particular order) included: Masayuki Hyodo, Yukio Nakata, Norimasa Yoshimoto and Motoyuki Suzuki (Yamaguchi University); Akira Masui and Kuniyuki Miyazaki (AIST); Tatsuya Yokoyama (Oyo Co.); Eiji Ogisako, Shinya Nishio (Shimizu Co.); Yoshihiro Nakatsuka (JOGMEC); William Winters (USGS); Eilis Rosenbaum (NETL - DOE); Marcelo Sanchez (Texas A&M U.); Costas Tsouris (Oak Ridge National Laboratory); Keith Hester (ConocoPhilips); Shun Uchida (U. Cambridge); Simon Falser (National University of Singapore); Eun Seok Bang (KIGAM); and Minsu Cha, Song-Hun Chong, Sheng Dai, Douglas Cortes, Lucio Cruz, Nicolas Espinoza, Haiying Huang, Jaewon Jang, Jongwon Jung, Seunghee Kim, Cesar Pasten, and Carlos Santamarina (Georgia Tech).

Spotlight on Research

FRED WRIGHT

Project Leader - Gas Hydrate Production
Natural Resources Canada
Geological Survey of Canada

The path that brought Fred Wright to the Geological Survey of Canada (GSC) was not your typical one. After spending 20 years in the electro-mechanical trades, he came to the realization that he had done all there was to do and that there would be very little new and exciting developing in his chosen profession at that time. So, he dropped out to become a scientist and enrolled at Carleton University in Ottawa, Ontario.

After completing his Master's in Geothermal Science and Modeling in 1995, Wright's foray into natural gas hydrates began. "I had just been hired by the GSC to do permafrost geology when Scott Dallimore stuck his head in my office and asked if I would like to work on gas hydrates," he recalls. "I said, 'Sure…what are gas hydrates?"

His first task was the physical establishment of the GSC gas hydrate research laboratory. "We performed a variety of experiments on the fundamental properties and behavior of gas hydrates in support of the major field research programs conducted at Mallik in 1998 and 2002," says Wright. "Ultimately, the cumulative results of this work helped define our (GSC's) contribution to the eventual achievement of six days of continuous gas hydrate production from the Mallik reservoir in March of 2008."

Fred is currently serving as the project leader for gas hydrate production at the GSC, which is a part of Natural Resources Canada (NRCan). He also manages a parallel gas hydrate R&D program funded by NRCan's Energy Sector and is "working to expand this Program to include research and development of other unconventional gas resources, shale gas in particular."

The most exciting and rewarding aspect of gas hydrate research for Wright has been the, "opportunity to progress (as an international community and within quite a short time span) from asking the most fundamental questions about gas hydrates in nature ('What/where are they?' 'Why do we care?') to the point at which we are now concerned with the design, engineering, and demonstration of actual production technologies," he says.

Wright says that one of the most important challenges facing hydrates researchers is, "maintaining the momentum for gas hydrate research. It may be a challenge in coming years, largely due to the continuing low price of natural gas together with recent forecasts of as much as 100 years of natural gas supply in North America. Much of this growing supply is expected to come from unconventional sources (excluding gas hydrates), mainly shale gas."

"Certainly the motivations for gas hydrate R&D vary between countries and agencies, ranging from geological curiosity, to climate change, to technology development and marketing, and energy security," he continues. "These different perspectives and the evolving global context for gas hydrate R&D are likely to result in changing intensities of motivation for some of the major players. This may make it more difficult in the future to sustain the kinds of international partnerships and levels of investment that have driven much of the progress realized to this point."

Wright encourages future hydrate researchers to, "be diligent in your work, creative in your thinking, open minded in your listening, and embrace the mantra 'high gas rates from gas hydrates!'" Looking back over his career, Wright says, "In many respects my work has not changed all that much, as I was addressing similar problems in the refrigeration business as I am presently (heat transfer, phase change, enthalpy, etc.), except that I'm now working at an arguably grander scale."