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Fire in the Ice

Vol. 9, Iss. 1 | Methane Hydrate Newsletter

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U.S. DEPARTMENT OF ENERGY

Assessment of Technically Recoverable Gas-Hydrate Resources on the North Slope of Alaska

By the U.S. Geological Survey National Oil and Gas Assessment Team

In recognition of the importance of gas hydrates as a potential energy resource, the U.S. Geological Survey (USGS) and the U.S. Bureau of Land Management (BLM) entered into an Assistance Agreement in 2002 to assess the volume of gas that could be produced from gas hydrates in northern Alaska. This effort included a detailed geological and geophysical investigation that delineated gas hydrate occurrences throughout the Alaska North Slope (ANS). Information gleaned from the latest field research programs and hydrate production computer simulations were then used to estimate technically-recoverable gas-hydrate resource volumes. Our estimate is that there are about 85 trillion cubic feet (TCF) of undiscovered gas resources within gas hydrates on the ANS that can be recovered using existing technologies (Table 1).

The area assessed in northern Alaska (Figure 1) extends from National Petroleum Reserve (NPRA) on the west through Alaska National Wildlife Refuge (ANWR) on the east and from the Brooks Range northward to the State-Federal offshore boundary (located three miles north of the coastline). This area consists mostly of Federal, State, and Native lands covering about 55,894 mi^2.

A critical finding of our geological and geophysical investigations is that gas hydrates on the North Slope occur within reservoir-quality sands as

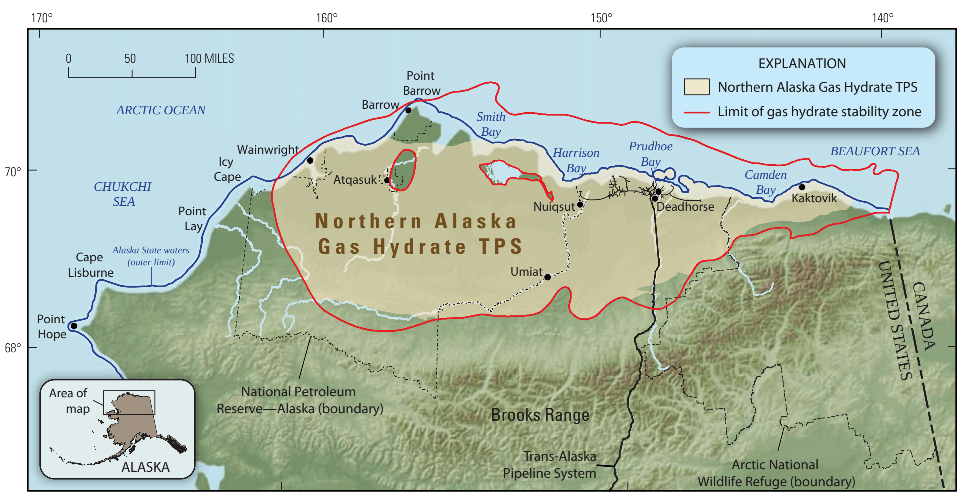

***Figure 1:** Map showing the Northern Alaska Gas Hydrate Total Petroleum System (TPS) (shaded in tan), and the limit of gas hydrate stability zone in northern Alaska (red outline).*

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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 281-881-8986.

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discrete accumulations in either stratigrahic traps or bounded by faults and downdip water contacts (Figure 2). We interpret this finding to reflect that the seismically-imaged gas hydrate accumulations were, for the most part, once conventionally trapped free-gas accumulations that were converted to gas hydrate at the onset of cold arctic conditions at the beginning of the Pliocene (about 1.88 Ma). For each of the gas hydrate prospects identified in this study, we were able to interpret key reservoir properties and in-place resource volumes using geophysical characterization techniques that were confirmed to be reliable by drilling at the 2007 "Mount Elbert" stratigraphic test well (see *Fire in the Ice*, Winter, 2008). As a result, this database of size and number of accumulations enabled us to assess ANS gas hydrate resources using the standard geologic-based methodologies developed by the USGS to assess conventional oil and gas resources.

A key feature of the USGS conventional assessment approach is that it assumes that the resource can be produced with conventional (existing) technology. Although verified by only limited field testing, numerical production models of gas hydrate-bearing reservoirs overlying the Milne Point and Prudhoe Bay oil fields suggest that gas can be produced from gas hydrate via simple depressurization using standard drilling and completion methods (see *Fire in the Ice*, Fall, 2008). In addition, gas production rates reported from recent gas hydrate testing at the Canadian Mallik site (see "Yamamoto and Dallimore," *Fire in the Ice*, Summer, 2008) compare favorably with the modeled production rates predicted for the gas hydrate occurrences in northern Alaska.

The Northern Alaska Gas Hydrate Total Petroleum System (TPS) includes Cretaceous and Tertiary reservoirs that have been divided into three assessment units (AUs)—from oldest to youngest, the Nanushuk Formation Gas Hydrate AU, the Tuluvak-Schrader Bluff-Prince Creek Formations Gas Hydrate AU, and the Sagavanirktok Formation Gas Hydrate AU. As a first

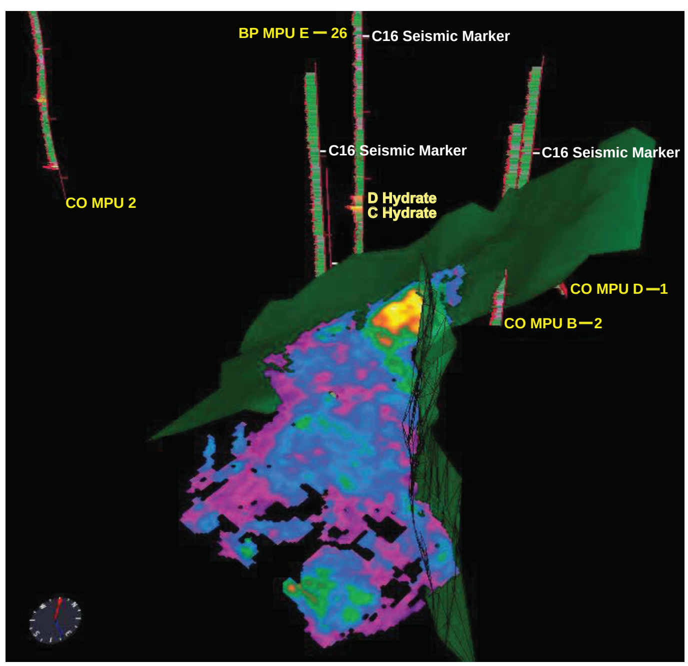

Figure 2: *Milne Point—Mount Elbert gas hydrate prospect. Three-dimensional image of a fault-bounded, high amplitude feature (in a pallette of colors ranging from yellow to magenta; the yellow-imaged portion of the structure contains the thickest and most concentrated gas hydrate). Also shown are the bounding faults (in green) and gas hydrate occurrences in nearby well penetrations. The well penetrations show downhole-measured geophysical data indicative of gas hydrate occurrence (in yellow).*

step, the factors controlling gas hydrate phase equilibria, mostly a function of formation temperature and pressure, were assessed to map the spatial distribution of the gas hydrate stability zone in northern Alaska. Only gas hydrates lying below the base of the permafrost and above the base of the gas hydrate stability zone were assessed. Free-gas potentially trapped below the gas hydrate stability zone was not assessed. Also, geochemical analysis of known gas hydrate occurrences revealed a link between gas hydrate accumulations and more deeply buried conventional oil and gas occurrences, in which methane migration from depth has charged the reservoir rocks in the gas hydrate stability zone. These geochemical studies have been used to further characterize and constrain the occurrence and distribution of the potential gas hydrate accumulations on the North Slope.

Given that relatively few wells have penetrated gas hydrate accumulations in northern Alaska, there is significant geologic uncertainty in these estimates, which is reflected in the range of estimates in Table 1. The mean estimate of 85.4 TCF of technically-recoverable gas within the gas hydrates of northern Alaska is considerably less than the 590 TCF of in-place resources reported in the 1995 USGS assessment of domestic natural gas hydrates. This difference is because this assessment deals only with technically recoverable gas within those accumulations of 20 bcf or greater that are of sufficient thickness to be confidently delineated on existing industry 3-D seismic data. Also, the 1995 assessment included offshore federal waters of Alaska, which were not included in this assessment. It should also be highlighted that further research, including long-term production tests, still is needed to demonstrate gas hydrates as an economically producible resource.

This research reflects ongoing efforts by USGS and BLM scientists and land managers to provide the Nation and its decision makers with reliable data as a basis for future energy policy. To learn more about USGS research on natural gas hydrates and to see results of the gas hydrate assessment in northern Alaska, please visit http://energy.usgs.gov/. To learn more about research in the Bureau of Land Management's Alaska office, please visit http://www.blm.gov/ak/st/en.html.

Total Petroleum System *and Assessment Unit*	Field Type	***Total Undiscovered Resources***							
		Gas (BCFG)				***NGL (MMBNGL)***			
		F95	**F50**	**F5**	**Mean**	**F95**	**F50**	**F5**	**Mean**
Northern Alaska Gas Hydrate TPS									
Sagavanirktok Formation Gas Hydrate AU	***Gas***	6,285	19,490	37,791	20,567	0	0	0	0
Tuluvak-Schrader Bluff-Prince Creek Formations Gas Hydrate AU	***Gas***	8,173	26,532	51,814	28,003	0	0	0	0
Nanushuk Formation Gas Hydrate AU	***Gas***	10,775	35,008	68,226	36,857	0	0	0	0
Total Undiscovered Resources		**25,233**	**81,030**	**157,831**	**85,427**	**0**	**0**	**0**	**0**

Table 1: *Alaska North Slope—Gas hydrate assessment results.*
[BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates. F95 represents a 95-percent chance of at least the amount tabulated; other fractiles are defined similarly. Fractiles are additive, assuming perfect positive correlations. NGL, natural gas liquids; TPS, total petroleum system; AU, assessment unit.]

Cruise Report: Imaging Gas Hydrate in the Gulf of Mexico using Marine Electromagnetic Methods

By Karen Weitemeyer, Steven Constable, and the SIO Marine EM Laboratory, Scripps Institution of Oceanography.

