Gas-Hydrate Observatories Workshop (GHOBS)

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Workshop organizing committee:

Marta Torres, Anne Trehu (Oregon State University)

Michael Riedel (McGill University)

Charlie Paull (Monterey Bay Research Institution)

Earl Davis (Geological Survey of Canada)

Sponsored by:

Consortium for Ocean Leadership

(Formerly Joint Oceanographic Institutions)

Department of Energy

National Energy Technology Laboratory

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EXECUTIVE SUMMARY

The development of seafloor gas hydrate observatories will enable direct measurements of geological processes as they occur and promise to revolutionize how Earth science is done. The proposed observatories go beyond traditional expeditionary science by taking advantage of both existing infrastructure and new technologies that allow a sustained presence to monitor and measure processes through time as they happen on and beneath the seafloor. Gas hydrates are prime targets for seafloor observatories because they are not static deposits, but continually change at rates that allow their evolution to be tracked on time scales that range from less than a second to more than a decade. Observatories focused on gas hydrate bearing sites will provide data critical for: 1) determining the factors influencing subsurface fluid flow and how this flow relates to stabilization/destabilization of gas hydrates; 2) studying the effects of microbial activity on gas hydrate processes; 3) gaining a better understanding of the role of hydrates in the global carbon cycle and their potential as an energy resource; and 4) exploring the effects of gas hydrate formation/destabilization on slope stability. In addition, a gas hydrate observatory will be a test bed for new technologies that will accelerate the development of new instruments and experiments to be used in a variety of other observatory settings.

The goal of this workshop, funded by the Consortium for Ocean Leadership (formerly Joint Oceanographic Institutions) and the Department of Energy (DoE) National Energy Technology Laboratory, was to define the scientific issues and challenges associated with conducting sustained, multi-disciplinary, in situ observations of marine gas hydrates. To achieve this, 75 scientists and engineers met in Portland, Oregon from July 18-20, 2007 to discuss strategies for borehole, seafloor and water column observatory-based experiments that can be implemented in the next several years and to develop guidelines for moving forward with these efforts.

The workshop included several invited presentations to provide background for scientific and technical discussions, contributed posters, working group discussions, and plenary sessions. All of the working groups agreed that the first phase of gas hydrate observatory development should be focused on sites of well-documented, active flow where the dynamics of the seafloor and subseafloor gas hydrate and free gas system are known to vary over spatial (lateral and vertical) and temporal scales that are measurable with currently available observatory technology. Discussions therefore focused on sites of active fluid flow in the Cascadia margin and the Gulf of Mexico, which have been extensively investigated during the last decade. At these sites, the amount of gas hydrate present and the pathways along which hydrocarbons migrate are well characterized, and there are good working hypotheses for gas hydrate dynamics that can be tested with seafloor and borehole observatories.

Although the ultimate goal is an integrated borehole-to-seafloor observatory, a staged approach is necessary to understand perturbations introduced by each of the observatory components. In general, installation of an observatory involves at least two phases: an observational phase to determine the ***natural baseline*** for the system and its response to various natural forcings (e.g., co-seismic strain events, tidal loading, current-induced temperature variations, etc.) and an experimental phase, when ***man-made perturbations*** are applied to the system. While some observations can be made with ***buoyed observatories***, others will require ***cabled ocean observatory technology*** to satisfy high power and/or bandwidth requirements (e.g. fluid pumping; heating of the system to avoid hydrate formation during fluid sampling or to perturb the hydrates; operation of downhole seismic and/or electromagnetic sources; high data rates; multi-year deployments needed to capture the various time scales operating in this system; and the need for real-time intervention to capture infrequent events or otherwise change experiment parameters). Similarly, while some observations can be made with ***seafloor and shallow sub-seafloor installations***, others will require ***deep boreholes***.

Some of the tools and sensors needed to adequately monitor combined tectonic, oceanographic and biological feedback mechanisms are available for deployment with little or no additional development (e.g., seafloor photography, seafloor flow meters, pressure sensors, broadband and short period seismometers, Doppler current meters, multifrequency acoustic backscatter bubble monitors). Others (such as reliable methane sensors for concentration and phase partitioning) require technical development to operate in a gas hydrate environment. We envision that viable seafloor observatories will be installed in the next several years using available technology, with provisions made for future expansion as additional instrumentation is developed. Recommended high-priority, near-term engineering developments include: 1) improvement in reliability and stability of sensors; 2) development of methods for in situ sensor recalibration; 3) development of instrumentation for long-term measurement of critical parameters in a borehole, specifically temperature, pressure, salinity, sediment resistivity, seismic sensors in the kHz range and methane concentration and speciation (gas, solution and hydrate phase). Some of the technologies associated with borehole implementation have been specifically addressed by the IODP Engineering Development Panel (EDP) as long term (3-5 years) objectives (www.iodp.org/eng).

As instrumentation is developed, tools and sensors need to be standardized so that any particular instrument can be used at a variety of sites and in different subsurface installations. Furthermore, as data acquisition is initiated there needs to be an efficient mechanism for data-handling, versatile database design, and coordination to facilitate collaborative use of the observatory installations and ancillary experiments.

Because of the relevance of this research to issues of societal interest, a gas hydrate observatory will provide numerous opportunities for education (both formal and informal) and outreach activities. Methane hydrates capture the attention of the public because of their potential as a significant future fossil fuel resource. The potential for massive landslides on the seafloor due directly to hydrate instability, and the resultant rapid release of methane to the sea surface and possibly the atmosphere are also dramatic implications of gas hydrate research that capture the public interest. A web-based window onto the seafloor will enable a variety of educational activities, ranging from live links to use of archived video and data as teaching tools.

WORKSHOP REPORT

1. INTRODUCTION

Climatic, oceanographic and tectonic processes affect gas hydrate stability conditions, resulting in seafloor and subseafloor environments that change rapidly on geologically short time scales. The dynamics of these changes can be understood through real-time monitoring of in situ conditions on and beneath the seafloor made possible by recent advances in technology. These technologies will allow Earth science to shift from making static measurements on samples and/or data collected on discreet expeditions to making continuous, in situ measurements of the processes as they happen. Because gas hydrate systems are so sensitive to subtle changes in environmental parameters, they are among the best places to track on-going changes in a natural marine setting.

Several plans for the development of gas hydrate observatories already exist and are in various stages of implementation. These include borehole and seafloor programs at several sites on the Cascadia accretionary complex and in the Gulf of Mexico. As these various efforts are developing simultaneously, it is important that a concerted effort be made to coordinate the various complementary programs within a coherent framework.

This workshop on gas hydrate observatories resulted from the immediate need to develop specific plans and strategies for the deployment of borehole and seafloor instrumentation to characterize the dynamics of gas-hydrate-bearing environments. The workshop was held in Portland, Oregon from July 18-20, 2007.

2. WORKSHOP ORGANIZATION

Prior to the workshop, all participants received a CD with a number of background documents. The workshop began with an evening poster session/registration/reception followed on the next morning by two sets of invited talks. Talks focused on scientific questions associated with gas hydrates and/or time-series observations in hydrologically dynamic submarine settings and on technological issues associated with borehole observatories, and were intended to provide background information to inform discussions conducted in smaller groups. Most of the workshop consisted of discussions by working groups focused on 5 themes: sites characterization, in situ physical properties, fluxes in boreholes, seafloor and water column observations, and opportunities for education and outreach. Group discussions were summarized in plenary sessions at two stages of the workshop. This report was constructed from working group reports prepared by the chairs of each working group and from notes taken by the organizing committee during plenary sessions. The meeting agenda, including listings of the working-group chairs, is included as Appendix 1. Additional information is listed in Appendix 2.

3. SCIENCE RATIONALE

WHAT IS AN OBSERVATORY?

An observatory is a sustained presence in the seafloor to and from which power and data are transmitted in real time through either buoys or cables to scientists on shore. Seafloor observatories harness the promise of emerging power and communication technologies to provide a remote, continuous, long-term, high-power, large-bandwidth infrastructure for multidisciplinary, *in situ* exploration, observation, and experimentation in gas hydrate settings.

An overarching goal of establishing observatories in a marine setting that includes gas hydrates is to unravel the interrelationships among tectonic, oceanographic and biologic processes in a complex hydrologic system in which gas hydrates constitute an important component of the carbon reservoir and dynamically affect the properties of the system. Questions involving gas hydrate interaction with the biosphere include the interaction of organisms on gas hydrates and associated element fluxes; the interactive role of external forcing (by carbon input) on biological processes; and the interactions of microbes and animals within and outside gas hydrate-supported systems.

Major gas hydrate research programs are currently underway in the US (DoE) and elsewhere to evaluate whether gas hydrates can be tapped as a rich natural gas resource. Although estimates of the total amount of methane currently stored in submarine gas hydrates varies over several orders of magnitude, depending on what assumptions are made, all estimates are large. Resource estimates hinge on our capability to resolve uncertainties in regional and local gas hydrate concentration, in the response of hydrate-bearing marine sediments to perturbations in temperature and pressure, and on the impact of gas hydrates on sediment permeability and fluid flow.

Numerous laboratory and field studies, including several drilling expeditions in the last decade, have provided critical data on the stability of gas hydrates and on the composition and distribution of these deposits in nature. These results have sparked the development of models and hypotheses pertaining to the mechanisms that control the transfer of methane from deep sources to and through the gas hydrate stability zone (GHSZ); the role of gas hydrates on slope stability; and the impact of this system on biological processes. Together these efforts have made it clear that geologically rapid processes are continuously modifying gas hydrate-bearing sedimentary sections, and thus these deposits are not static, but rather part of dynamic and changing systems. Because of the dynamic nature of the processes at play, many first order questions in gas hydrate research can only be addressed with observatory science.

WHY ARE GAS HYDRATE OBSERVATORIES NEEDED?

To characterize and test existing models of system evolution and its response to transient internal and external forcing, it is essential that we monitor and measure processes as they happen. This requires a sustained presence on the seafloor to:

1) **Establish the dominant processes (oceanographic, tectonic, biological) that drive and modulate methane dynamics within and below the gas hydrate stability zone;**
2) **Evaluate the structural and sediment property controls for fluid and gas flow, and establish how the rates are affected by changes in hydrological parameters triggered by oceanographic, tectonic and diagenetic processes;**
3) **Determine how these controls and modulations are transferred and manifested at the seafloor and how the biosphere perturbs and responds to changes in the chemical composition of the fluid;**
4) **Establish the fate of the hydrate methane in the water column and potential transfer to the atmosphere.**
5) **Stimulate engineering and technology developments that will make it possible and practical to conduct sophisticated experiments in situ on and within the seafloor**

3.1 Carbon Cycling.

- What are the ***fluxes of material*** into and out of the hydrate system over a wide range of timescales? What is the relative significance of dissolved and gas phase transport of methane within the sediment? How do solid hydrate rafting, bubble transport, and dissolved phases (advection or diffusion) contribute to the flux of carbon into and out of the system?

- What ***natural forcing functions*** perturb gas hydrate systems? What is the role of temperature transients driven by tides, season, interannual variations, and global change? What is the significance of pressure change on hydrate stability and methane fluxes related to winter storms, pressure pulses created by bottom currents interacting with topography, geostrophic variations and sea level rise? What role do tectonic forces and loads induced from co-seismic strain have in driving methane fluxes within the sediment?

- What controls ***free gas dynamics, its transport through the sediment and water column and transport of methane through the ocean into the atmosphere***? Obtaining a full understanding of the mobility of free gas beneath the hydrate stability zone and the mechanisms for its migration into and through the stability zone is important. What fraction of this free gas is trapped in new hydrate within the stability zone and how much escapes at the seafloor? What processes may trigger discharge of the trapped methane into the water column? What is the fate of hydrate methane dissolved in the water column? Does significant methane arrive to the atmospheric from gas hydrate sources?