On 7th October 2008 the Research Vessel *Roger Revelle* steamed into the Gulf of Mexico to carry out an experiment to map gas hydrates using state-of-the-art marine electromagnetic (EM) methods. (Figure 1) This work is funded in roughly equal parts by a consortium of industry sponsors, NETL, and University of California Shipfunds Committee. Over the following 18 days the science party deployed a fleet of 30 seafloor electric and magnetic field recorders a total of 94 times, broadcasting 103 hours of electromagnetic signals from a towed transmitter. While it will take some time to process and interpret the 70 Gigabytes of data collected on this cruise, shipboard appraisal shows that the quantity and quality of the data exceed all expectations.

By using equipment and techniques developed as part of the search for offshore oil and gas, and building on a pilot experiment carried out over Hydrate Ridge in 2004, our work aims to create 2-D and 3-D images of resistivity throughout the hydrate stability field. Well logs and laboratory experiments show that hydrate is more electrically resistive than host sediments, and more than ten years ago Nigel Edwards proposed the use of controlled-source EM methods as a way to evaluate the resource potential of gas hydrate. Since then several groups have fielded equipment to do just this, including ourselves, Nigel, Rob Evans, Tada-nori Goto, John Dunbar, and Katrin Schwalenberg (we were fortunate to have Katrin join our 2008 experiment). The approach used by all these workers is to drag or tow a transmitter close to the seafloor to inject an electric curren. across two electrodes separated by 10's or 100's of meters. An EM receiver, usually an inline electric field antenna dragged or towed some distance behind the transmitter, records the amplitude and phase of the transmitted signal. For low frequency transmissions, a DC-type resistivity measurement can be made, but higher frequency transmissions will propagate preferentially through more resistive seafloor rocks and provide greater sensitivity to seafloor structure. Magnetic field transmitters and receivers can also be used.

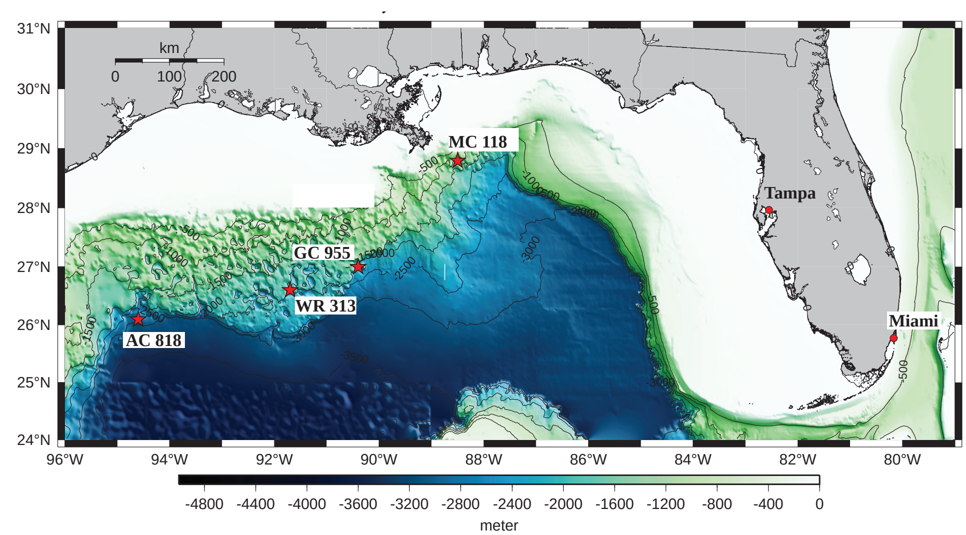

***Figure 1:** Map of areas surveyed in October 2008.*

Several aspects of our work differentiate it from these earlier studies. The deployment of large numbers of seafloor receivers results in an expanded set of transmitter--receiver offsets and extends the depth of investigation from the seafloor to the base of the hydrate stability field, and even deeper. Seafloor recorders collected every EM component except the vertical magnetic field (Ex, Ey, Ez, Bx, and By). We supplemented the deployed instruments with a receiver ("Vulcan") towed at a constant offset of 300 m behind the transmitter antenna, to provide short-offset data for all transmitter positions. Our transmitter and towed receiver operate at altitudes of 50-100 m above the seafloor, allowing us to operate in areas with seafloor infrastructure or rough terrain, rather than being dragged in contact with the sediments and rocks. The towed receiver records all three axes of electric field instead of just the inline Ey field, and because it is not in contact with the seafloor has much lower noise levels. Instead of transmitting a single fixed frequency, we transmitted a binary waveform with about two decades of frequency content, from 0.50 Hz to about 50 Hz (Figures 2, 3, 4).

The areas studied in detail during the cruise are in different water depths and have different geologic controls on the way hydrate is thought to be distributed:

Alaminos Canyon 818-Chevron encountered a thick hydrate-bearing section (20 m) a few hundred meters below seafloor in an exploration well on this block, with high resistivities (30-40 Ohm-m) evident in the logs (see Smith *et al.*, *Fire in the Ice*, Fall 2006). Water depth is around 3,000 m, which is deep for exploration but easily within the 6,000 m operating depth of our equipment. Initially we were hoping to impact future Joint Industry Project (JIP) drilling plans, but shortly before the cruise we heard that AC 818 was dropped from the JIP program. However, as one of the few locations with gas hydrate at high saturations in sands confirmed in a high quality well log data set, this area remained the highest priority for our own studies. We deployed 30 receivers and made four transmission tows, centered on the Chevron well location. Two instruments failed to record data.

Mississippi Canyon 118-This block has been designated as a Minerals Management Services observatory. Large outcrops of hydrate occur on the seafloor in relatively shallow water depths of 800-900 m, but there is yet no direct evidence of hydrate at depth. This area provides the opportunity to coordinate and collaborate with many other ongoing scientific programs, including shallow resistivity surveying. We deployed 24 receivers in a 6 x 4 array and towed 10 transmitter lines in a grid pattern (avoiding the already installed seafloor equipment). All receivers recorded data.

Green Canyon 955-This prospect is in intermediate water depth (2200 m) and shows evidence of gas and gas hydrate accumulation in channel sands near the base of the hydrate stability field (see Hutchinson *et al*., 2008). GC

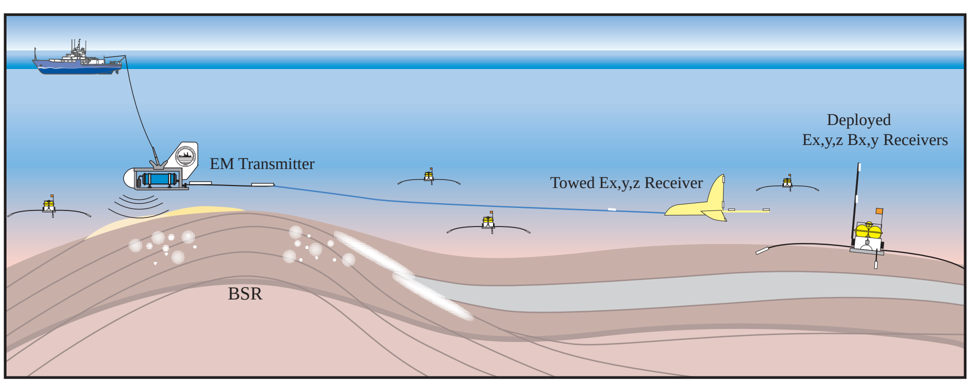

Figure 2: *Schematic of survey equipment operation.*

955 is a priority site for 2009 drilling by the JIP program. Unfortunately, current exploration drilling prevented us from carrying out our survey as originally planned. Nonetheless, we were able to deploy 20 seafloor instruments (all of which collected data) along two lines that pass very close to the primary targets for the JIP drilling.

Walker Ridge 313-This fourth prospect was added at the request of NETL to the 3 sites above selected in consultation with our industry sponsors. It is in intermediate water depths on the lower slope of the northern Gulf of Mexico, within a tabular salt minibasin province and having a very low geothermal gradient (hence a very thick gas hydrate stability zone). Evidence for hydrate comes from seismic data, gas mounds, and focused fluid expulsion sites (see Hutchinson *et al*., 2008). WR 313 is a priority site for 2009 JIP drilling, so clearly it is desirable to have marine EM data for comparison with the drilling results. We decided that if we had cooperative weather (we did) and scaled back the GC 955 survey by a few sites it would be possible to carry out a two-line survey similar to the one at Green Canyon. These lines pass directly over the permitted JIP drilling sites. Again, we had 100% data recovery.

Figure 3: *Deck of R.V. Roger Revelle showing instruments used for this survey.*

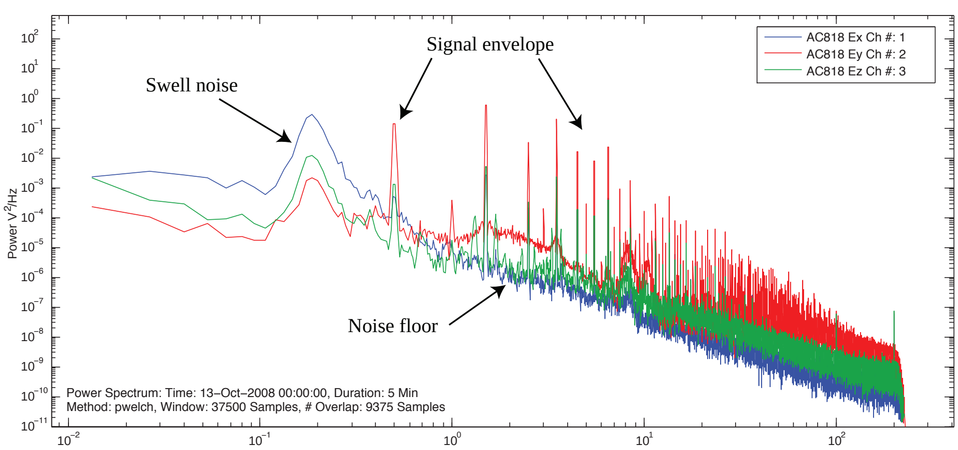

Figure 4: *Spectrum of signals recorded on towed receiver Vulcan.*

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Interpreting Upward Methane Flux from Marine Pore Water Profiles

By Gerald R. Dickens and Glen T. Snyder, Rice University

The amount of gas hydrate in a sediment sequence must ultimately depend on the inputs and outputs of gas over time. For most marine gas hydrate systems, where methane is the dominant gas, anaerobic oxidation of methane (AOM) in shallow sediment is one potentially important output. This microbially mediated reaction, $CH_4 + SO_4^{2-} \dashrightarrow HS^- + HCO_3^- + H_2O$, appears to happen across a thin depth horizon between the seafloor and the uppermost occurrence of gas hydrate. The horizon, often called the sulfate methane transition (SMT), is characterized by near depletion of CH_4 and SO_4^{2-} in pore waters, with dissolved CH_4 concentrations increasing downward, and dissolved SO_4^{2-} concentrations increasing upwards toward the seafloor (Figure 1).

Direct measurements of CH_4 fluxes into the SMT are not straightforward, in part because significant quantities of CH_4 can escape sediment cores during their recovery and handling. As pointed out by numerous authors though, the present-day flux through AOM across a particular SMT might also be determined from pore water profiles of sulfate or alkalinity (e.g., Borowski *et al*., 1996), species whose concentrations are much easier to collect and analyze. This approach comes with two fundamental assumptions: (1) AOM proceeds by the equation above (1 mole of HCO_3^- is produced per mole of CH_4 and SO_4^{2-} consumed), and (2) AOM, rather than particulate organic carbon (POC), dominates net sulfate consumption. Accurate conversion of measured concentration gradients to fluxes is also crucial.

Pore water SO_4^{2-} gradients in shallow sediment can clearly be affected by upward fluxing CH_4. This is obvious in small regions of the seafloor where core transects pass across locations of active CH_4 venting. In these cases, the rain of sediment through the water column, including POC, is similar, but the SMT consistently shoals toward the sediment-water interface around the locations of CH_4 advection (e.g., Kulm *et al*., 1986; Paull *et al*., 2005). There are also a series of arguments based on pore water chemistry to suggest that AOM within the SMT drives net consumption of pore water SO_4^{2-} in regions

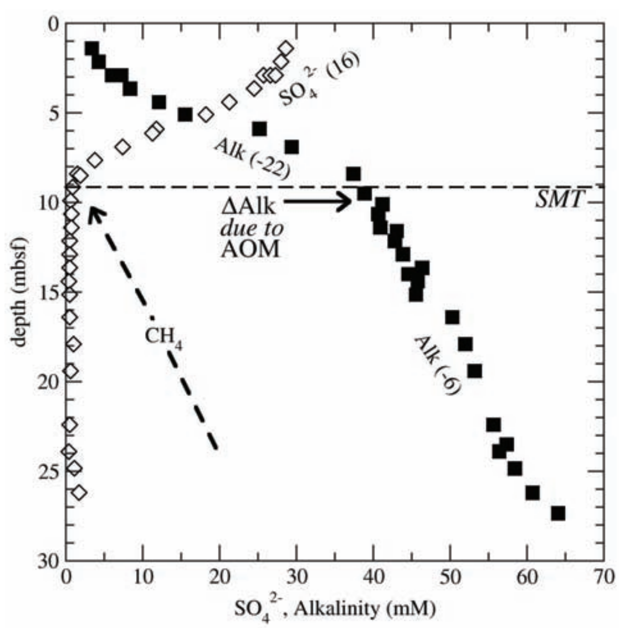

Figure 1: *Pore water data in shallow sediment at Ocean Drilling Program (ODP) Site 1244, Hydrate Ridge (Trehú et al., 2003). Also shown are the sulfate-methane transition (SMT), and estimated fluxes of dissolved species (mol/m²-kyr) in and out of this horizon calculated following Snyder et al. (2007). Note that 22 mol/m²-kyr of carbon leave the SMT as shallow alkalinity, while 22 mol/m²-kyr of carbon enter the SMT through sulfate consumption (AOM) and deep alkalinity.*

of high methane flux; these include, in many cases, the near linearity of the SO_4^{2-} concentration profile above the SMT, and the absence of change in the gradient of dissolved N and P species across the SMT, constituents that would be released from decomposition of POC (e.g., Borowski *et al*., 1996). Moreover, a few studies have endeavored to account for all carbon fluxes in shallow sediment above gas hydrate systems, and these indicate that AOM consumes most of the SO_4^{2-} at the SMT (Luff and Wallman, 2003; Snyder *et al*., 2007).

However, several authors have stated that, even in regions with gas hydrate and presumably high upward CH_4 fluxes, much of the net SO_4^{2-} consumption in shallow sediment may result from reactions with POC rather than CH_4 (e.g., Claypool *et al*., 2006; Kastner *et al*., *Fire in the Ice*, Summer 2008). If this is correct, pore water SO_4^{2-} and alkalinity gradients cannot be used to constrain upward CH_4 fluxes above marine gas hydrate systems. This conclusion seriously impacts current research in the gas hydrate community because any mechanistic explanation for understanding the formation and development of gas hydrate systems needs to account for inputs and outputs of carbon over time. So, we wish to examine these arguments further.

The first argument that has been made against methane driven sulfate consumption as the primary control on the nature of the SMT is based upon comparisons of changes in SO_4^{2-} and "excess alkalinity" in pore waters of shallow sediment. Excess alkalinity is, effectively, the amount of HCO_3^- that would occur in pore waters if authigenic carbonate had not precipitated; its change can be calculated by summing the deviations in pore water alkalinity, Ca^{2+}, and Mg^{2+} relative to their concentrations in seawater. Such comparisons at Hydrate Ridge and other locations can show a nominal 2:1 slope for the change in excess alkalinity versus the change in SO_4^{2-} in shallow pore water where the change in SO_4^{2-} is less than 30 mM and the change in excess alkalinity is less than 60 mM (Figure 2). One might suggest that this relationship signifies a reaction where the consumption of one mole of sulfate releases two moles of HCO_3^-, which would support sulfate reduction by POC (Kulm *et al*. 1986; Claypool *et al*., 2006; Kastner *et al*., 2008). However, a fundamental problem arises when one expands the concentration and depth ranges for the species of interest. In many locations, the ~2:1 slope only pertains to pore waters above the SMT; once SO_4^{2-} has been exhausted,

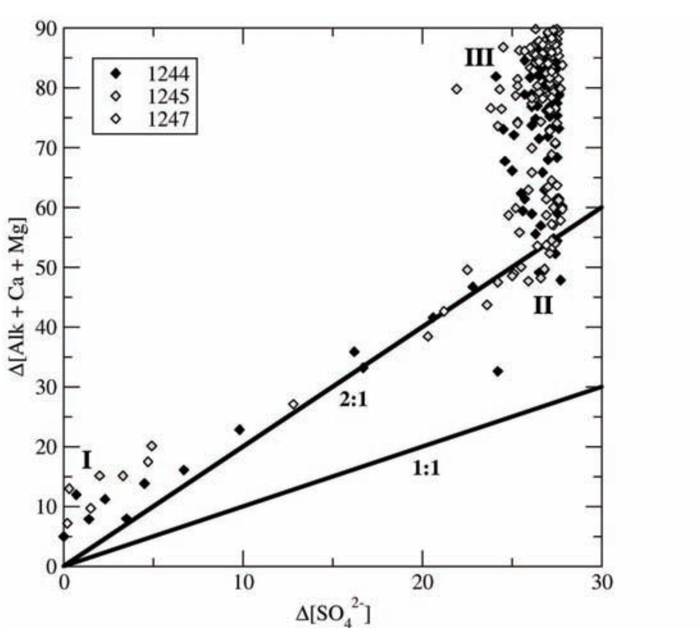

Figure 2: *The change in sulfate and the change in "excess alkalinity" for shallow sediment at three sites on Hydrate Ridge (original data from Trehú et al., 2003). As emphasized by Kastner et al. (2008), there is a nominal 2:1 relationship for pore waters above the SMT. Note, however, that excess alkalinity continues to rise below the SMT. There is an upward flux of* HCO_3^- *from deeper sediment, which necessarily implies that only a portion of excess alkalinity above the SMT comes from shallow sediment.*

excess alkalinity continues to rise (Figure 2). This implies a flux of HCO_3^- from below. Independent of POC contributions, HCO_3^- concentrations in shallow pore waters above many gas hydrate systems represent a sum of that produced by AOM and that coming from other, deeper processes, presumably related to fermentation and methane production (e.g., Luff and Wallman, 2003; Snyder *et al*., 2007).

The relative proportions of excess alkalinity across the SMT derived from AOM and other sources can be assessed using established equations and parameters (e.g., Snyder *et al*., 2007). Here, it is worth noting that different dissolved species have significantly different diffusion coefficients, so that a plot comparing concentrations (e.g., Figure 2) is not an appropriate means to represent the stoichiometry of chemical reactions in shallow sediment. Using the ODP Leg 204 database (and including additional information such as porosity), we have calculated SO_4^{2-} and HCO_3^- fluxes in shallow sediment for sites on Hydrate Ridge (Figures 1 and 3). Our estimates show that, once the deep flux of alkalinity and differences in diffusion have been accounted for, the change in alkalinity across the SMT is much closer to a 1:1 relationship, as predicted by AOM. For example, at ODP Site 1244, approximately 16 mol/m^2-kyr of SO_4^{2-} enter the SMT from above, 6 mol/m^2-kyr of HCO_3^- enter the SMT from below, and 22 mol/m^2-kyr of HCO_3^- leave toward the seafloor (Figure 1). (Mass balance closure across the SMT at this location is less precise than indicated because carbonate precipitation may remove an additional 4 mol/m^2-kyr of HCO_3^-).

Surprisingly, there have been very few efforts to constrain carbon mass balances across SMTs above gas hydrate systems, such as that shown in Figure 1. We have published such information for sites in the Japan Sea (Snyder *et al*., 2007), and have made preliminary estimates for sites on Hydrate Ridge, Blake Ridge, and the Namibian Margin. After concentration profiles have been converted to fluxes, and the deep flux of HCO_3^- has been accounted for, excess alkalinity across the SMT supports a 1:1 relationship at all these locations, as predicted by AOM (Figure 3).