3. 2. Biological Systems:

- How do the variations in ***rates and composition of migrating fluids affect the biological community structure***? Do temporal variation in fluid flux influence the biosphere activity, and does the system variability affect the rates of microbial processes associated with methane generation and consumption?

- What are the ***interactions*** (competition/facilitation/succession) ***between seafloor biota and microbes*** in hydrate-bearing sediments and what forms of exchange occur between hydrate-associated biological communities and the background continental margin assemblages (migrations, predator-prey interactions, humans, fishing)?

3. 3 Energy and geohazards

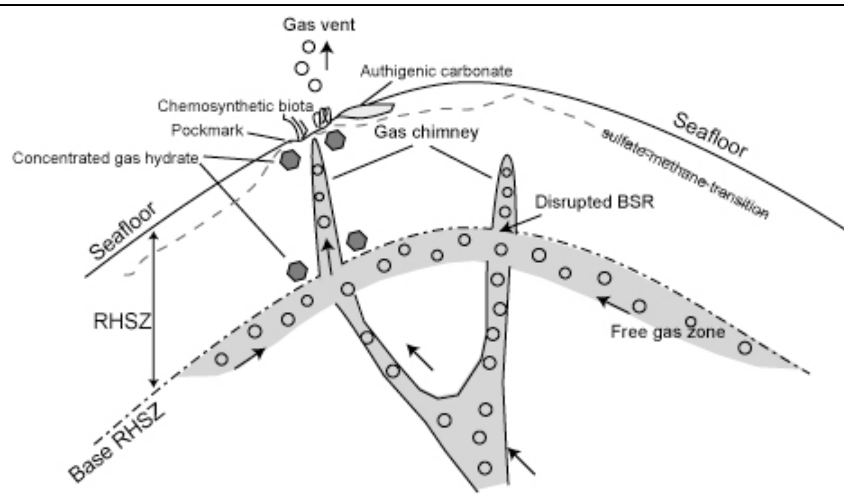
- At what ***rate is gas hydrate being formed***? How fast will a gas hydrate field be replenished if the gas is produced?

- What ***impact*** does intentional dissociation of gas hydrate have on sediment ***properties***? Can gas production lead to uncontrolled gas hydrate dissociation and potential slope instability, resulting in hazards to offshore structures, submarine landslides and possibly causing tsunamis?

- How do ***boreholes through gas hydrate deposits*** affect the gas hydrates? Do these effects represent a hazard to existing and future hydrocarbon production infrastructure?

4. CHARACTERISCTICS OF CANDIDATE SITES FOR GAS HYDRATE OBSERVATIONS

The consensus of workshop participants was that first-generation installations of gas hydrate observatories should target gas hydrate deposits associated with active seafloor seeps. Key parameters that must be constrained at candidate observatory sites include: 1) the horizontal distance and depth ranges over which characterization measurements must be made to understand the system; and 2) the timescales over which parameters must be measured to fully characterize the most important signals and their variability.



Schematic illustration of an active methane seep.

This schematic shows features that commonly characterize seeps at the seafloor, within the gas hydrate stability zone, and within the free gas zone. The regional hydrate stability zone (RHSZ) is perturbed, fluid and gas flows toward the seafloor are enhanced, and gas hydrate typically reaches concentrations much higher than in the surrounding sediment. Changes in the hydrogeologic system that controls the distribution of free gas and gas hydrate occur on time scales short enough to be detectable by observatory instrumentation. Figure modified from Liu and Flemings (Journal of Geophysical Research, v. 112, doi:10.1029/2005JB004227, 2007).

The overall vision of such an observatory encompasses ~1 km2 of seafloor within which are embedded one or more sectors of interest. Experience with various seafloor seep settings suggests that 1 km2 is a large enough area to contain the environmental heterogeneity needed to address the major science questions, yet it is small enough to be covered by routine high-resolution surveys using seafloor and sea-surface vessels.

Sectors of interest at the seafloor will include one or several of the following environmental features (Figure 1), which in some cases may occur within a very small footprint (10's to100's of meters): 1) an active seep emitting methane gas bubbles; 2) a seafloor exposure/outcrop of a hydrate; 3) a methane-derived carbonate outcrops; 4) various biological communities including, but not limited to, bacterial mat, tube-worm, and bivalve dominated settings. Sectors of interest in the subsurface include potential transfer zone(s) and pathways for hydrocarbon migration (fractures, high permeability horizons) that feed active seeps on the seafloor and that can be

WHERE SHOULD THE OBSERVATORY BE LOCATED?

First generation gas hydrate observatories should be located on gas hydrate deposits associated with active seeps. Locations for which there is a good existing knowledge base include several sites on the Cascadia Margin (Hydrate Ridge, Barkley Canyon, Bulls Eye vent) and in the Gulf of Mexico (Bush Hill, Green Canyon). At these locations the dynamics of the subseafloor gas hydrate and free gas system vary over spatial (lateral and vertical) and temporal (seconds to decades) scales that enable detection of perturbations with currently available observatory technology.

Intensive efforts over the last decades have been dedicated to mapping these systems in three dimensions. These studies have generated a well-developed understanding of specific properties of each region, including gas hydrate concentration and distribution, the sub-hydrate free-gas migration "plumbing" system, and the nature of the methane discharge at the seafloor. These have been discussed in a number of documents, and summary reports can be found at:

Leg 204 Synthesis: Gas Hydrate Distribution and Dynamics in the Central Cascadia Accretionary Complex (Trehu et al., 2006;

http://www-odp.tamu.edu/publications/204_SR/synth/synth.htm)

Leg 311: Cascadia Margin Gas Hydrates (Riedel et al. 2006; (http://publications.iodp.org/proceedings/311/311title.htm)

Gulf of Mexico Gas Hydrates Seafloor Observatory Project (http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/projects/DOEProjects/GOMMon-40920.html)

intersected by boreholes. Seeps may also be characterized by the coexistence of free gas with gas hydrate and high salinity pore fluids within the nominal regional gas hydrate stability zone. Acoustically-transparent sediments charged with free gas often occur in so-called gas "chimneys," which can stretch from beneath the seep downward beneath the regional bottom of gas hydrate stability.

STRATEGIES FOR IMPLEMENTING A GAS HYDRATE OBSERVATORY

Several essential tools could be deployed on the *seafloor* with little new technical development needed. Broadband seismometers, temperature and pressure sensors, cameras, and osmotic fluid flow meters are likely candidates to characterize fluid flow rates and methane distribution and transport mechanisms, monitor oceanographic and tectonic forcing factors, and document the impact on the local and regional biosphere. Higher-frequency observations by a variety of sensors are site- and science-dependent. Measurement time scales range from days or hours for visual observations down to milliseconds for acoustic and seismic observations. Several efforts are underway (OOI, Neptune Canada, DoE) to independently initiate the acquisition and deployment of basic seafloor facilities.

The first generation of instruments to monitor the subseafloor in a *borehole* is likely to be a self-sealing instrumented array with temperature, pressure and resistivity sensors. While there are proposals submitted for the development of these tools (S-CORK, SCIMPI), funds have not yet been secured. Further engineering guidelines for borehole needs in the next 3 to 5 years are detailed in the latest IODP Engineering Development Panel (EDP) technology roadmap (www.iodp.org/eng).

Cabled installations will provide an unmatched potential to conduct controlled *perturbations* of P, T and chemical conditions and monitoring the system response, which will generate key data (e.g. hydrate formation rates) that cannot be obtained by passive monitoring. *Cross-hole experiments* (e.g. seismic tomography, tracer injection) supported by power and communication resources will aid our understanding of the system hydrology and its response to regional forcing and artificial perturbations.

There are several examples of well-characterized sites that may be suitable for a hydrate observatory worldwide; however, in order to make progress describing experiments and instrumentation, the model observatories described here represent our vision for installations on the Cascadia margin or in the Gulf of Mexico. These locations are all excellent candidates for the emplacement of an observatory; however, no consideration was given to the timing of opportunities at each specific site, as these are variable and not the charge of this workshop.

Although active seeps represent the prime target for initial observatory efforts considered at this workshop, gas hydrate systems within hydrocarbon basins, low-flux end-members and in the Arctic, provide unique insight into natural gas hydrate systems and their response to natural or imposed perturbations. For example, while seafloor observatories on the Cascadia margin or in the Gulf of Mexico will be subjected to short-term temperature changes due to currents, an Arctic observatory provides the best opportunity for observation of longer-term temperature changes due to climate change. Even over the next decade, substantial bottom water warming is predicted for parts of the Arctic with continued global climate change and sealevel rise. Simply monitoring temperature, pressure, and salinity changes at an Arctic location characterized by shallow marine gas hydrates would substantially expand knowledge about the sensitivity of marine hydrates to climate forcing.

5. A PLAN FOR A GAS HYDRATE OBSERVATORY

To achieve the overall goal of understanding gas-hydrate dynamics, the gold standard would be a comprehensive program that includes continuous monitoring of the water column and seafloor in an area of known surface manifestations of fluid venting and gas hydrate deposits, linked to borehole monitoring of the methane reservoir, the gas hydrate stability zone, and transfer zones. While some experiments may be feasible with ***buoyed observatories***, others may require ***cabled ocean observatory technology*** to satisfy the high power and/or bandwidth requirements for some of the experiments. Examples of experiments that can uniquely be done with such observatories include: prolonged operation of seismic and/or electromagnetic sources; high data rate transfer; fluid pumping; heating of the system to avoid gas hydrate formation during fluid sampling or to perturb the gas hydrates; and the need for real-time intervention to capture infrequent events or change experiment parameters.

In the following sections we summarize some of the possible scenarios discussed by workshop participants. We classify the discussions into three categories – observations of natural changes on the seafloor, observations requiring deep boreholes, and experiments in which the environment is perturbed to increase the rate of change and test models for processes that occur too infrequently or too slowly to be captured by observations of the natural system. The various tools needed for these experiments are at different stages of development (Table 1). Nonetheless, several of the tools needed to observe natural changes are good candidates for implementation in the next few years with available technologies. Borehole instrumentation and active perturbation experiments require further technological development. These needs have been identified by the IODP Engineering Development Panel (EDP) as important priorities in engineering development in the next 3 to 5 years (www.iodp.org/eng), which are vital to achieve the science goals of IODP as enunciated in the Initial Science Plan (www.iodp.org/isp).

5.1 SEAFLOOR OBSERVATIONS

5.1.1 Visual and acoustic observations of the seafloor and overlying ocean:

To quantify fluxes of material out of the gas hydrate system, the drivers of the variation in flux (e.g. chemistry, physics, seismic loading), the associated biological feedbacks to the system, and the contribution and transience of methane from gas hydrate reservoirs to the ocean and atmosphere carbon inventories. Instruments for observatory-scale observations of the seafloor include a broad-band seismometer, a CTD system with accurate bottom pressure sensor, a video camera system, an upward-looking ADCP current profiler that samples to depths shallower than the hydrate stability PT conditions in the water column (~500 m depth), and a multifrequency acoustic scanner. The detailed scientific role and operational constraints for each of these instruments are discussed in Table 1. All of this instrumentation is available "off the shelf" or with minimal adaptation for a seafloor observatory environment. The experimental design will include a program to test hypotheses that are coupled to the period of known external forcing as well as the ability to respond to events through either pre-programmed adaptive sampling or shore-based reprogramming. Future enhancements to a seafloor facility envision periodic surveys using a seafloor-docked Autonomous Underwater Vehicle (AUV) and long-baseline navigation system for immediate event response.