The second argument is based on observations that the carbon isotopic composition ($\delta^{13}C$) of dissolved inorganic carbon (DIC) across SMTs can be significantly greater than that predicted if it was sourced entirely from

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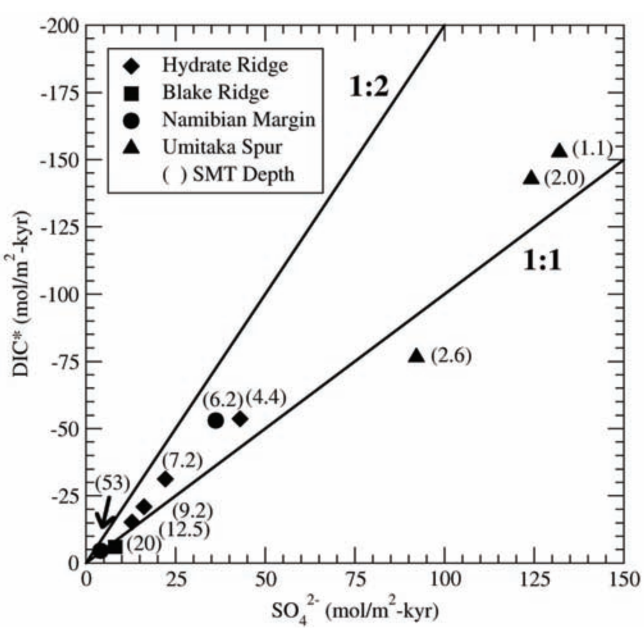

Figure 3: *Estimated fluxes of sulfate and net dissolved inorganic carbon (DIC) at the sulfate-methane transition (SMT) at several locations with underlying gas hydrate. Fluxes were calculated according to the approach presented by Snyder et al. (2007). The net DIC flux was determined by subtracting the deep alkalinity flux and by adding the carbonate precipitation flux.*

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CH_4 oxidation (e.g., Kastner *et al*., 2008). However, as suggested above, the concentration of HCO_3^- across an SMT, and by inference the $\delta^{13}C$ of DIC in this horizon, depends on contributions produced by AOM within the SMT and that fluxed from lower sediment. The deep flux of alkalinity will be, in most locations with gas hydrate, greatly enriched in ^{13}C because of methane production. Consider, for example, ODP Site 1244, where our preliminary interpretations suggest that ~73% (16/22) of the total HCO_3^- entering the SMT comes from AOM, and ~27% (6/22) comes from deep sources (Figure 1). At depths well below the SMT, CH_4 at this site has a $\delta^{13}C$ of -65‰ (Claypool *et al*., 2006), and DIC has a $\delta^{13}C$ of +14‰ (Torres and Rugh, 2006). A simple 7:3 mixing of these sources would predict a $\delta^{13}C$ of HCO_3^- across the SMT of -38‰, which approaches the observed value of -22‰ (Torres and Rugh, 2006). The difference might be explained by one of several processes, each which would increase the expected $\delta^{13}C$ of DIC at the SMT from simple mixing. These include: loss of DIC below the SMT because o. "gas sparging" during core recovery (so the upward alkalinity flux below the SMT is higher); methane production from DIC at or near the SMT, or preferential loss of ^{12}C into the microbial biomass at the SMT. For example, satisfactory mass balances would occur for all carbon fluxes (including carbonate) and carbon isotopes at ODP Site 1244 if the upward HCO_3^- flux was 10 mol/m^2-kyr.

We believe that careful analyses of pore fluid metabolites in shallow sediment above marine gas hydrate systems can yield meaningful estimates of upward fluxes of CH_4. In particular, we suggest that profiles of SO_4^{2-}, alkalinity, and the $\delta^{13}C$ of DIC are quantitatively related to the present-day outputs of CH_4 across the SMT when they are examined on the basis of fluxes (not concentrations), and account for ^{13}C-depleted HCO_3^- rising from below. This conclusion is important to the gas hydrate community because AOM represents a major output of gas from most marine gas hydrate systems.

There should be a link between present-day CH_4 fluxes across the SMT and the occurrence of gas hydrate in the deeper subsurface if certain conditions and parameters governing the gas hydrate system have remained constant over long time intervals (Bhatnagar *et al*., 2008). Scientific drilling into gas hydrate systems clearly demonstrates that pore water chemistry profiles in uppermost sediment are not directly coupled to the amount and distribution of gas hydrate below (e.g., Paull *et al*., 2000; Tréhu *et al*., 2003; Kastner *et al*., 2008). Pore water chemistry data (and interpreted fluxes) in shallow sediment, therefore, serve as a constraint for understanding the formation of the underlying gas hydrate system, but generally not as a proxy for the amount and distribution of gas hydrate because there are multiple inputs, outputs and migration pathways for gas, each which can vary over space and time. Furthermore, the specific geology of any site, including sediment composition and structural deformation, can exert profound influences on local gas hydrate distribution that may be independent of present-day fluxes.

Occurrence and Variety in Seismic Expression of the Base of Gas Hydrate Stability in the Gulf of Mexico, USA

By Bill Shedd, Paul Godfriaux, and Matt Frye, MMS; Ray Boswell, DOE; Debbie Hutchinson, USGS

The Gulf of Mexico is the primary area for ongoing federal research into the resource potential of marine gas hydrates. The Gulf is favorable for many reasons, including the existence of a proven, world-class petroleum system, clear evidence of large volumes of gas traversing the gas hydrate stability zone (GHSZ), an extensive existing geological and geophysical knowledge base, and a well-developed infrastructure to support research operations. However, in the past, subsurface gas hydrates in the Gulf of Mexico were thought to be rare. One perception was that much of the gas was perhaps by-passing the GHSZ through fault-related vent systems, resulting in surficial mounds being the primary form for Gulf of Mexico gas hydrates. The Gulf was also thought to be a place of anomalous thermal and chemical regimes that would further hinder subsurface gas hydrate formation. Supporting this general perception was the paucity of observed geophysical indications of subsurface gas hydrate such as bottom simulating reflectors (or BSRs).

In recent years, a number of investigators have presented evidence of subsurface gas hydrates in the Gulf. McConnell and Kendall (2002) described geophysical evidence for gas hydrate accumulations that resulted in discontinuous anomalies along the presumed base of gas hydrate stability (BGHS). Smith *et al* (2005) showed more classical, continuous BSRs. A drilling program in 2005 resulted in a series of investigations of gas hydrate from two sites at about 1300-m water depth in the northern Gulf (Ruppel *et al.*, 2008, and papers in the MPG special volume). Wood *et al.* (2008) showed highly-upwarped reflections interpreted to reflect the BGHS in areas with strong vertical fluid (and associated) heat flux.

A regional subsurface investigation of the Gulf of Mexico is currently underway by the U.S. Minerals Management Service (MMS) to support the MMS's gas hydrate resource assessment of the GOM (see Frye *et al.*, *Fire in the Ice,* Spring 2008), as well as to support the site selection process of the

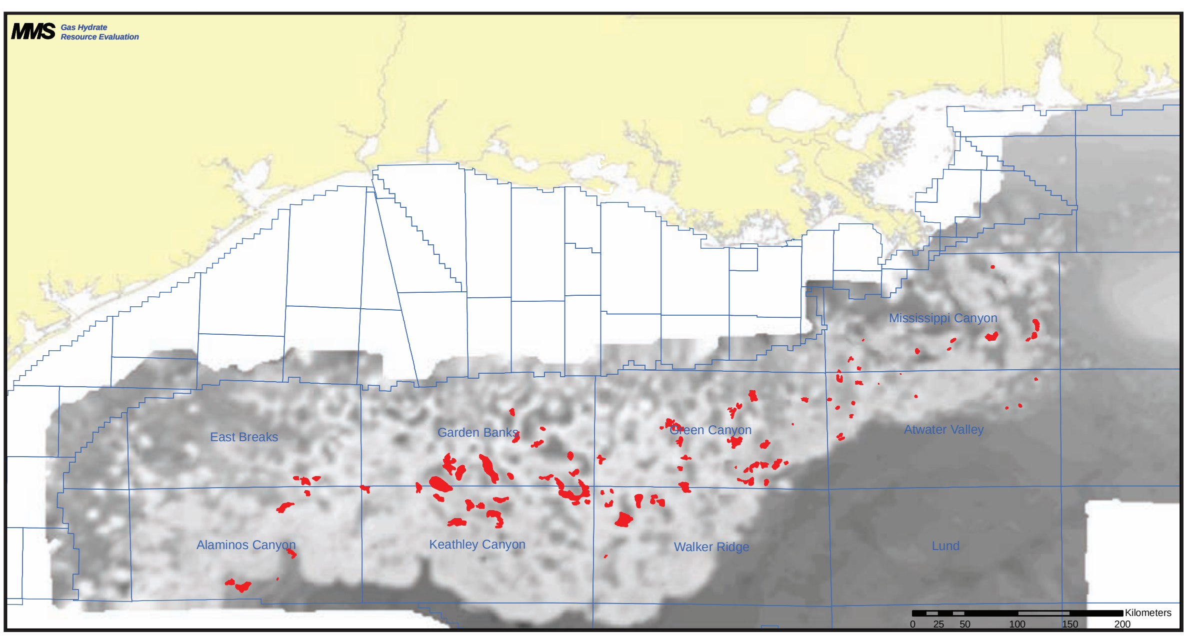
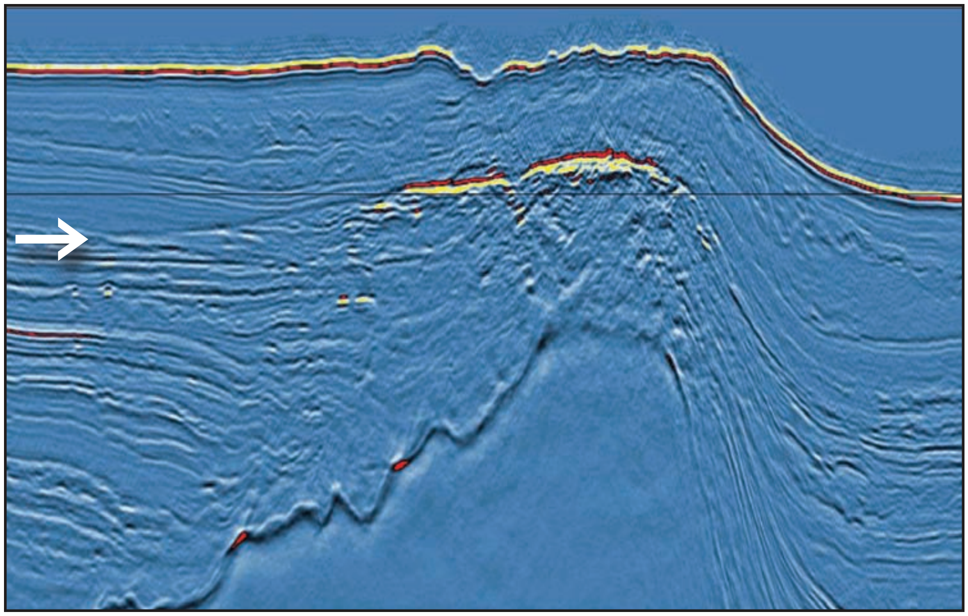


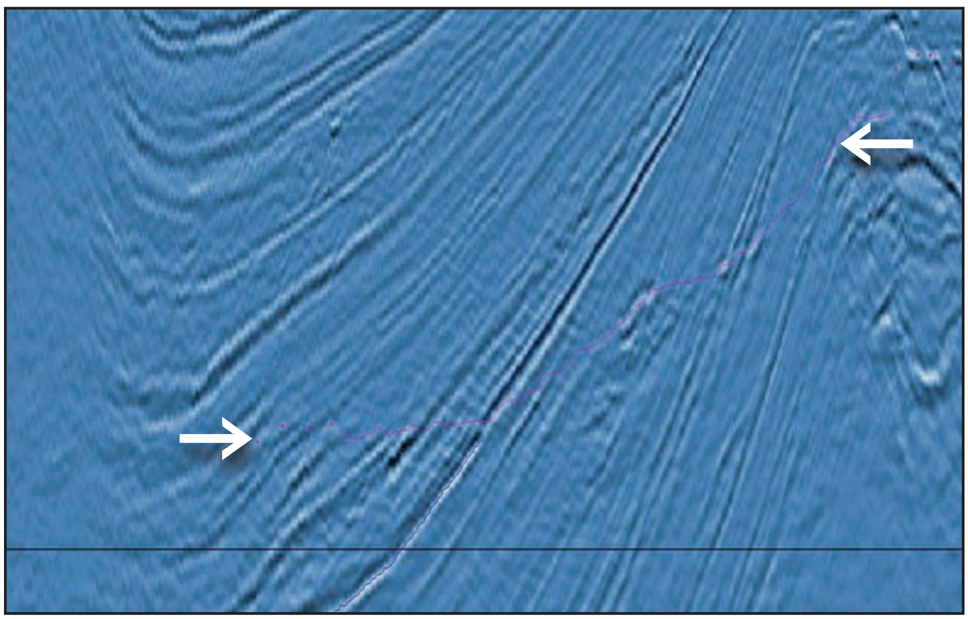
Figure 1: *Location of mapped geophysical expressions of the BGHS in the Gulf of Mexico.*

Figure 2: *Four examples of way the base of gas hydrate stability (BGHS) is expressed in seismic data in the Gulf of Mexico.*

Data courtesy of WesternGeco.



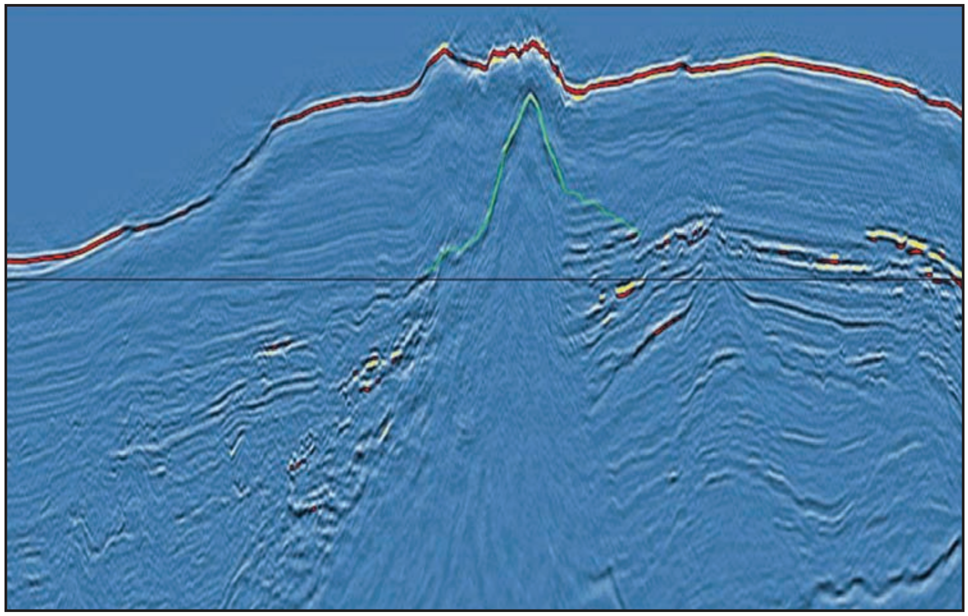
2A) *a Continuous BSR with polarity opposite the seafloor and clear cross-cutting relationship to strata. Data courtesy of WesternGeco.*



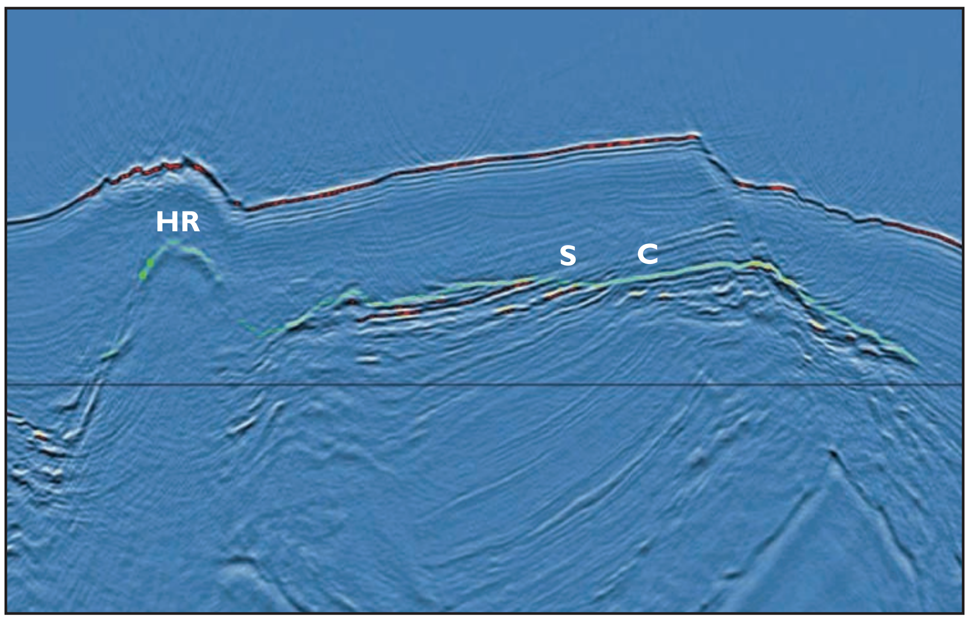
2B) *a Segmented "BSR" formed by the alignment along a sea-floor simulating horizon of anomalous seismic events including bright spots, terminations, and phase reversals. Data courtesy of WesternGeco.*

Department of Energy's gas hydrate JIP drilling program (see Hutchinson *et al*., 2008). This effort has accessed roughly 200,000 km^2 of industry 3-D seismic data to assess the occurrence of gas hydrate regionally throughout the Gulf. This study, which is still underway, has yielded an inventory of over 100 locations where geophysical indicators of BGHS exist. The unexpected frequency of such features lends support to the view that the Gulf may hold significant quantities of gas hydrate in the subsurface. We expect many more such features to be located as the work continues.

In keeping with previous work, we have segregated the observed seismic expressions of the base of gas hydrate stability among three end-member categories: *continuous BSRs. segmented "BSRs"*, and *high-relief "BSRs"*. Combination features that contain elements of these different types are also



2C) *a High-relief "BSR" (denoted by green line) which is not bottom-simulating and represents locations where the BGHS is perturbed by local variations in heat flow. Data courtesy of WesternGeco.*



2D) *a example where the BGHS shown a combination of High-relief (HR), segmented (S) and continuous (C) morphologies. Data courtesy of WesternGeco.*

observed. In Figure 1, we show the areal distribution of the various types of seismic features. As compared with other regions around the globe, these features are somewhat limited in extent in the Gulf of Mexico, with the average feature being 6,848 acres in size. In addition, the MMS's mapping shows that 81% of these features are located below the position of seafloor amplitude anomalies interpreted to be associated with hydrocarbon seeps. In Figure 2, we provide examples of each feature in seismic data.

Continuous BSRs (Figure 2A) represent 12% of the mapped features in the Gulf of Mexico. Continuous BSRs were most common over shallow diapiric salt structures (Figure 2A) and were less common within mini-basins. We interpret the general lack of continuous BSRs to be a reflection of the basin's complex stratigraphy and structure. Fluid and gas migration along preferred pathways (including both dipping high-permeability beds and fault conduits) has limited the extensive accumulation of gas in non-permeable units that would support the development of regional and continuous BSRs.

The most common expression of the BGHS in the Gulf are segmented "BSRs", accounting for 58% of the mapped features. Consistent with previous interpretations, these features are not unique reflectors, but instead appear as a series of clearly separated "bright" spots (indicators of free-gas accumulations) that, when connected, mimic the geometry of the seafloor (Figure 2B). These features are very common on the flanks and centers of mini-basins, and are interpreted to indicate where the BGHS cross-cuts a stratigraphic section consisting of interbedded sands and shales. The bright spots are inferred to correlate with sand-rich units and the intervening sections being more clay-rich. In addition, as first shown by McConnell and Zhang (*Fire in the Ice*, Fall 2005), the phase of the seismic response often appears to reverse as the units exhibiting the gas charge are traced across the inferred BGHS, suggesting that up-dip gas hydrate fill is responsible for the trapping of the free gas below. In many cases, the bright "gas" anomaly is also seen to dim out down-dip in accordance with structure, suggesting a potential gas-water contact (Figure 3). The inferred ability for the mapped horizon to segregate pore fluids (gas hydrate updip, water down-dip, and gas in between) is additional evidence that supports the sand-rich interpretation for these units.

High-relief "BSRs" (Figure 2C) account for 5% of the features and include both continuous and discontinuous features that are not bottom-simulating, but instead, rise close to the seafloor in the shape of a cone or plume. High-relief "BSRs" are interpreted to mark the BGHS in areas prone to laterally variable heat flow, especially near the flanks of salt, where vertically migrating gas, oil, and warm brine cause the hydrate stability zone to thin dramatically. Finally, roughly 25% of the mapped seismic features contain elements of two or more of the categories (Figure 2D).

The authors invite everyone interested in Gulf of Mexico gas hydrates to visit our poster at the AAPG Annual Meeting in Denver in June 2009.