5.1.2 Seismometers for monitoring tectonic forcing, slope instability and sudden fluid motion:

A broadband seismometer (periods of <30 – 0.1 s), combined with land-based seismic networks, will record ground motions due to global and regional earthquakes. With addition of several short-period seismometers (~1-0.01 s), small local events that are not well-recorded by the land networks can be detected. These local events may be due to small earthquakes, sudden fluid motion resulting from fluid pressure build up, or slope instability and may either initiate or result from fluid flow. Note that the short-period seismometers used for tectonic monitoring will also be used in the repeated controlled-source seismic surveys.

5.1.3 Seafloor geophysical studies for subsurface imaging of gas hydrate and free gas distribution:

Several geophysical methods can be used to provide initial site characterization and detect temporal changes in physical properties directly related to gas hydrate concentration. These include seismic reflection, seismic velocity and attenuation tomography, controlled source electromagnetic (CSEM) imaging of electrical resistivity, and measurement of seafloor compliance. Deploying seismic and electromagnetic sources and receivers permanently on the seafloor and in boreholes allows for more frequent and higher resolution measurements than are possible with expedition-mode science. This is especially true for those measurements that use naturally occurring signals as a source (e.g. compliance, seismicity, earthquake tomography).

Even in those cases for which a ship is needed to provide the source, acquisition of data is greatly facilitated by having well-coupled sensors with known, constant source and receiver positions already installed in the borehole or on the seafloor. Note that different geophysical methods provide complementary information on the physical properties of seafloor sediments. For example, compliance measurements, which require co-location of a differential pressure gauge and a gravimeter or broadband seismometer (NCE #3), may be successful in regions where attenuation due to the presence of free gas limits the resolution of seismic data. CSEM measurements are very sensitive to porewater salinity, unlike seismic and compliance measurements. Modeling studies are needed to determine the optimum spacing of sensors and appropriate repeat times for surveys.

5.2 BOREHOLE OBSERVATIONS

5.2.1 State properties of the formation:

Resistivity, pressure, and temperature must be monitored at depths where the gas hydrate/free gas system is most sensitive to short-term, repeated natural forcings. Although more challenging, an important component of the experiment is to monitor conditions associated with free gas, including pressure in the free gas column and gas flux. Sensors for subsurface monitoring are well-established tools in the onshore geotechnical community, although considerable engineering and testing remain to be done to adapt these tools for a marine borehole environment. Possible approaches to obtaining these data have been proposed to obtain continuous data on key subseafloor parameters within an array of low cost installations named SCIMPI and S-CORK. This new type of sub-seafloor observing system is based on the use of off-the-shelf components, and takes advantage of the natural tendency of the borehole wall to collapse and seal the instrumented observatory. These tools are significantly less expensive and time consuming than deploying traditional CORKs, and are not adversely affected by formation of hydrate within the hole. It seems prudent to expand the idea of an observatory beyond a single borehole, with monitoring occurring in multiple locations at each borehole.

5.2.2 High spatial resolution temperature measurement:

Another approach to obtaining in situ temperature data, which provides very high temporal and spatial resolution, is to use changes in the speed of light along a fiber optic cable. Such Distributed Temperature Sensing (DTS) systems are currently undergoing considerable commercial development for a wide range of practical and research applications. Changes in in situ temperature and in the temperature gradient with time can be diagnostic of changes in the amount of gas hydrate and in fluid flow patterns in or near a borehole. Preliminary studies in gas hydrate-bearing sediments at the Mallik well and in the Nankai trough illustrate the promise of this technique for gas hydrate studies. It is important to note that although DTS systems are generally limited to constraining temperature at intervals no smaller than 1 m along the cable, much smaller spatial sampling intervals can be obtained by wrapping the cable around pipes to form short probes. Such short probes may be very useful for constraining 3D fluid flow patterns near the seafloor. Although systems to record high-resolution temperature time series from at least 10 km of cable are currently available "off the shelf", they will need additional adaptation for use in a submarine observatory setting. Because of the data rates and power demands of these systems, a cabled observatory setting is required for optimum exploitation of the technology.

5.2.3 CORK observatory:

The existence of an open instrumented borehole makes possible certain in situ physical measurements, chemical analyses and microbiological studies, and provides a working space in which fluids may be captured for subsequent recovery and analyses. Chemical and isotopic characterization of the fluids, and the relative contributions of dissolved and free gas methane transport are key to our understanding of the processes controlling gas hydrate formation and distribution in the system. An open cased hole will also facilitate the installation of seismic and electromagnetic sources. Because of the likelihood of manifold freezing within the zone of gas hydrate stability, osmosamplers will be deployed below the GHSZ targeting specific horizons known to serve as pathways for fluid/gas flow.

The experimental design envisions instrumenting the site(s) so as to perform monitoring before and during deep sea drilling. This includes deployment of seafloor instrumentation and subsurface probes/cores (e.g., Johnson "stingers," break-away corers, mini-CORKS, etc.).

Extensive pressure-core samples need to be collected prior to establishing a CORKed borehole observatory. One to two main CORKed boreholes should be established at a given site and be accompanied by a spatial array of simpler instruments to measure state parameters (see Experiment #4). A "box-model" approach to determining gas hydrate processes and rates of formation and dissociation will be applied to the observatory site in order to examine in detail the inputs to the system, the size of the gas hydrate reservoir, and the outputs from the system.

The parameters to be monitored for which there is currently available technology are: temperature (thermistor strings, memory temperature loggers, DTS), pressure changes driven by tides and/or tectonic or other forcing functions (pressure sensors), fluid composition below and above the gas hydrate stability zone (osmosamplers), fluid flux (osmotic flow meters - good for rates as low as 1 mm/yr; thermistor strings – good for flow rates of ~10 – 1000 mm/yr), microbial activity rates and populations (microbial growth chambers).

Instrument development priorities for additional monitoring efforts include in situ methane sensors, in situ mass spectrometers, Raman spectrometer, conductivity/salinity sensors, resistivity probes (formation-penetrating), nitrate sensors (proxy for seawater contamination), seawater recirculation sensors (SCIMPI, instrumented stingers, break-away core, etc.) and down-hole seismometers. The seismometers would optimally be deployed both in the main CORKed hole(s) and in other subsurface installations. They should be designed to eliminate the need to cement the seismometers in place to avoid contamination of formation fluids. We recognize that there are problems of calibration, bio-fouling and chemical fouling that must be addressed with these types of sensors if they are to be deployed for extended periods.

5.2.4 Cross-hole imaging and fluid flow experiments:

These experiments represent a class of investigations that involve multiple boreholes in which instrumentation is installed for the duration of an experiment or in which specific active experiments are conducted and effects monitored in another borehole. Examples of the former category of experiments include various forms of tomographic imaging, including seismic, resistivity, and CSEM. The latter category of experiments includes tracer tests to constrain flow rates and pathways and aquifer testing to determine bulk permeabilities between boreholes. These experiments can be conducted initially to characterize the system and then repeated to determine changes due to natural or man-made perturbations.

The oil and gas industry routinely conducts crosshole tomography using borehole sources and receivers to detect fluid and gas migration between boreholes. A marine equivalent would be very similar in design, and reasonably feasible with a seafloor cable system to supply power and data transmission. Low-power Chirp sources are potentially non-destructive to the borehole and provide high-resolution signals for the receivers. A crosshole tomography observatory will have a minimum of two holes, but an additional 3rd or 4th hole, allows determination of additional properties, such as anisotropy that can lead to a better the characterization of a system in 4 dimensions.

The main advantages of a crosshole tomography experiment are that it would have high vertical and horizontal resolution to detect localized changes in hydrates and free gas, it would have fixed source and receiver positions for the repeated sampling needed to detect small travel-time changes generated by hydrate and free gas changes. The short source-receiver offsets require minimal seismic source energy, and as a fixed installation the data will be recorded frequently to detect variation for a range of intervals including very short intervals. The temporal variability of hydrate concentration and distribution and the associated free gas migration is currently poorly known. Campaign style experiments require that the magnitude and frequency of gas hydrate and free gas will vary to justify a repeat experiment. A crosshole tomography experiment with frequent observations would avoid the need to know when to resurvey in the "campaign" style. The main issues to be resolved with a long-term cross hole tomography experiment are survey design to assure a reasonable balance between range and resolution, long-term reliability of instruments, instrument drift, and issues related to hole deviation.

Simpler, cheaper versions of the crosshole tomography experiment are the repeat VSP and experiments using short period sensors on the seafloor. A VSP measures the same seismic parameters as the crosshole tomography experiment, but uses receivers in the borehole and sources either at the seafloor or at the sea surface. Although resolution and coverage are not as good as for a crosshole experiment, this approach will increase the volume of the subsurface that is imaged.

5.3 PERTURBATON EXPERIMENTS

5.3.1 Seafloor microbial incubation and substrate colonization:

Basic hydrological and geochemical experiments can be envisioned that are primarily based on the ability to run pumps for sustained periods. While geomicrobiology investigations are still based on the collection of samples, the future suggests that the next phase will involve the development of in situ biosensors and bio-assays, that allow us to further understand the interrelationships between fluid transport of metabolites and the community structure. Microbial incubation experiments can be installed in or in the immediate vicinity of gas hydrate outcrops to understand the influence of organisms on hydrates and the influence of gas hydrates and associated fluxes on biological processes. Colonization of substrates (e.g. carbonates) placed at seep sites will illuminate the role of different substrates on the systems ecology. Future geomicrobiology systems will make use of the bi-directional communications provided by the submarine cable by allowing direct manipulative experiments and modifications to be made based on information extracted from the incoming data without physically revisiting the sites.

5.3.2 Controlled changes in temperature, pressure or chemical composition:

These experiments are designed to more rigorously and quantitatively test models for the effect of changes in T, P and chemical composition. Possible scenarios include warming the formation near the borehole while the borehole is maintained at hydrostatic pressure (open) or the interval near the warming isolated to prevent flux of fluids or gas. After warming, the borehole could be cooled to the ambient state and conditions monitored as the equilibrium begins to be re-established. Alternatively, the pressure in the borehole could be lowered using a pump, and the salinity conditions can be altered to change the thermodynamic stability conditions for gas hydrate. These experiments must be conducted in a controlled sequence and their impact evaluated in advance based on sophisticated numerical models to provide reasonable assurance that the experiments would not alter the site in undesirable, and perhaps unrecognized, ways.

Key parameters to be monitored are pressure, temperature, pore water salinity, fluid and gas fluxes, and gas/hydrate concentrations and distributions. Such an experiment could provide data on the mobility of the liberated gas, kinetics of gas hydrate formation, system response to natural changes (e.g., global warming, sea level rise, changes in the fluid source for subseafloor flow systems), and the likelihood that gas hydrate decomposition could generate slope instability. At the same time, they can simulate scenarios for potential production of gas hydrates as an energy source.

5.3.3 Proof-of-concept for CO2 sequestration:

A specific perturbation experiment to test some proposed ocean floor CO2 sequestration scenarios would introduce CO2 into the gas hydrate system and track diffusional exchange of CO2 for methane. Recent technological developments have increased the potential for this approach to release significant quantities of methane from gas hydrates, particularly when injection is combined with thermal stimulation. The phase diagram for CO2 represents one challenge for this type of experiment, since liquid CO2 is the stable phase at some pressures of relevance to marine gas hydrate observatories.

5.3.4 Induced Seepage:

This experiment involves drilling through the base of the regional gas hydrate stability zone and monitoring gas and fluid flux and hydrate formation in the open borehole. Ancillary investigations might include tracking organisms that colonize the seafloor near the induced seep or changes in microbial community function within the borehole itself. This experiment also has potential benefits for understanding the impact on borehole instrumentation of drilling through the hydrate stability zone to the depth of the concentrated free gas zone. We note that unmonitored experiments of this type have been conducted as a result of ODP and IODP drilling on the Blake Ridge and in Cascadia.

In another configuration of an artificial seep experiment the borehole might be sealed; here the goals are more biological than physical, and drilling to the level of the base of the stability zone is probably unnecessary. Using the observatory borehole to provide a well-characterized source of fluid and gas, manipulative microbiological experiments and/or organism-level experiments to monitor community structure could be carried out at the artificial methane seep represented by the borehole.

REQUIRED ENGINEERING DEVELOPMENT NEEDS

Recommendations for near-future engineering developments to advance the feasibility of gas hydrate observatories include, in no particular order:

1. Development of inexpensive and robust temperature and pressure monitoring to a depth of several hundred meters below the seafloor in boreholes that may contain both fluid and free gas.

2. Development of capabilities for long term measurement of pore water salinity. Whether these measurements are made via conductivity sensors, refractometry, or self-potential, substantial development effort will be required.

3. Improvement of borehole seismic sensors in the kHz range, including better data recording and enhanced coupling technologies.

4. Development of sensors that can be cheaply and reliably installed at multiple depths within a borehole to measure the in situ sediment resistivity.

5. Concerted effort to develop new instruments that can reliably measure methane concentrations and its speciation (dissolved, gas and/or gas hydrate phase) in a borehole. Miniaturized and rugged Raman spectroscopy technology currently in use on land appears to be a good candidate for adaptation to borehole observatories. Mass spectrometry and METS sensors are more applicable to seafloor and water column installations.

6. New approaches to determining gas and water fluxes. Although more challenging, it is desirable to characterize fluid flow in multiphase systems.

7. Improvement in the cost and flexibility of installing observatory sensors and recalibrating, maintaining, downloading data from sensors.

6. TOOLS AND SENSORS

Fundamental issues with sensors to be deployed at any seafloor observatory include: (a) characterization of sensor drift and sensitivity to strain in boreholes; (b) robustness and serviceability, including the possibility that some of the sensors be purposely designed with a limited life or without the potential to be serviced; (c) recalibration, particularly recalibration strategies to be applied with the sensors in place; (d) mode of deployment, including the potential of direct push technologies that drive 50-60 m in soft formations; (e) reliability analysis, which is now standard in many fields that rely on instrumentation; (f) integration of the different spatial scales (pore-lab-field-regional) represented by measurements made by individual sensors and keying the sensors and their locations to the spatial scales that are important for describing system dynamics; (g) determination of the impact of the measurements themselves on the natural system; and (h) proper isolation of sensors and coupling to the borehole walls at intervals within a borehole observatory.

Several instrumentation issues also arise from the unique conditions encountered in gas hydrate systems. For example, the sensors themselves serve as loci for hydrate nucleation and growth, open water in boreholes will rapidly form gas hydrate under some conditions, and the presence of free gas can affect some types of sensor readings. In any borehole measurement, maintaining contact with the formation can be difficult, but such problems might be exacerbated in hydrate-bearing sediments. For example, a borehole may acquire a non-uniform diameter as it progresses through soft, plastic clays containing little gas hydrate and interbedded sands containing high concentrations of mechanically strong gas hydrate as pore fill. In some places, it may be necessary to do experiments inside casing, to perforate casing, to use annular fill material, or to program longer sensor recording periods for detection of true conditions in the formation outside of casing or annular fill.

7. OUTREACH AND EDUCATION OPPORTUNITIES

There are promising targets for education opportunities both in formal and informal venues. These include gas hydrates as a potential alternative energy resource; gas hydrates as natural hazards (drilling, tsunami generation); the role of gas hydrates in climate and atmospheric variability – and of climate variability on hydrates. In addition, gas hydrate research provides rich examples to teach fundamental science (chemistry, physics, etc), the process of science (pushing the frontiers of exploration, innovation and instrumentation), and opportunities for training the next generation of scientists and engineers (career paths and choices).

Several specific and potentially exciting ideas emerged from our education discussions that would be excellent components to build into a gas hydrates observatory proposal creating a web-based window onto the seafloor. Such facilities will create the capability to archive video, pictures, and data from events at observatories to use as teaching tools; and provide exciting partnering opportunities with science centers to develop traveling exhibits and associated materials. There is potential to create a GLOBE-like program for sharing data and contributing to the scientific process by allowing students to monitor seafloor webcams located at the observatories, recording and reporting data to each other and scientists via the web. This can be extended to include controllability of seafloor cameras for presentations in science centers and/or for groups of students who have previously had not such experiences.

Depending on which individual message scientists and educators choose to focus on at a given time and the specific target audience, some educational tools that are used effectively by the Deep Earth Academy (formerly JOI Learning) and can be easily integrated into outreach packages include: Classroom activities, available on-line in PDF format; posters (one already exists, but there is certainly potential for others); career profiles that can be added to the Deep Earth Academy's existing on-line collection and teacher training workshops. Berths and support for single or small teams of teachers at sea on cruises to the observatories and creation of associated interactive websites and post-cruise products for students will provide additional and valuable opportunities for outreach and education.

As the science questions, technology needs, equipment and experiment designs evolve and more forward, educators look forward to further refining these ideas and helping to develop specific and targeted outreach plans for each desired audience.

8. LIST OF RECOMMENDATIONS

1. Maintain and enhance contact with industry to compile experience on drilling and long term monitoring of borehole parameters.

2. Develop critical instrumentation for full implementation of a gas hydrate observatory. Encourage a modular approach to technology development that takes advantage of opportunities and produces tools that will be transferred to a comprehensive gas hydrate observatory.

3. Test long-term reliability of instrumentation. Investments in instrumentation that is to be embedded in the seafloor for a long time require a different level of certainty than is required for expeditionary science.

4. Encourage development of ways to embed strings of closely-spaced sensors into the seafloor to depths of meters to hundreds of meters.

5. Standardize sensors, tools, recorders, and interfaces so that they are useable at a variety of sites and in a variety of subsurface deployment installations.

6. Revisit sites of active vents to monitor natural recovery of the system after significant drilling perturbation. For example, at the Bulls Eye vent in northern Cascadia, holes drilled in 2005 can still be observed one year later but the lateral impact of drilling is limited. To date no detailed post-drilling surveys have been documented at the Hydrate Ridge sites drilled during ODP Leg 204, where many holes were drilled on an active seep.

7. Encourage investigators to seek opportunities for testing of instruments and prototype experiments in existing facilities, such as the gas hydrate observatory in the Gulf of Mexico. Furthermore, it is recommended that tools be tested on cabled seafloor installations as they become available (e. g. MARS, VENUS, NEPTUNE).

8. As observatory plans get underway, coordinate the collaborative use of the observatory installations and the design of ancillary experiments in the vicinity of the observatory to avoid interference between efforts.

9. Develope a mechanism for data-handling, efficient database design and data dissemination.

10. NSF, working with the Consortium for Ocean Leadership, needs to develop a structure for long-term support of observatory facilities. We recognize that OOI and IODP have somewhat different policies and management structures. Its important that these policies be compatible and clear to the science community.

9. PARTICIPANT LIST

Last Updated: October 30, 2007

First Name	Last Name	Institutions	E-Mail
Nathan	Bangs	University of Texas at Austin	nathan@ig.utexas.edu
Keir	Becker	University of Miami	kbecker@rsmas.miami.edu
Brian	Bornhold	University of Victoria	bornhold@uvic.ca
Brandon	Briggs	Oregon State University	briggsb@onid.orst.edu
Paul	Carini	Oregon State University	carinip@onid.orst.edu
Robert	Collier	Oregon State University	rcollier@coas.oregonstate.edu
Sandy	Colvine	GSC Pacific	scolvine@nrcan.gc.ca
Rick	Colwell	Oregon State University	rcolwell@coas.oregonstate.edu
Sharon	Cooper	Consortium for Ocean Leadership	scooper@oceanleadership.org
Earl	Davis	Natural Resources Canada	edavis@nrcan.gc.can
Nigel	Edwards	University of Toronto	edwards@core.physics.utoronto.ca
Jon	Erickson	Monterey Bay Aquarium Research Institute	jon@mbari.org
Julie	Farver	Consortium for Ocean Leadership	jfarver@oceanleadership.org
Melissa	Feldberg	Oregon Sea Grant	melissa.feldberg@oregonstate.edu
Peter	Flemings	University of Texas	pflemings@jsq.utexas.edu
Patricia	Fryer	University of Hawaii	pfryer@hawaii.edu
Masafumi	Fukuhara	Schlumberger Moscow Research	fukuhara1@slb.com
Ning	Fulong	China University of Geosciences	nflzx770803@163.com
Sabodh	Garg	SAIC	gargs@saic.com
Holly	Given	Consortium for Ocean Leadership	hgiven@oceanleadership.org
Ross	Haacke	Pacific Geoscience Centre	rhaacke@uvic.ca
Patrick	Hart	US Geological Survey	hart@usgs.gov
Jan	Henninges	GeoForschungsZentrum	janhen@gfz-potsdam.de
Melanie	Holland	GeoTek	melanie@geotek.co.uk
Matthew	Hornback	University of Texas at Austin	matth@utig.ig.utexas.edu
Gary	Humphrey	Fugro-McClelland Marine Geosciences, Inc.	ghumphrey@fugro.com
Paul	Johnson	University of Washington	johnson@ocean.washington.edu
Miriam	Kastner	Scripps Institution of Oceanograohy	mkastner@ucsd.edu
Deborah	Kelley	University of Washington	kelley@ocean.washington.edu
Alison	LaBonte	PGC Geological Survey of Canada	alabonte@ucsd.edu
Malcolm	Lall	DGH India	mvlall@dghindia.org
Laura	Lapham	Florida State University	lapham@ocean.fsu.edu
Ira	Leifer	University of California, Santa Barbara	ira.leifer@bubbleology.com
Lisa	Levin	Scripps Institution of Oceanography	llevin@ucsd.edu
Dennis	Lindwall	Naval Research Lab	lindwall@nrlssc.navy.mil

Phil	Long	PNNL	philip.long@pnl.gov
Ian	MacDonald	Texas A&M University, Corpus Christi	ian.macdonald@tamucc.edu
Kevin	Mandernack	Colorado School of Mines	kmandern@mines.edu
Gene	Massion	MBARI	magene@mbari.org
Thomas	McGee	University of Mississippi	tmm@olemiss.edu
Kate	Moran	University of Rhode Island	kate.moran@uri.edu
Michele	Morsilli	Universita` di Ferrara	mrh@unife.it
Greg	Myers	IODP-MI	GMyers@iodp.org
Charlie	Paull	Monterey Bay Aquarium Research Institute	paull@mbari.org
Tom	Pettigrew	Mohr Engineering	tom.pettigrew@stress.com
John	Pohlman	US Geological Survey	jpohlman@usgs.gov
Alan	Rempel	University of Oregon	rempel@uoregon.edu
Michael	Riedel	McGill University	mriedel@eps.mcgill.ca
John	Ripmesster	National Research Council Canada	john.ripmeester@nrc.ca
Ellis	Rosenbaum	DOE National Energy Technology Laboratory	eilis.rosenbaum@netl.doe.gov
Carolyn	Ruppel	US Geological Survey / MIT	cruppel@usgs.gov
Derryl	Schroeder	Texas A&M University	schroeder@iodp.tamu.edu
Peter	Schultheiss	GeoTek	peter@geotek.co.uk
Dendy	Sloan	Colorado School of Mines	esloan@mines.edu
Laura	Snow	Consortium for Ocean Leadership	lsnow@oceanleadership.org
Evan	Solomon	University of California, San Diego	esolomon@ucsd.edu
Ralph	Stephen	WHOI	rstephen@whoi.edu
Erwin	Suess	GEOMAR	esuess@ifm-geomar.de
Hitoshi	Tomaru	Kitami Institute of Technology	tomaru@mail.kitami-it.ac.jp
Marta	Torres	Oregon State University	mtorres@coas.oregonstate.edu
Anne	Trehu	Oregon State University	trehu@coas.oregonstate.edu
Michael	Tryon	Scripps Institution of Oceanography	mtryon@ucsd.edu
William	Ussler	Monterey Bay Aquarium Research Institute	methane@mbari.org
Robert	Vagnetti	DOE National Energy Technology Laboratory	robert.vagnetti@netl.doe.gov
Heinrich	Villinger	University Bremen	vill@uni-bremen.de
Andy	Ward	Pacific Northwest National Laboratory	andy.ward@pnl.gov
Jill	Weinberger	Lamont-Doherty Earth Observatory	jillw@ldeo.columbia.edu
Ele	Willoughby	Natural Resources Canada	ele.willoughby@nrcan.gc.ca
Wu	Xiang	China University of Geosciences	wubox@126.com