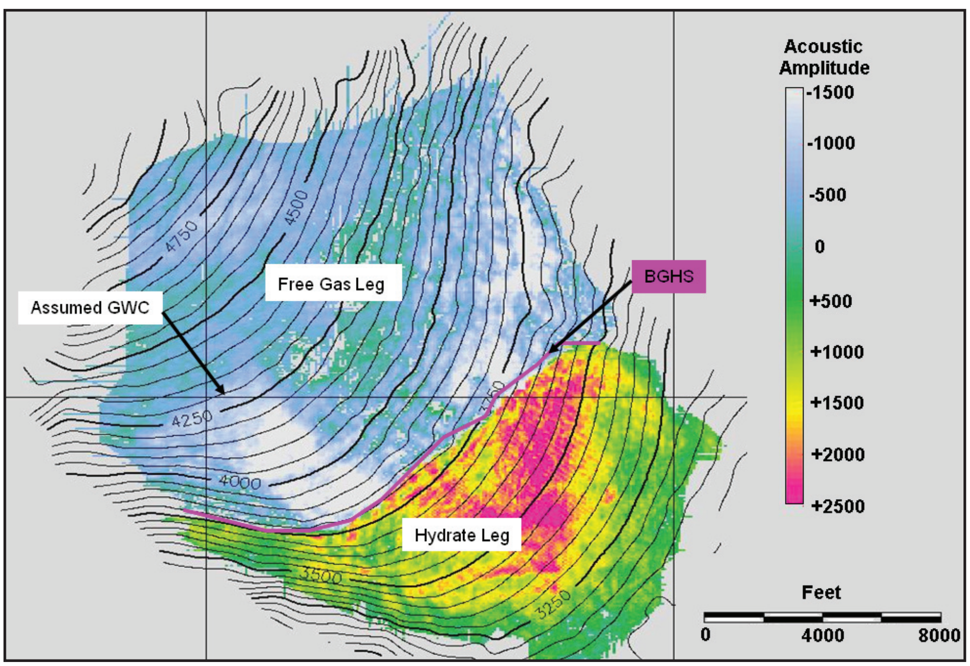


Figure 3: *Time structure map of a possible hydrate saturated sand and downdip gas leg. The phase reversal across the BSR is illustrated on the amplitude overlay. Note that the downdip termination of the high negative amplitude conforms to structure fairly well.*

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Gas Hydrate Investigation in Taiwan

By Yunshuen Wang (Central Geological Survey), Char-Shine Liu (National Taiwan University), and the Taiwan gas hydrate research team

Bottom simulating reflectors (BSR) were first identified in the early 90's from a set of six-channel seismic reflection data collected for the studies of the crustal structures of the subduction to arc-continent collision systems offshore southern Taiwan (Reed *et al*., 1991). A BSR distribution map was later compiled by Chi *et al*. (1998) that reveals widely distributed BSRs in the accretionary wedge offshore southern Taiwan. Liu (2002) examined seismic reflection data collected from eight different cruises in the area offshore southwestern Taiwan, and showed that well developed BSRs are densely distributed there. The BSR distribution maps compiled from these studies suggest that gas hydrate may widely be present beneath the sea floor south of Taiwan over an area of 20,000 km^2, extending from the passive margin of the South China Sea continental slope to the Luzon accretionary wedge, in water depths from 700 m to over 3500 m.

As a consequence, the Central Geological Survey of Taiwan started a four-year gas hydrate investigation program in 2004 to explore the potential of gas hydrate accumulations in the area offshore southwestern Taiwan. Marine geological, geophysical, and geochemical surveys have been carried out in an area over 10,000 km^2 offshore southwestern Taiwan between 118°40'E to 121°E and 21°20'N to 22°50'N (Figure 1). Various techniques have been employed for the gas hydrate investigation, including multi-channel seismic (MCS) reflection survey, chirp-sonar sub-bottom profiling, ocean bottom seismometer (OBS) observation, heat flow measurement, deep-towed camera imaging, and gravity and piston coring. Geological and geochemical analyses of bottom sea water and cored sediments have been performed. The objectives of this gas hydrate investigation program are: to map the regional gas hydrate distribution, and to understand the regional geological, geophysical, and geochemical characteristics. A gas hydrate database and information system, named Taiwan Gas Hydrate Data Base has

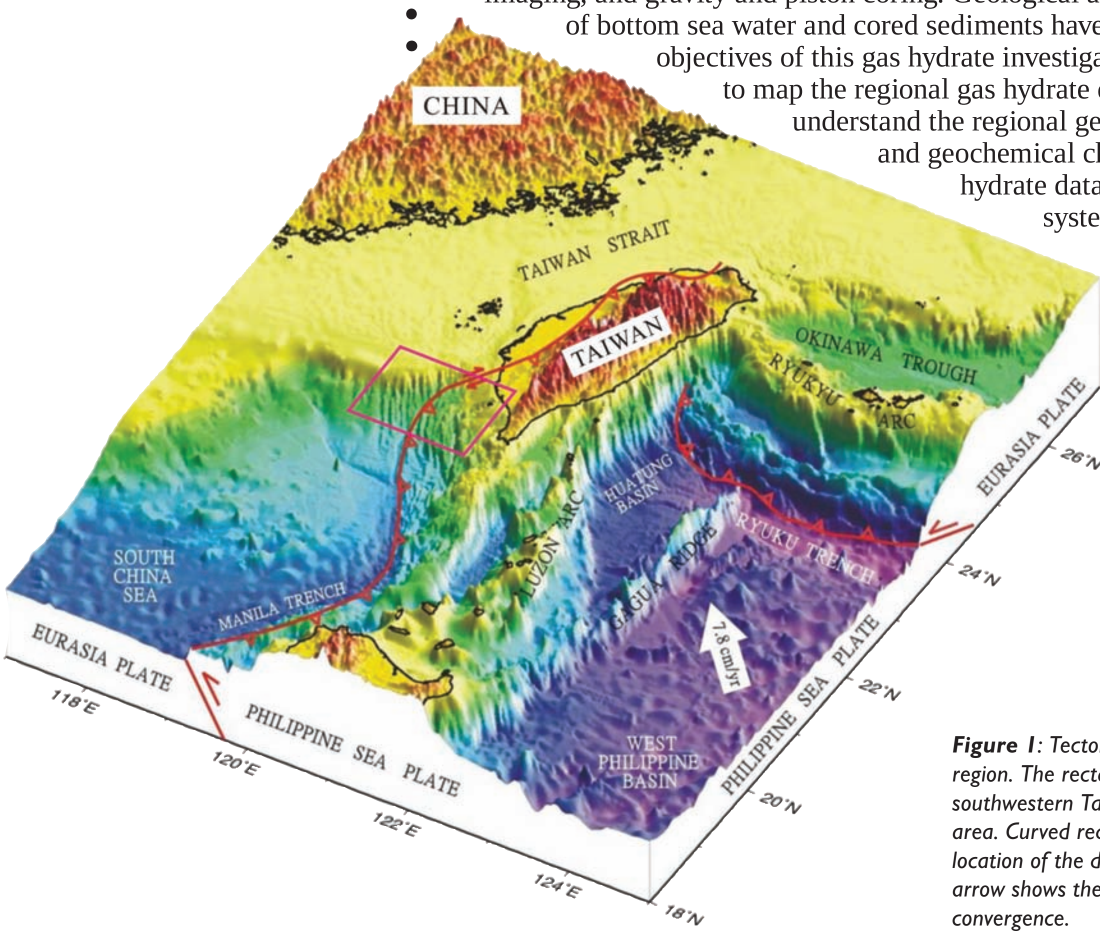

***Figure 1**: Tectonic framework of the Taiwan region. The rectangle in the offshore of southwestern Taiwan indicates the investigation area. Curved red line with teeth represents the location of the deformation front. The white arrow shows the direction and velocity of plate convergence.*

also been established to preserve the vast amount of data collected, and to facilitate their use.

Near 10,000 km of MCS reflection data were collected during this four-year gas hydrate investigation program period. From this data set, a new BSR distribution map has been compiled which suggests that gas hydrates are densely distributed in an area over 11,000 km^2, from the passive margin of the South China Sea continental slope to the submarine Taiwan accretionary wedge (Liu *et al*., 2006) (Figure 2). Velocity structures derived from pre-stack depth migration and from analyzing the wide-angle reflection and refraction data collected by the OBSs reveal that low velocity zones exist underneath BSRs, indicating the presence of free gases below the gas hydrate bearing layers. Submarine mud volcanoes and gassy sediments revealed from chirp sonar data are also widely distributed in both the accretionary wedge and the passive continental margin offshore southwestern Taiwan (Chiu *et al*., 2006).

More than 270 piston and gravity cores as well as approximately 60 water columns have been collected for the geological and geochemical analyses during the four-year investigation period. Results from geochemical analyses reveal extremely high methane concentration, a very shallow sulfate/methane interface, and the common occurrence of authigenic pyrite at many coring sites of the investigation area. Anaerobic methane oxidation is indicated by sulfate and methane depletion, hydrogen sulfide formation and an increase in alkalinity in the sediments. The deep-towed camera images illustrate fluids/gases venting from structures, chemosynthetic communities composed of bacteria mats and clams, as well as widespread authigenic carbonate on the seafloor. These features indicate that active fluid/gas vents have developed in the survey area. The formation of these vents could be the result of gas

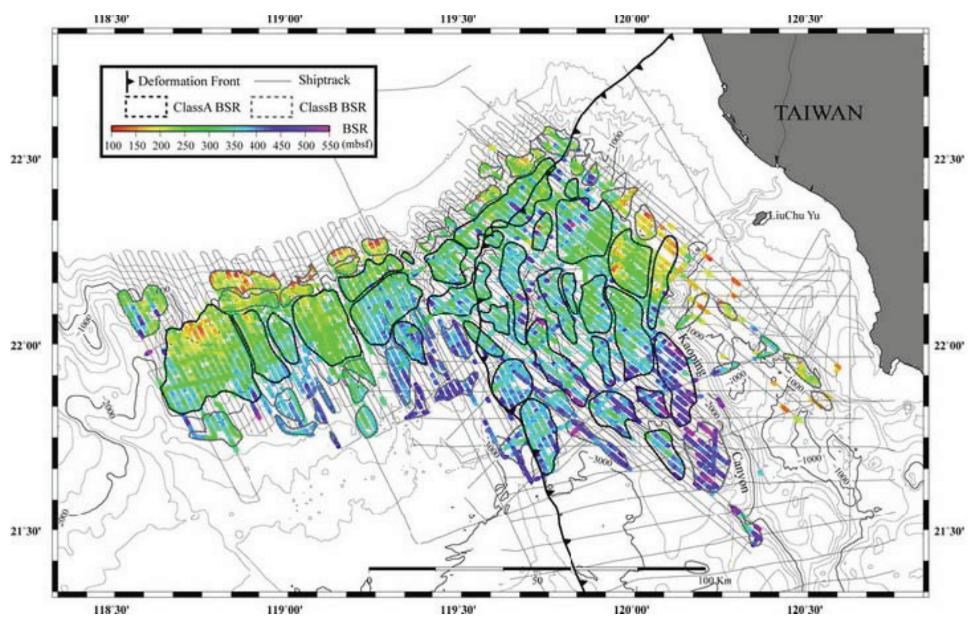

Figure 2: *BSR distribution grouped by the quality of BSR appearance. Class A: clear and prominent BSR; Class B: possible BSR. Color indicates BSR sub-bottom depth. Curved black line with teeth represents the location of the deformation front which separates the convergent accretionary wedge province to the east from the passive South China Sea continental margin province to the west.*

hydrate dissociation and the rising of high-pressure fluids/gases along faults. The deeply rooted thrust faults identified on seismic reflection profiles in the accretionary wedge may provide major pathways for fluid/gas migration. On the other hand, the vent sites observed on the slope ridges of the South China Sea continental margin may be related to fluid/gas migration through west-dipping passive margin strata and east-dipping normal faults (Lin *et al*., 2009).