Theme	Instruments	Costs	Development	Sampling rate	Spatial resolution	Power	Issues	Details of Use	Perturbation	Hypotheses addressed	O and E
Seafloor											
Visual and chemical survey (pre observatory and at regular intervals subsequently)	Dedicated docked AUV:Water column chemistry (Methane, sulfide, DO, pH sensor), Photomosaics, Subbottom chirp profiling, multibeam bathymetry with cm resolution, nested surveys, electrical conductivity (salinity), small water samples,	Very high	Capability exists in ship-based mode; seafloor docking systems under development	AUV operating modes: (1) initial baseline, (2) regular survey monthly and (3) event or PI driven mode	meters to cm	high power demands	needs to avoid moorings, high expense, biofouling may require annual cleaning	AUV Use in periodic and event response mode: AUV visual surveys of regular grid covering 1 km2 and encompassing specific features: mounds, bubbles, biological communities, hydrate formation, carbonates, . 20 mab, 10 mab, cm scale. Document temporal variation in watercolumn and seabed processes. Helps address calibration issues 60 lines in a mission.	Could be used to provide immediate detailed study of natural or artificial perturbations		photomosaics could provide means for teachers to teach aspects of spatial biology, mapping skills etc.
Seismic measurements/Event detection	Seismic network - short period and broad band	high	Technology exists	Continuous	?		needs to be several hundred m away from other instruments		Could be used to provide immediate detailed study of natural or artificial perturbations		
Seafloor photography	Real time adaptive visual imaging (video and still) - pan tilt, zoom, translate capability, quantitative visual Rotary	moderate	Technology exists	Continuous or regulated from shore	cm	high power needs for lights	light pollution	rotary or tracked camera that covers a 200m diameter circlular area encompassing a variety of biological community types	Could be used to provide immediate detailed study of natural or artificial perturbations		periodically could be the basis of varied educational activities
Acoustic imaging of water column, seabed for bubble, fish and zooplankton studies	seafloor and AUV-mounted acoutic imaging: multibeam system (characterizing bubbles); sector scanning sonar. Fan beam (vertical and horizontal components).	?	Technology exists	Continuous or regulated from shore	?	?	acoustic interference	Deployment with scales of cm for addressing fluxes of methane via bubble studies, fish and plankton abundance and movements above the seabed			
Current profiling	ADCP (1) water column - one vertical mooring 200 m looking up, 100 m looking down - 600khz (2) 3 bottom sites (looking up) within 1km2;ooking up 100 m, multiple frequency.	$15k each	Technology exists	Cotinuous, typically minutes	0.1 kt?	??	Moorings create hazards for ROV/AUV use, keep to a minimum, Fisherman capture concerns	Continuous deployment with scales of m For addressing fluxes of methane, larval transport, linked to AUV measurements			Could provide data for teaching interpretation at upper levels.
Thermal mapping	Thermister string - water column, temperature probe - sediments	Low	Exists	Cotinuous, typically minutes	0.001 deg	?	same as mooring?				
Bottom-water oxygen, subbottom oxygen	Optode/oxygen profiler	Low/high	Optode technology exists/ profiler deployments are short term	Cotinuous, typically minutes		?	optodes require periodic cleaning, sensors - short term	Move to respond to events.			
Basic environmental descriptor	Bottom pressure (1), temperature (multiple), transmissometry, salinity, subottom pressure (multiple in different biological habitats), fluorometer, marine snow	Low-Moderate	Technology exists				Hydrate fouling (subbottom pressure probes)	Provides integrative/supportive data for biological and geochemical studies			
Fluid flow	CAT meter (Tryon)	$5-20k	Exists	Continuous daily resolution for approx. 1 year	1 mm/yr	none	limited to sediments, not electronic so not cable-ready	Requires ROV for placement, consider placing on carbonate structures and use hydrothermal technology for cementing. Also recovers time series fluid and dissolved gas samples.	Could be positioned for perturbation studies		
Fluid flow	OTIS (LaBonte)	$60k	Prototype done, additional development needed	Continuous, ~1 hour resolution	1 cm/yr	low	biofouling, drift, limited to sediments	Requires ROV for placement			
Fluid flow	ECAT (Tryon, LaBonte. Ziebis)	Low to moderate	under development	Continuous, daily resolution	1 mm/yr	low	limited to sediments	Requires ROV for placement			
Gas flow station	Camera system with lights (decimeter scale), Scanning multibeam (30 m radius)	?	?	Continuous or regulated from shore	decimeter			camera should be repositionable, Scanning multibeam (30 m radius), for ground truthing, measure fluid flows, inject dye tracer,			
Mound/carbonate drilling with strain and chemical sensors	Osmosamplers..	?	?	Continous	?	?	Don't know consequence of drilling hydrate	need ROV retrieval of samples			
Strain	GEOCE (Chadwell, Tryon, Send, Brown) Fiber-optic strain (Zumberge) GPS acoustic (Chadwell)	high	under development	10s of minutes to months	cm	moderate	requires knowledge of water column, GEOCE is only one doing this	GEOCE is 3D, fiber is 1 or 2D, acoustic is 2D subset of GEOCE			
vertical strain	various instruments (Zumberge)(Villinger) and GEOCE above	high	under development	10s of minutes to months	cm	moderate	complete quantification of overlying water column needed - GEOCE does this				
Pore pressure	PUPPI-II (Tryon, Schultheiss, Driscoll)	$75-100k	under development	minutes/seconds	1 Pa	low/ moderate	presence of gas limits transmission of pressure perturbations	Proxy for strain	Ideal for monitoring effects of perturbations from stress to temperature		

Theme	Instruments	Costs	Development	Sampling rate	Spatial resolution	Power	Issues	Details of Use	Perturbation	Hypotheses addressed	O and E
Tilt	Tilt sensors	low	Exists	10s of minutes typically	microradians?	low					
heat flow	Probe and Thermister array/ thermal blanket	low to moderate	Exists	10s of minutes typically but could be less	0.001 deg/meter	low		Establish patterns of heat flow relative to bubbles, presence of hydrate, etc.			
Bottom pressure	pressure sensors (Paroscientific)	$15-20k	Exists	minutes	1 Pa	low	none		Tidal effects	Tidal effects on hydrate/bubbles	
Bottom sampling periodic (e.g., annual)	Crawler or ROV: periodic closup imaging, coreing, sensor profiling, respirometry,	high	technology exists	quarterly or annual				Periodic ROV or crawler based sampling for sediment cores (microbiology, macrobiology) animals, filtered water			
Bottom sampling - continuous	Remote access fluid sampler	moderate	technology in development?	Continuous				Seafloor: capturing fluids and particulate DNA			
Zooplankton/larvae	Flow cam, plankton recorder, L-OPC, larval traps	50k/30K/50K /20k	technology exists	continuous/periodic			requires ground truthing with ROV samples	for studies of water column: larval dispersal, plankton dynamics			
Microbial diversity	Water sampling or DNA Array chip?, DNA and whole cell archiving weekly, response to event - extra sampling. Probes for gene expression	?	Technology under development?	Weekly		?		Requires sample recovery via ROV?			
Carbon, S, N cycling	In situ mass spectroscopy	high?	Technology in late development?	?	?	?	?	?			
Hydrate detection	In situe Raman Spectroscopy	high?	technology in late development?	?	?	?	?	?			
Marine snow	Sediment traps	low	Technology exists	regular, integrated over days, weeks, etc.	?	?	?	To relate snow to other fluxes			
Additional Process studies (respiration etc.)	ROV/Crawler	high	Technology in late development	periodic	decimenters to meters		creates disturbance	Used to collect core samples, deploy intrumentation, make measurements			
Moorings for sampling water column (upward profiling and/or fixed) Sensors from above.											

Borehole

Theme	Instruments	Costs	Development	Sampling rate	Spatial resolution	Power	Issues	Details of Use	Perturbation	Hypotheses addressed	O and E
Time series of in situ temperature, pressure, and electrical resistivity to provide information on physical state variables that control gas hydrate formation.	SCIMPI	high	development needed to adapt technology from onshore geotechnical engineering applications	minutes/seconds	10 of meters	low/ moderate	questions about hole collapse and coupling to the borehole.				Real-time viewing of subseafloor "weather"
Time series of temperature with high spatial as well as temporal resolution to provide information on physical state variables that control gas hydrate formation.	Ditributed Temperature Sensors (DTS)	moderate	development needed to adapt established onshore technology to seafloor. Has already been done by Schlumberger.	minutes	1-1.5 m	moderate	optical fiber is fragile. Coupling to borehole wall.				Real-time viewing of subseafloor "weather"
High frequency micro and nano-seismicity	Short period (>1 kHz) seismometers	high	develop borehole coupling strategy, seafloor recording package, and borehole source	several kHz	meters	high	very high data rate				
Sample borehole fluids and measure in situ temperature and pressure	CORK	very high	some development needed to adapt isosampler and biotraps	minutes/ seconds	10s of meters	low/ moderate	hydrate may form within GHSZ				
High resolution imaging of gas hydrate and gas distribution and amount to detect temporal changes	Downhole seismic sources and receivers, with additional receivers on the seafloor (ocean bottom cables or individual ocean bottom seismometers)	high	has been developed by industry	repetition rate for sources on the order of seconds; for receivers several kHz; continue for several minutes or hours at relatively infrequent intervals	10s of cm	high, when data acquisition is active	Can be done, but with lower resolution, through repeated campaign-mode surveys				Can be used to make colorful animations. Analogy to medical imaging of the human body ha public appeal.
High resolution imaging of gas hydrate and gas distribution and amount to detect temporal changes	Downhole electromagnetic sources and receivers (CSEM)	high					Can be done, but with lower resolution, through repeated campaign-mode surveys				

Appendix 1

Gas-Hydrate Observatories Workshop (GHOBS)

July 18-20, 2007; Portland, Oregon

Agenda – July 2, 2007

July 18, 2007

6:00 – 10:00 pm	Sign in and informal reception and poster session at the Hotel Monaco.

July 19, 2007

Theme: What are the important science questions concerning submarine gas hydrates? Why are observatories needed? What measurements are needed?

9:00 – 9:15 am	Welcome and summary of workshop objectives and logistics (Torres)
9:15 – 9:30 am	History and future of gas hydrate research (Paull)
9:30 – 9:45 am	The GoM observatory (MacDonald)
9:45 – 10:00 am	CORKS (Davis)
10:00 – 10:15 am	The Marianas CORK (Fryer)
10:15 – 10:30 am	Neptune Canada (Riedel)
10:30 – 10:45 am	The Regional Cabled Observatory (Kelley)
10:45 – 11:00 am	Numerical modeling of submarine gas hydrate processes (Flemings)
11:00 – 11:10 am	Outreach opportunities (Cooper)
11:10 – 11:45 am	Break
11:45 – 12:30 pm	Plenary Session (Trehu) – Discuss science questions and charges to working groups. Note: preliminary charges and group memberships and group chairs will be determined prior to the meeting based on responses to comments on the agenda, and an updated agenda and working group sign-up list will be circulated prior to the meeting.

12:30 – 1:30 pm Lunch

Theme: How can we make the needed measurements in the coming decade?

1:30 – 1:45 pm	Introduction to objectives of this session (Davis)
1:45 – 2:00 pm	Communications and power overview (Massion)
2:00 – 2:15 pm	Alternatives to CORKs (Moran)
2:15 – 2:30 pm	Borehole seismic measurements (Stephen)
2:30 – 2:45 pm	MiniCORKS (Johnson)
2:45 – 3:00 pm	Distributed temperature measurements (Fukahara)
3:00 – 3:15 pm	In-situ sensing of chemical changes (Ripmeester)
3:15 – 3:30 pm	Methane sensors (Suess)

3:30 – 4:00 pm	Break
4:00 – 6:00 pm	Discussion (Riedel) Summary of Science and technology issues, discussion of charges to working groups.
6:00 – 7:30 pm	Poster Session
7:30 pm	Dinner

July 20, 2007

Theme: Discussions

8:00 – 8:15 am	Plenary session (Torres); Logistics
8:15 – 12:30 pm	Working Groups meet*
12:30 – 1:30 pm	Lunch
1:30 – 3:30 pm	Plenary Session (Paull): Working group chairs present results followed by discussion. The objective is to develop a realistic plan to provide guidance to the scientific community and funding agencies on how to proceed. Meeting adjourned.
4:00 – 6:30+ pm	Planning committee and working group chairs meet to put together an outline of the report, determine writing assignments and establish a time-table for report completion.

*Preliminary list of working groups.

Group 1: 4D Site characterization
Group 2: Fluid and microbial borehole measurements (sampling and in situ)
Group 3: Physical state parameters in situ in boreholes
Group 4: Fluid and microbial seafloor observations
Group 5: Education and outreach opportunities

Charges to Groups 1-4:

- Short statement of science questions.
- Review current technology: evaluate readiness, identify special challenges posed by gas hydrate.
- Implementation issues: evaluate the need for cable or mooring technologies, discuss installation and maintenance challenges.
- Propose/suggest experiment and/or strategies that incorporate technology to address key science questions.
- Fill in table with OOI requirements for tools and sensors.

Appendix 2

SITE CHARACTERISTICS

Establishment of an observatory necessitates detailed surveys to map the system in 4 dimensions (i.e. 3 spatial dimensions with repeat measurements at intervals that depend on the rate of change of that parameter and measurement resolution). Key properties that need to be constrained include gas hydrate concentrations, distribution, vertical or horizontal layering, the sub-hydrate free-gas migration "plumbing" system, and potentially, free gas concentration within the hydrate stability zone. Such a survey would be best accomplished through a series of coincident, nested observations using tools listed below to fully characterize the gas hydrate system prior to installation of an observatory. This might mean acquiring measurements of certain parameters at logarithmically increasing distances from the observatory site and at numerous discrete depths from piston cores. Cores recovered from boreholes around and directly at the observatory site will also be needed.

Hydrate and Gas Distribution and Amount: The amount and distribution of gas hydrate and free gas must be constrained using a variety of indirect and direct methods. Indirect techniques include high-resolution ***seismic reflection and refraction studies*** to define the stratigraphic and structural setting of the gas hydrate system and to estimate the amount of gas hydrate and free gas present in the sediments. This is done by recording p-wave and shear-wave reflections and by deriving p and s-wave velocity, attenuation and anisotropy. These measurements will be possible with surface, deep-towed, and borehole seismic sources and hydrophones and by placing hydrophones and geophones on the seafloor using ocean bottom cables (OBC) or ocean bottom seismometers (OBS). ***Seafloor compliance*** and ***controlled source electromagnetic*** (CSEM) surveys provide additional indirect constraints on the pre-existing distribution/concentration of gas hydrate and free gas near the observatory site at different, overlapping lateral and vertical resolution. ***Coring, nondestructive imaging of cores*** (e.g., thermal IR, CT scan, X-ray), and ***pore water/void gas analyses*** yield more direct constraints on free gas and gas hydrate distribution and amount on a local scale, and should be used to calibrate and validate results obtained through geophysical remote sensing.

Sediment Rheology: Rheological measurements are important for predicting borehole stability and the impact of seafloor and borehole deformation on the numerous observatory sensors that are sensitive to strain. Particular focus should be placed on studying sediments close to the seafloor, where effective stress is small and where small changes in effective stress can produce substantial changes in rheological properties. One of the most formidable challenges to determining the rheology of near-seafloor sediments is the difficulty of obtaining samples that have mechanical properties representative of those in situ. Developing capabilities to measure a limited set of rheological parameters in boreholes or with instrumentation that directly test near-seafloor sediments away from boreholes may provide better constraints than laboratory tests on recovered cores. Another critical issue is the impact of gas hydrate or free gas and the changing distributions of each on the rheology of sediments at an observatory site.

Temperature, Pressure, and Salinity: Formation temperature and pressure and pore water salinity are key parameters that determine the thermodynamic stability of gas hydrate. Overall, temperature and pressure measurements at an observatory site need to be made at better spatial resolution than has been typical of academic borehole measurements in the past. Pressure measurements should particularly focus on lithologic boundaries. Pore water salinity constraints can be garnered directly through conventional analyses of pore water chemistry in recovered cores and indirectly through geophysical monitoring using electrical methods that detect a combination of formation porosity and pore water salinity.

Regional Heterogeneity: Defining the critical length/depth scales of geologic heterogeneity, as well as heterogeneity in gas hydrate distribution, in the vicinity of the observatory site is crucial. These spatial scales control some of the dynamics of the gas hydrate system and modulate the distribution and concentration patterns for free gas and gas hydrate. The characterization of geological heterogeneity (lithologic and tectonic) of the area also helps to define the number and resolution of measurements that are required to understand the key controls on the hydrogeologic system.

Permeability and Compressibility: Permeability, whether controlled by lithology, structure (e.g., faults), stratigraphic boundaries, or the gas hydrate/free gas system itself, affects fluid migration and the patterns and loci of hydrate concentration. Even simple constraints on horizontal and vertical permeabilities and on the scales of permeability variations at an observatory site will provide critical information about the controls on gas hydrate reservoir dynamics. Superposed on the permeability is the compressibility, another poorly understood property and one that describes the response of the sediments to the effective stress conditions.

Fluid Fluxes: Quantifying fluid (including free gas) fluxes is critical to understanding the hydrogeology of gas hydrate systems, but direct methods for determining these fluxes remain elusive. Furthermore, even if the fluxes are measured at one discrete location, hydrologic variability and the arrangement of permeable conduits at seep sites can lead to significantly different fluxes over short spatial scales.

Free gas detection: Tracking the amount of free gas below the depth of gas hydrate stability is critical for calibration of indirect measures of free gas saturation (e.g., seismic velocities) and for determining how migration of free gas from below, metastable conditions at the base of gas hydrate stability, and changes in hydrostatic pressure, temperature, and sediment thickness affect the generation of free gas from gas hydrate. Within the hydrate stability zone, detecting the presence of free gas provides constraints on the nature of gas migration through the gas hydrate stability zone, the concentrations of gas within "chimneys," and the coexistence of three phases (gas, gas hydrate, and dissolved gas) at some depths within the hydrate stability zone.

In addition, the distribution and amount of gas hydrate in the subsurface must be well defined, and working hypothesis(es) for how methane is delivered to and passes through the gas hydrate stability zone are developed.

Appendix 3

Gas Hydrate Observatories (GHOBS) Workshop

July 18-20, 2007

Portland, Oregon

POSTER ABSTRACTS

ROV-Serviceable, Submarine Cable-Connected Wellheads for IODP Borehole Observatories

Jon Erickson[1], William Ussler III[1], Gene Massion[1], Larry Bird[1], and Charles K. Paull[1]

[1] Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA

ABSTRACT

A new wellhead design that is easily ROV/HOV serviceable has been developed for installation at IODP borehole observatories. The original impetus for this development was the need for an ROV-serviceable, submarine cable-connected wellhead design for the Monterey Bay Borehole Observatory IODP drilling expedition once scheduled for late 2005. This expedition was removed from the active schedule because of permitting issues, but the design has been completed.

The evolution of cased holes that could be re-entered started during the Deep Sea Drilling Project (DSDP) with the initial objective of replacing drill bits and reentering the existing hole to achieve greater total depth. This was achieved with the installation of seafloor reentry cones with casing extending down into the borehole. However, over the next decade the potential of using cased legacy holes for subsurface monitoring was realized and has been increasingly utilized by either CORK or seismometer installations. Modifications to the initial designs of the reentry structures were incremental, and ROV/HOV servicing of borehole monitoring experiments was achieved by placing a metal platform on top of the reentry cone to provide a place for the ROV/HOV to land. One result of this configuration is that the monitoring equipment rises several meters above the reentry cone into the water column. Because most previous Ocean Drilling Program (ODP) and Integrated Ocean Drilling Program (IODP) observatory installations have been in remote deepwater locations, this exposure of the monitoring equipment and the upper part of the borehole CORK body or instrument hangers has not been a major design consideration. However, several developments are occurring that require a substantial redesign of the current seafloor expression of the reentry cone and completion equipment. First, drilling operations involving cased reentry structures are increasingly being proposed for shallower water depths (<2 km) on continental margins. Second, the increasingly sophisticated observatory deployments and experiments conducted during the IODP will increase the dependence on ROV/HOVs to service these facilities. Finally, there is the intention to be able to connect instruments on the seafloor to submarine cables. To ensure the long-term viability and science return of these observatories, newly designed wellheads will be deployed that are intended to protect the scientific instrument, facilitate servicing by ROV/HOV, and able to accommodate seafloor cable connections.

The surface expression of the new wellhead design is a radical departure from traditional re-entry cone designs used by the ODP and IODP. However, the design dimensions of the mud skirt have not changed, nor has the interface with the Drill Quip casing hanger assemblies been modified. The mud skirt has been modified to accept modular

assemblies, which includes a substantially smaller re-entry cone module, which are indexed and bolted onto the mud skirt.

Highlights of the design changes include:

- A shape that is trawl-resistant, limiting liability.
- A modular design that allows reconfiguration by an ROV or HOV.
- A re-entry cone that has been reduced from 8-ft vertical height to a 3-ft height and integrated into a removable central module.
- A re-entry cone module that can be removed and replaced by an ROV or HOV.
- Side modules adjacent to the central re-entry cone module that form a shock absorbing structure that is designed to withstand and deflect drillpipe hits.
- ROV-serviceable science and submarine-cable communications modules that replace the drilling modules after borehole completion.
- A wellhead designed to accept an ROV-serviceable mini-packer for sealing the well opening.
- ROV-serviceable fluid and electrical connections to a casing manifold.
- A non-corrosive ROV hot stab for making downhole fluid connections.

These designs are available for implementation on future IODP borehole observatories and will be posted on an IODP website in the near future.

Data Report: Long-term Temperature Measurements in Holes 1253A and 1255A off Costa Rica, ODP Leg 205

Martin Heesemann[1], Heinrich Villinger[1], Hans W. Jannasch[2], Miriam Kastner[3], and the IODP-Expedition 301T Scientists

[1] Universität Bremen, Department of Geoscience, Klagenfurter Strasse, 28359 Bremen, Germany. heesema@uni-bremen.de
[2] Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing CA 95039, USA.
[3] Scripps Institution of Oceanography, University of California, San Diego, Geoscience Research Division, 8615 Discovery Way, La Jolla CA 92093

ABSTRACT

Long-term temperature measurements using miniaturized temperature loggers (MTLs) were performed in Ocean Drilling Program Holes 1253A and 1255A across the Middle America Trench off the Nicoya Peninsula, Costa Rica. All three recovered loggers, which were retrieved fully functional, provided high-resolution temperature records. These records cover a time span of ~2 yr and were sampled at an interval of 17 min. There are a number of signals in the temperature data that are most likely caused by hydrologic events. These events are also present in the pressure data recorded by CORK-IIs that are installed in these boreholes. Moreover, the temperature data are important input parameters for calculating pumping rates of the OsmoSamplers, within which the MTLs were integrated. Therefore, the MTL temperature records combined with the CORK-II pressure measurements and the data from the OsmoSampler fluid samples allow the investigation of subduction zone hydrologic processes.