Results from the first four years of gas hydrate investigation indicate that enormous amounts of gas hydrate should occur beneath the seafloor offshore southwestern Taiwan. The Central Geological Survey therefore started the second phase of the gas hydrate investigation program in 2008, scheduled to last for another four years. In this phase, gas hydrate prospects will be selected for high-resolution intensive surveys which include pseudo 3-D MCS and OBS surveys, dense heat flow measurements, swath bathymetry mapping, deep-towed side-scan sonar and chirp sonar surveys, deep-towed camera images, and ROV observations and sampling. More cored sediments, bottom water, chemosynthetic communities, and carbonate crusts at the selected gas hydrate prospects will be sampled and analyzed. The objectives of these investigations are: (1) to discover the active venting of fluids/gases and the exposure of gas hydrate at the sea floor; (2) to study the biogeochemical activity and the productivity of chemosynthetic communities at vent sites; (3) to investigate the gas origin, its transport mechanisms and migration pathways, as well as its incorporation in gas hydrate; and (4) to understand the spatial variations of BSR distribution and its relation to the local structures.

In 2008, 17 drill sites were selected from 13 potential prospects. A gas hydrate drilling proposal has been submitted to the Ministry of Economic Affairs of Taiwan to seek funds for a drilling expedition. A large-offset MCS reflection combined with OBS surveys will be conducted in spring 2009 using the R/V *Marcus Langseth* to investigate the deep structural framework and seismic characters of the hydrate-bearing strata in the area offshore southwestern Taiwan.

The field investigation and drilling data will be used: (1) to provide details of the reservoir structure, sediment stratigraphy and gas hydrate occurrence; (2) to develop a "gas hydrate" petroleum system model; and (3) to estimate the amount of gas hydrate and/or free gas in the sedimentary strata. These results will be integrated and used to assess the possibility of future gas hydrate exploration and exploitation. In addition to the field investigations, thermodynamic and kinetics of gas hydrate nucleation, growth, and decomposition will be simulated and modeled to provide insights into production technology. The area offshore southwestern Taiwan provides a unique opportunity to investigate characteristics of gas hydrate in both passive continental margin and active accretionary wedge settings.

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Improved Pressure Core Analysis Provides Detailed Look at Korean Cores

By K.P. Park, J.J. Bahk, M. Holland, T.S. Yun, P.J. Schultheiss, and C. Santamarina

The first Korean drilling expedition took place on the R/V *REM Etive* in the fall of 2007, led by the Korean Gas Hydrate Development Organization. It was designed to investigate the gas hydrate resource potential of sites in the Ulleung Basin, East Sea (see *Fire in the Ice*, Spring 2008). As part of the coring program, 15 cores were recovered under pressure using the Fugro pressure coring tools and analyzed at sea. The onboard pressure core analysis included routine core measurement in the Geotek Pressure Multi-Sensor Core Logger (MSCL-P). The MSCL-P provided continuous profiles of *P*-wave velocity and gamma density at *in situ* pressure and temperature conditions, as well as providing high-resolution 2-D X-ray images, including rotational series. The shipboard MSCL-P data showed that a number of cores contained a dense network of gas hydrate veins. These cores were not depressurized onboard, but instead were transferred under pressure to HYACINTH storage chambers and saved for detailed post-cruise analysis.

In January, 2008, a team of scientists from KIGAM (Korea Institute of Geoscience and Mineral Resources) and Geotek transported the eight saved pressure cores to Sun General Hospital in Daejeon, Korea, where X-ray computed tomography (CT) scans were performed on the cores through the aluminum storage chambers. These scans confirmed the MSCL-P data, showing a complex fracture structure within the sediment that was filled with gas hydrate. Using this information, further testing locations were chosen inside cores relative to the sedimentological and gas hydrate structures. These specific locations would be tested using the Instrumented Pressure Testing Chamber (IPTC), using direct-contact probes to measure *P*-wave velocity, *S*-wave velocity, electrical resistivity, and strength.

In February, 2008, the IPTC team, made up of Tae Sup Yun (Lehigh Univ.), Jong-Sub Lee and Changho Lee (Korea University), and Carlos Santamarina (Ga. Tech.), joined the KIGAM and Geotek teams at KIGAM in Daejeon, where the Pressure Core Analysis and Transfer System (PCATS) had been mobilized. Seven cores were individually transferred from their storage

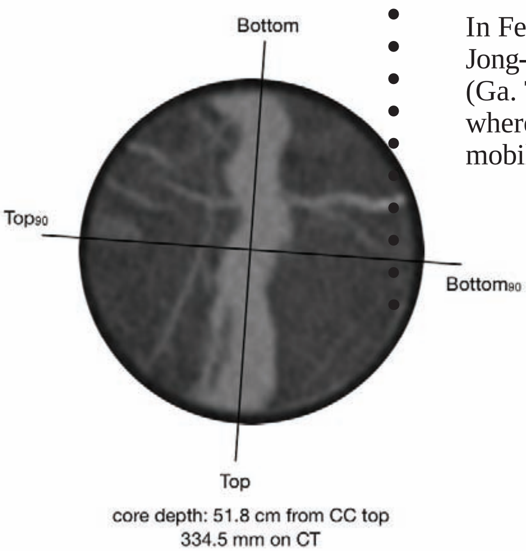


Figure 2: *Horizontal slice through one of the pressure cores showing two locations where IPTC measurements were made. Hydrate veins are white; clay sediments are dark.*

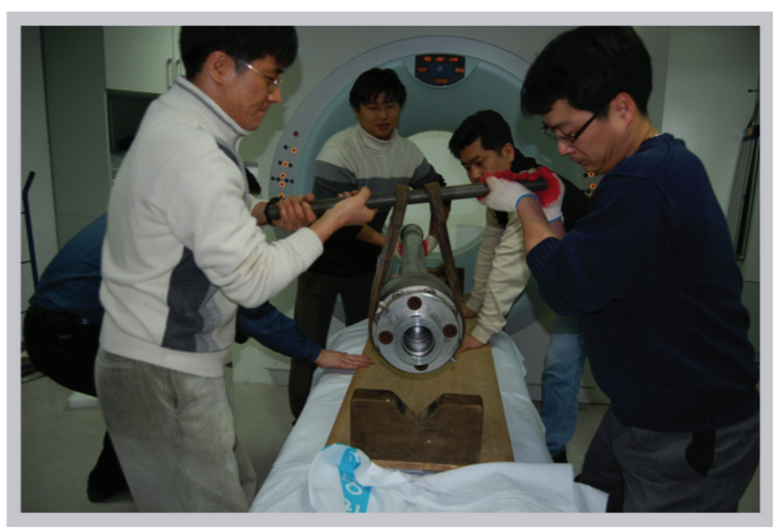


Figure 1: *Scientists from KIGAM load a pressure core in a storage chamber onto the bed of the X-ray CT machine in Daejeon, Korea.*

chambers back into the PCATS with the IPTC connected. The combined translational and rotational precision of the PCATS and the radial precision of the IPTC allowed probes to be inserted into the cores with millimeter accuracy. Some cores were re-tested at varying angles to understand the anisotropic nature of the hydrate fractures. After testing, the cores were X-rayed again in the MSCL-P to double-check the exact position of the probes relative to the gas hydrate features. All transfers and measurements were conducted under pressure and at low temperature so that cores remained within the gas hydrate stability field. The preliminary data indicated that physical properties varied on a sub-centimeter-scale in these pressure cores containing thin hydrate veins.

Mini-production tests were run on five of the cores after the full-pressure suite of measurements was completed. The mass balance measurements from the pressure cores were required to complete the methane concentration data set gathered during the cruise. During the controlled release of pressure, gases were collected, measured, and sampled for later compositional analysis; from these depressurization experiments, we conclude that the hydrate saturation varied between 11% and 27% in the tested cores. IPTC measurements made during the pressure release monitored the properties of the sediment as the gas hydrate dissociated. Properties measured included: *P*-wave velocity (clearest indicator of free gas formation), *S*-wave velocity (best way to assess the evolution of the sediment stiffness, even after

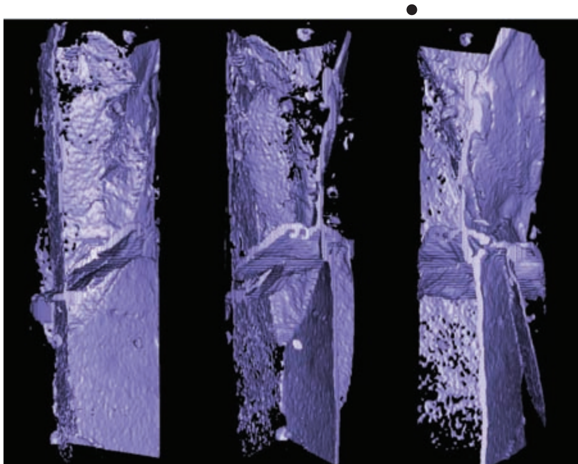


Figure 3: *A three-dimensional reconstruction of a short section of core. Sediment is transparent, gas hydrate is blue. Hydrate veins in the pressure cores were generally subvertical, but at varied orientations.*

Figure 4: *Carlos Santamarina and Tae Sup Yun making measurements on a pressure core using the IPTC.*

dissociation), electrical conductivity (determined by the volumetric fraction of unfrozen water and ionic concentration), and temperature.