Measuring Temporal Variability in Pore-Fluid Chemistry Within Gulf of Mexico Hydrate-Bearing Sediments

Laura Lapham[1], Jeff Chanton[1], Chris Martens[2], Paul Higley, Hans Jannasch[3], and Bob Woolsey[4]

[1] Department of Oceanography, Florida State University, Tallahassee, FL
[2] Department of Geological Sciences, University of North Carolina at Chapel Hill
[3] Monterey Bay Aquarium Research Institute, Moss Landing, CA
[4] Department of Geosciences, Mississippi State University, Starkville, MS

ABSTRACT

Hydrate formation and decomposition events may result in temporal changes of methane, chloride, and sulfate concentrations dissolved within pore-fluids. To follow such changes and collect pore-fluids over time, we designed a specialized Pore-Fluid Array (PFA) made up of an interchangeable instrument package that houses four individual OsmoSamplers (Jannasch et al., 2004), a connector that allows the instrument package to be changed out while minimizing sample disruption, and a 10-meter long probe tip along which 8-filtered ports are evenly spaced. At each port, pore-fluids are slowly pumped up the probe tip, across the connector, and into long length of small-diameter tubing coil using OsmoSampler technology to collect ~4 months data with week resolution. Two of the four samplers were plumbed into a high-pressure valve that, when closed on the seafloor, kept the sample from degassing upon ascent through the water column. In May 2005, the PFA was deployed at a cold seep site in Mississippi Canyon lease block 118 (MC 118), Gulf of Mexico, on the northern edge of a bright acoustic seafloor anomaly known to have outcropping hydrate. After 1.5 years, the PFA's instrument package was successfully recovered and the individual OsmoSamplers were found to be collecting from the overlying water, 1.2 m, 3.2 m, and 8.5 m below the seafloor. From the sampler coils, pore-fluids were extracted and measured for chloride, sulfate, and methane concentrations and methane isotope ratios. The overall results showed normal seawater conditions in the bottom waters, averaging 549 mM chloride and 30 mM sulfate. At deeper depths, there was evidence for brine fluids, averaging 4561 mM chloride and 0.7 mM sulfate. Since brine inhibits hydrate formation, the discovery of brine radically changes the hydrate stability zone. At deeper depths, high methane concentrations were also measured, averaging 4.2 mM with a maximum of 14 mM, whose $\delta^{13}C\text{-}CH_4$ averaged -32.35±3.4‰, suggesting a mixed biogenic and thermogenic source. Over the 4 month collection, temporal variations in methane concentrations and isotopic ratios suggest this mixed source methane is accompanied by spikes of purely thermogenic fluid. Although hydrate formation and decomposition events were not evident in this deployment due to the presence of the brine, the PFA is a valuable instrument needed to follow hydrate formation and decomposition over time.

Catastrophic Seepage and Hydrate Climate Impact

Ira Leifer[1,3], Jim Boles[2], Jordan F. Clark[2], and Bruce P. Luyendyk[2,3]

[1] Marine Science Institute, University of California, Santa Barbara, CA,
ira.leifer@bubbleology.com
[2] Department of Earth Science, University of California, Santa Barbara
[3] Institute for Crustal Studies, University of California, Santa Barbara

ABSTRACT

The emission of methane that is trapped in deep-sea methane hydrates has been postulated to explain abrupt climate change; however, dissolution to the water column presents a sever obstacle to its effect on the atmosphere. We present quantitative observations of methane emissions from a blowout from a shallow (22 m) hydrocarbon seep. Emissions were determined from atmospheric plume measurements. Observations for the blowout and for non-blowout seepage were used to validate a bubble propagation model. Simulations suggest a 1.1% gas loss to dissolution compared to ~10% loss for a typical low-flux bubble plume for this shallow blowout. Transport to the atmosphere largely was enhanced by the rapid upwelling flows induced by the massive discharge. Model simulations for deeper blowouts suggest that similar size blow-outs within the hydrate stability zone could allow a significant fraction of the emitted methane to atmospheric methane budgets.

Passive and Active Vector Acoustic Observatories for Monitoring and Imaging of Hydrate Deposits

Dennis Lindwall

Marine Geosciences Division, Naval Research Laboratory, Stennis Space Center, MS 39529, lindwall@nrlssc.navy.mil

ABSTRACT

Using newly developed vector acoustic sensors we can locate sound sources in three dimensions using a very small number of sensors. When we employ a pulsed sound generator, we can generate 3D images of multiple, discrete, scattering targets with a single, fixed vector acoustic sensor. We demonstrated this concept in a scaled water tank experiment. Vector acoustic observatories could be deployed next to a borehole in hydrate regions that have associated fluid flow. These passive observatories could monitor not just the level of activity but map the location in 3D of the sound-generating fluid flow. They would be anchored on the bottom and floating in the water column. The vector sensor in the water retains near ideal coupling with the particle motion in the water unlike bottom mounted geophones or even down-hole geophones. The high-fidelity coupling allows for more reliable and accurate directional sensing. The addition of active sound sources, surface towed, bottom or down-hole mounted, would enable one to image the hydrate deposits. A water-column towed source would enable one to survey the general region. A bottom mounted or borehole mounted seismic source would generate shear waves as well as compressional waves. Shear waves should scatter more strongly than comperssional waves off of hydrate deposits and may allow for differentiation of gas and solid hydrates. Near-borehole observatories would be a valuable addition to downhole sensors for short term imaging of local geological structures as well as long term monitoring of fluid flow activity. This work was supported by the Office of Naval Research, program element 61153N.

Using Ambient Noise to Image the Interior of a Carbonate/Hydrate Mound

Tom McGee[1], Peter Gerstoft[2], and Ross Chapman[3]

[1] Center for Marine Resources and Environmental Technology, University of Mississippi
[2] Marine Physical Laboratory, University of California - San Diego
[3] School of Earth and Ocean Sciences, University of Victoria, B. C.

ABSTRACT

A sea-floor observatory is being installed in Mississippi Canyon Lease Block 118 (MC118) by the Gulf of Mexico Hydrates Research Consortium. MC118 is located about 100km southwest of the mouth of the Mississippi River. The sea floor there is within the hydrate stability zone. The observatory will use ambient seismo-acoustic noise to monitor physical changes within a carbonate/hydrate mound over five-to-ten years.

The block has been surveyed by an AUV equipped with a swath fathometer. An oblique view of the resulting bathymetric image is shown. The sea floor is seen to be smooth except for a canyon that cuts across the northeast corner of the block and a region of irregular bathymetry in its south-central portion. The irregular bathymetry shows the kilometer-wide carbonate/hydrate mound to be monitored is at about 900m depth.

The observatory includes six line arrays of seismo-acoustic sensors: a vertical watercolumn array, four horizontal sea-floor arrays cross configuration and a vertical array in a borehole. At first these arrays will be used with artificial sources at known locations to generate a model of the mound's interior. Later, they will operate in a passive listening mode to record ambient noise, i.e. passing ships, wind and waves at the water surface, microseisms, etc.

The impulse response of each propagation path between pairs of sensors can be determined by processing ambient signals from all possible sensor pairs. Doing this over a period of time long enough to include noise sources that are distributed more-or-less uniformly around the mound will allow a tomographic image of the interior of the mound to be generated. Doing this over a much longer period of time will generate a sequence of images that reveal any internal changes that may occur. Examples in recent literature demonstrate that this method, known as seismic interferometry, is extremely sensitive to small changes in the medium of propagation.

Why and How Hydrates Fill Fractures in Soft Sediments

T. M. McGee[1], C. B. Lutken[1], R. E. Rogers[2], C. A. Brunner[3], J. S. Dearman[2], F. L. Lynch[4], and J. R. Woolsey[1]

[1] Center for Marine Resources and Environmental Technology, University of Mississippi, Oxford, MS
[2] Department of Chemical Engineering, Mississippi State University, Starkville, MS
[3] Department of Marine Science, University of Southern Mississippi, Stennis Space Center, MS
[4] Department of Geosciences, Mississippi State University, Starkville, MS

ABSTRACT

The Gulf of Mexico Hydrate Research Consortium has postulated that gas hydrate occurs in fine-grained sediments by filling fracture porosity. That was confirmed recently when fracture-filling hydrate was observed on x-ray images of fine-grained cores recovered under *in-situ* pressure. Laboratory experiments sponsored by the Consortium reveal why the fracture filling occurs. Those experiments show that biosurfactants produced by the microbe *Bacillus subtilis* catalyze hydrate formation, increasing its rate by orders of magnitude and decreasing the length of time prior to its onset. The experiments also show that biosurfactants promote hydrate nucleation on particles of smectite clay but not on kaolinite clay particles or quartz sand grains.

These findings have particular relevance in the northern Gulf of Mexico where smectite is a significant fraction of the fine-grained hemipelagic material that covers much of the sea floor. The material occurs in the water column as “marine snow” and is deposited on the sea floor as a gel. Soon after deposition, the gel develops a state of internal tension that produces a system of interconnected extensional fractures. Smectite is exposed along the walls of the fractures where it provides nucleation sites when conditions are favorable for hydrate formation.

Evidence is presented that it is possible, perhaps even probable, that a system of extensional faults exists within portions of MC798. If so, it could provide fracture porosity that would facilitate circulation of fluids past smectite particles lining the fracture walls. If the fluids contain water and hydrocarbon gas, hydrates would form within the fractures. Convincing evidence for this would be a horizontal slice through a 3-D volume that confirms that extensional faults intersect in a polygonal pattern. It has been demonstrated that such suitably high-resolution 3-D volume can be obtained using an AUV.

Borehole Monitoring of Gas Hydrates for Future Drilling Well

Fulong Ning[1], Guosheng Jiang[1], and Xiang Wu[1]

[1] China University of Geosicences, Wuhan,China

ABSTRACT

One of the goals of setting gas-hydrate observatories should be served for drilling well of the future gas hydrate exploitation.

Gas Hydrate Drilling Problems

The environment of drilling is very poor because gas hydrate deposits exist mostly in the permafrost and deep ocean zones. Besides, the formations containing gas hydrates are weak and friable and the hydrates are very unstable. These factors cause the complicated drilling problems (Fig 1). Sampling difficulty, borehole instability such as collapse and enlarged hole, kick and even blowout are main challenges. To realize controlled and safe drilling, some measures should be taken to confront the challenges. Detecting gas hydrates prior to drilling is a good method so that hydrate-bearing sediments can be avoided or safely managed where avoidance is not feasible or necessary. In addition, proper drilling fluids which have the right density and low temperature and penetration rate are also available means to prevent gas hydrates from dissociating largely.(Ning Fulong,2005). However, if we want to carry out these measurements successfully, we must character the gas hydrates and its bearing formations in situ. Therefore, some properties and their changes need monitoring in the gas-hydrate observatories.