Extensive laboratory characterization studies after depressurization, conducted by J.S. Lee and co-workers at Korea University, provided valuable sediment data including index properties, SEM microphotographs, compressibility and effective stress dependent shear wave velocity and complex permittivity. SEM images highlight the diatomaceous nature of these sediments, i.e., they are clay-size but are not made of clay minerals.

Some of the cores were preserved for further gas hydrate studies. Two of the cores that were tested were rapidly depressurized and portions stored in liquid nitrogen for further testing. In addition, the most lavishly-veined core was not tested invasively and remains stored under pressure, awaiting equipment to be designed for further pressurized analyses. These post cruise measurements, made using the combined capability of the PCATS and IPTC, are the most detailed measurements made on natural gas hydrate in pristine condition to date. They illustrate how, with appropriate planning and the correct equipment, sophisticated measurements can be made on seabed samples without ever releasing the *in situ* pressure and hence with the minimum of disturbance. Together, borehole logging, pressure core characterization, monitored mini-production studies, and detailed, post de-pressurization sediment characterization gave us unprecedented information related to this hydrate-bearing formation.

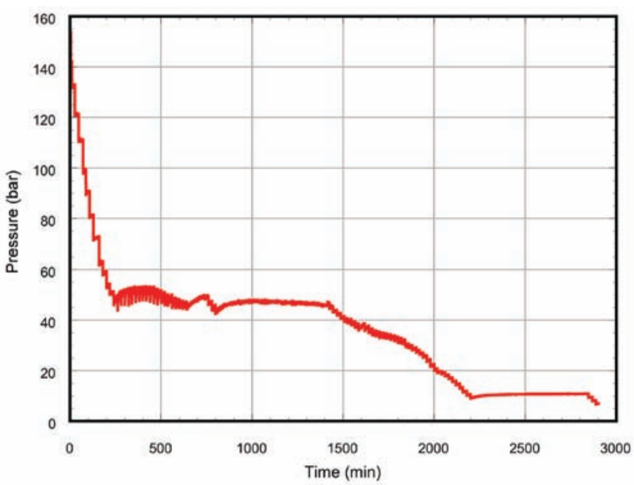


Figure 5: *Depressurization curve for a core showing extended pressure "plateau" at hydrate stability boundary.*

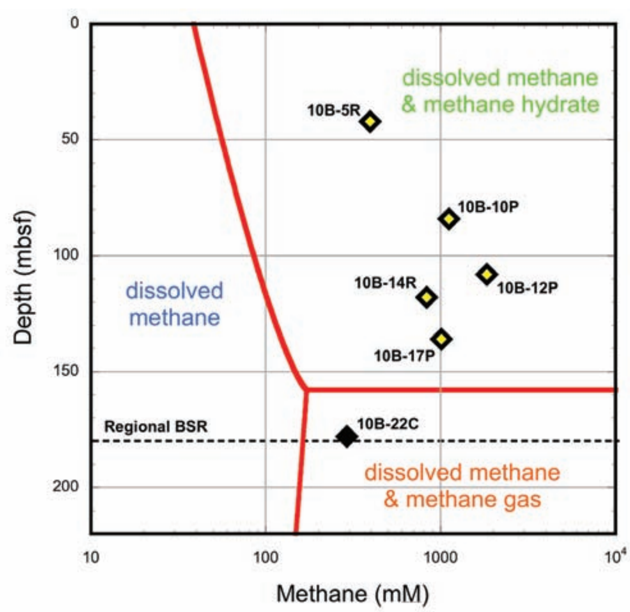


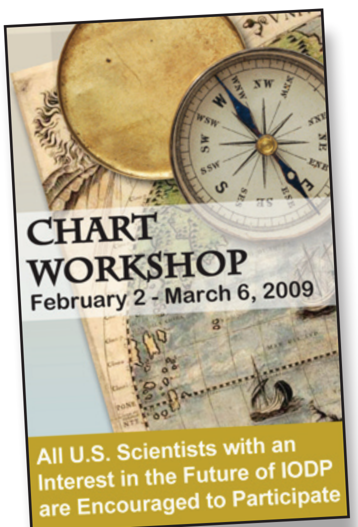
Figure 6: *Methane concentration at a site in the Ulleung Basin, where gas hydrate was present as veins. Yellow diamonds indicate that IPTC measurements were made during depressurization.*

Upcoming Meetings: AAPG and ACS

The AAPG Annual Convention and Exhibition will be held June 7th through 10th in Denver, Colorado at the Colorado Convention Center. The convention offers a varied course program that seeks to address the challenges presented by both conventional and unconventional sources of energy. For more information and to register, please visit http://www.aapg.org/denver/index.cfm.

The ACS National Meeting and Exposition will be held March 22nd through 26th in Salt Lake City, Utah. Programming is planned by 34 technical divisions that cover all scientific fields and will feature over 7200 presentations featuring important research advance organized by technical division. For more information and to register, please visit www.acs.org.

Charting the Future Course of Scientific Ocean Drilling



Do you want to influence the research priorities of the Integrated Ocean Drilling Program? Have you used IODP, ODP, or DSDP data or samples in your research? Does your science benefit from data collected through scientific ocean drilling?

Planning is underway for the next phase of the Integrated Ocean Drilling Program and your input is needed for its success. If you are a U.S. scientist interested in the future of IODP, we invite you to participate in the online workshop Charting the Future Course of Scientific Ocean Drilling (CHART). CHART is an important opportunity for the U.S. community to organize its science priorities and goals. The resulting white paper will be a key part of the IODP renewal process and will foster planning at the international INVEST Workshop. Your input and support will help ensure that we retain access to ocean drilling technology for producing transformative, world-class science.

Mark your calendar for this key meeting and plan to participate starting February 2, 2009. Registration is free and open to all U.S. scientists.

Contribute Online: February 2 - March 6, 2009
http://www.oceanleadership.org/chart

National Research Council Announces Public Meeting

The National Research Council will hold a public meeting as part of their "Assessment of the Department of Energy's Methane Hydrate Research and Development Program" on March 6-7, 2009 in Washington, D.C.

The assessment is a formal review of the progress made under the methane hydrate research and development program and will make recommendations for future methane hydrate research and development needs as part of the Energy Policy Act of 2005, Section 968.

Meetings will be held at the Keck Center located at 500 5th Street, NW. To register to attend or to obtain more information about the meetings, please contact Nicholas Rogers at nrogers@nas.edu.

Perkins Research Conference Set for Houston in 2009

Unconventional energy resources will be the focus of the 29th annual Bob F. Perkins Research Conference to take place on December 6-9, 2009. The aim of the conference is to discuss the geosciences involved in the discovery and economic production of unconventional resources within the framework of social and environmental responsibility.

This conference is sponsored jointly by the Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists (GCSSEPM) and the Energy Minerals Division of the American Association of Petroleum Geologists (AAPG). For more information on the conference, please visit www.gcssepm.org.

KELLY ROSE

Geologist, Research Lead

Methane Hydrates Field Studies Laboratory

National Energy Technology Laboratory

In her off time, Kelly and her husband Joe can be found immersed in the renovation of their 100-year old house with "much character and a multitude of….challenges" on two acres in Morgantown, West Virginia. In addition, Kelly enjoys the wealth of local live music including NPR's *Mountain Stage*, reading, hiking, kayaking, and traveling. "With good friends and family all across the country, there is always someplace to go and something new to experience."

Kelly Rose – A Stratigraphy of Experiences

We all have someone in our past that had a hand in shaping our future. National Energy Technology Laboratory (NETL) geologist Kelly Rose credits two grade school teachers from her days in East Lansing, Michigan for promoting her fascination with earth science to be something more than a passing interest, eventually leading her to ports of call around the world and furthering her knowledge of methane hydrate bearing geologic systems. "I had a rock collection from the time I was old enough to walk," says Rose, however, it was encouragement from her 5th and 6th grade teachers, Mr. Harner and Mr. Letwin that formally sparked her interest in natural sciences. Mr. Harner spent much of the year teaching in-depth ornithology, ichthyology, botany, and geology," says Kelly. "In 6th grade Mr. Letwin introduced me to an earth science laboratory, and yes, there were hand lenses and rock hammers. Their passion for these subjects went beyond the norm, was inspiring, and is something that has stuck with me."

"By the time I finished High School I was probably one of the only kids at East Lansing High School who knew I was walking on a glacial esker to get to and from school. So while Michigan is fairly devoid of rock outcrops, the geomorphology and geologic history of the region always interested me," says Rose. As a result, when Rose arrived at Denison University in Granville, Ohio in 1992 she had already declared as a Geology major. Rose completed a summer research project examining loess deposits in central Ohio, and a senior research thesis focused on the evaluation of the Blue Ridge Province in North Carolina. She received her degree in Geology in 1996 and completed her Masters thesis in Structural Geology at Virginia Tech in Blacksburg, Virginia in 1999.

Upon graduation, Kelly worked as an exploration geologist for Marathon Oil Company in Wyoming, Oklahoma, and Texas, focusing on the geologic evaluation of tight gas accumulations in deep continental basins such as the Greater Green River and Anadarko Basins. In 2001 she joined NETL's site support research team, led by Ray Boswell, where she applied her past experience to the assessment of tight gas resources in Western U.S. basins. Throughout her career Kelly has pursued opportunities to grow and develop her geologic capabilities, with an increasing focus on the evaluation of geologic controls on natural gas accumulations, ranging from the microscopic to the regional scales. She is currently the research lead for DOE-NETL's Methane Hydrates Field Studies Laboratory.

In 2006, Joel Johnson at the University of New Hampshire and Tim Collett with the USGS, helped turn her attention towards methane hydrates related studies. Starting with India's NGHP Expedition 01 in 2006, Kelly served as a shipboard sedimentologist, an experience that then led to her serving in the same position during Korea's UBGH-01 and Canada's 2008 Cascadia margin expeditions. She also participated in methane hydrate related research expeditions in the waters off of China and the United States. In February 2007 she assisted with core processing for the BP-DOE hydrates stratigraphic test and research well on the North Slope of Alaska, and has since completed the lithostratigraphic description of those cores.

From the tropical climes of the Bay of Bengal to the freezing tundra of the North Slope, Kelly has had the opportunity to work with individuals with a variety of backgrounds and expertise which she finds to be very rewarding. "I have enjoyed working with and learning from the researchers and people in the hydrates R&D community. They are diverse and dynamic."

NETL