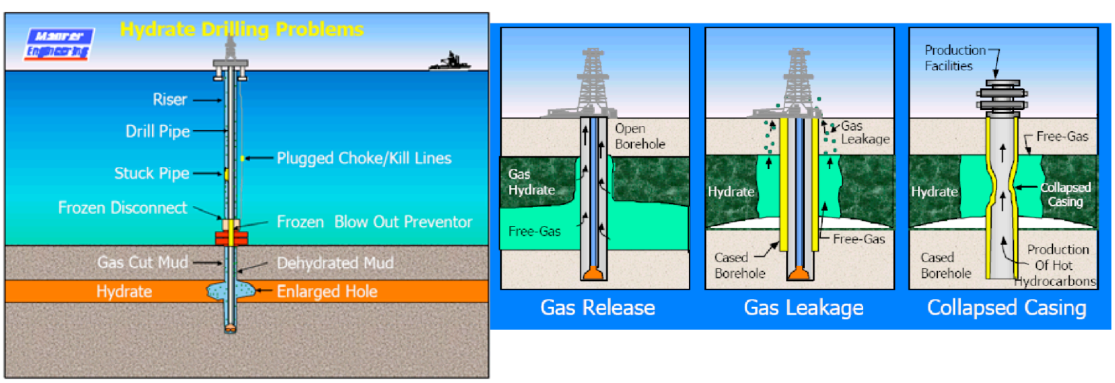


Fig.1 The problems of gas hydrate drilling

Main properties which should be monitored by gas-hydrate observatories from the viewpoint of drilling

Obviously temperature and pressure in situ should be monitored and recorded firstly, the same with other goals. In order to detect gas hydrates prior to drilling, acoustic, resistive or electromagnetic properties and distribution model of gas hydrates bearing formations need to be acquired, such parameters should be observed as density, acoustic velocity, resistivity and frequency etc. To study the borehole stability and safety, it also needs to obtain the physical and mechanics properties such as saturation of gas hydrate in sediments, porous water pressure, porosity, permeability etc. Besides, the gas component and pore water salinity are also needed and should be considered.

How to observe these parameters

The University of Mississippi carried out the Gulf of Mexico Gas Hydrates Seafloor Observatory Project with the support of DOE (Fig 2). Texas A&M University observed the hydrate mound of the GOM slope with the support of DOE-NETL, NSF, NOAA and etc. However, the two observations are both in the sea floor but not in the borehole. In ODP and IODP, CORK and ACORK are borehole observatories and can monitor the thermal and pressure characterization, allow studying the hydrological, chemical, microbiological, and thermal regimes, as well as hydrologic responses to seismic ground motion, tides, and barometric loading. Hence, while considering the geomechanical stability of hydrate-bearing sediments, referring to the experience of MWD and LWD in oil&gas drilling, it may be a feasible way to monitor those parameters through improving ACORK in the borehole. Our idea about gas-hydrate observatory is illustrated as Fig. 3.The key difficulties or problems we think are selection of parameters observed, sensors integration and data transmission.

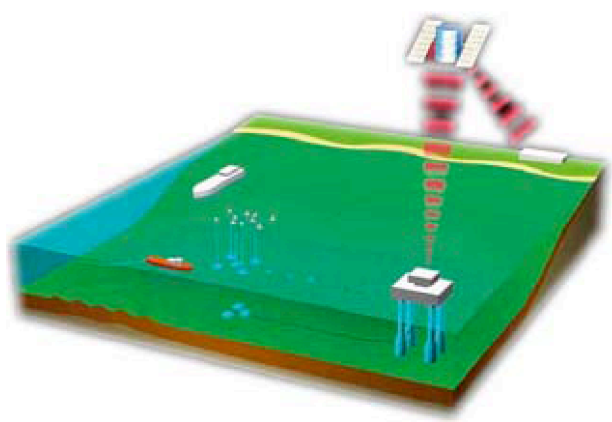


Fig.2 Gulf of Mexico Gas Hydrates Seafloor Observatory

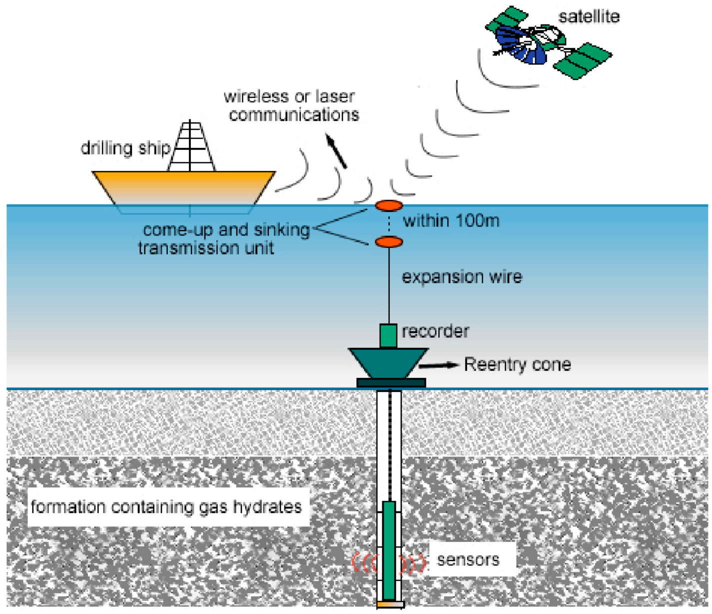


Fig.3 The schematic diagram of gas-hydrate Observatory

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Making the Case for In Situ Characterization of Gas Hydrate-Bearing Sediments at Observatories: Laboratory and Catwalk Results Testing the Impact of Core Retrieval

J. Carlos Santamarina[1], C. Ruppel[2], J.Y. Lee[3], and T.S. Yun[3]

[1] School of Civil and Environmental Engineering, Georgia Tech; carlos@ce.gatech.edu
[2] U.S. Geological Survey, 384 Woods Hole Rd., Woods Hole, MA; cruppel@usgs.gov
[3] School of Civil and Environmental Engineering, Georgia Tech, Atlanta

ABSTRACT

A major motivation for gas hydrate observatories is the need to characterize gas hydrate reservoirs under *in situ* conditions. Results obtained at Georgia Tech since 2002 provide two key classes of results (laboratory experiments on natural and synthetic cores and catwalk measurements on pressure cores) that underscore the need for in situ characterization of hydrate-bearing sediments, either in an observatory setting or during/just after drilling:

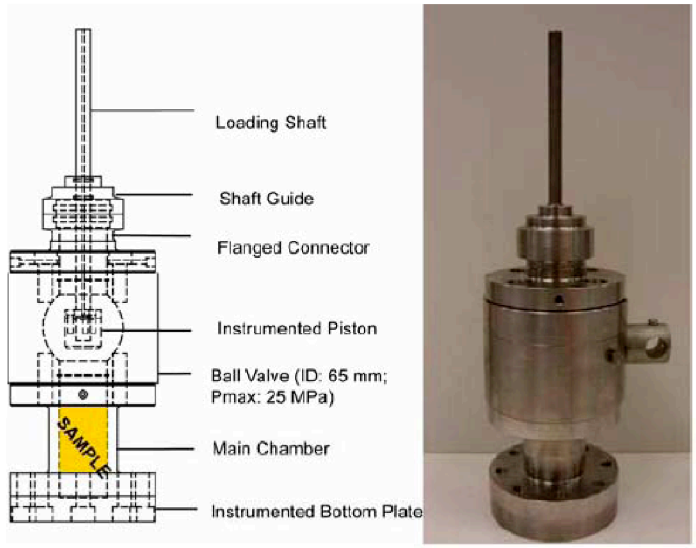
1. ***Laboratory experiments*** to measure the mechanical, seismic, and electrical properties of sand, silts (precipitated and crushed), and clay subjected to different confining pressures and containing well-controlled concentrations of THF hydrate (from 0% to 100% of pore space) formed from the dissolved phase demonstrate clear changes in the properties of hydrate-bearing sediments during unloading and during phase transformation (Yun et al., 2005, 2007; Lee, 2007). Similar experiments were conducted on natural Gulf of Mexico sediments in which we formed synthetic gas hydrate with THF (Lee et al., in review). Recently, we demonstrated that THF and methane interact with sediments and pore fluids in a similar way and that THF hydrate is an apt analog for methane hydrate for mechanical experiments (Lee et al., 2007).

Our results on synthetic and natural cores containing synthetic hydrates show that laboratory recovery of the in situ physical properties of hydrate-bearing sediments are best when the sediment fabric experiences the least disruption during coring and the subsequent retrieval/hydrate phase transformation process (Lee et al., in review). The best prospect for sampling hydrate-bearing sediments and measuring laboratory properties that are representative of the in situ characteristics is to obtain cores subject to low in situ vertical effective stress (so that expansion due to stress relaxation is low) and with high hydrate concentration (probably >50%) using thin-wall samplers that cause only minimal strains during sampling. Restoring vertical effective stress on the core as quickly as possible after retrieval is also critical (Lee, 2007). Because most natural gas hydrate deposits do not occur at shallow depths (low vertical effective stress) or have gas hydrate concentrations >50% of pore space, it is generally advisable to study hydratebearing samples either in situ or using pressure core samples for which effective stress can be rapidly restored.

2. ***Catwalk measurements***. In 2005 and 2006, a special pressure chamber (Instrumented Pressure Testing Chamber or IPTC) developed at Georgia Tech was used to measure the physical properties of IODP-style pressure cores obtained in the Gulf of Mexico (GoMex) as part of the DOE-Chevron Joint Industry Project and off India as part of the National Gas Hydrate Project. These “catwalk measurements” represented the first time that a suite of physical properties measurements was ever collected on pressure core material that had never been subjected to depressurization and that had been maintained at *in situ* hydrostatic pressure (Yun et al., 2006). The GoMex cores did not contain gas hydrate, while the Indian cores did. For the Indian project, the IPTC was also used to monitor changes in physical properties during depressurization of a hydrate-bearing core as part of a mini-production test.

A comparison of seismic velocities, undrained strength, and electrical properties measured on conventional cores, conventional cores that have been repressurized, and pressure cores that had never experienced depressurization demonstrates that the pressure cores yield seismic velocities closest to those determined in situ by downhole logging.

The first generation IPTC operated on full-length (~1 m) pressure cores at in situ hydrostatic pressures. The IPTC drilled through the core liner to access core material for various physical properties measurements (Yun et al., 2006). A second generation chamber has now been developed with JOI and JIP funding and is available for use in IODP programs. This chamber, shown below, accommodates a whole round section (up to 100-mm-long) that has been extracted from a pressure core by third party instrumentation. With the new chamber, we can restore vertical effective stress, while maintaining the hydrostatic pressure at in situ conditions at all times. The new chamber, which can accommodate pressure cores obtained with either the Fugro (FPC) or HYACINTH (HPC) pressure coring systems, is instrumented to measure P- and S-wave velocities, electrical conductivity, and undrained shear strength. This chamber is particularly convenient for small-scale production tests on the undisturbed specimens with simultaneous monitoring of critical mechanical (e.g., volume contraction, produced gas and liquid) and geophysical parameters (Vp, Vs, electrical conductivity and thermal characteristics). Future chambers can be modified for a range of physical and chemical property measurements, for chemical or biological sampling, or even for incubation experiments under in situ conditions, as discussed by Yun et al. (2006).



The new testing chamber developed at Georgia Tech with JOI and JIP support can measure the physical properties of a whole round (up to 100-mm-long) from an IODP (FPC or HPC) pressure core that has never been depressurized and can restore the in situ vertical effective stress, a critical factor in controlling the physical properties of hydratebearing sediments. Currently, third party instrumentation is used for subsampling of the pressure core to extract the whole round section and transfer of the core section through a series of ball valves into the Georgia Tech chamber.

Acknowledgments
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Methane Sensor Deployment for Deep-Sea Observations

Erwin Suess[1,2], Xiqiu Han[3], Jens Greinert[4,5], Anne Krabbenhoeft[6], and Robert Collier[2]

[1] Konsortium Deutsche Meeresforschung (KDM), Markgrafenstr. 37, 10117 Berlin, Germany
[2] College of Atmospheric and Ocean Sciences (COAS), Oregon State University, Corvallis, OR 97331-5503
[3] Key Laboratory of Submarine Science and Second Institute of Oceanography, State Oceanic Administration (SOA), 310012 Huangzhou, Zhejiang, China
[4] Renard Centre of Marine Geology (RCMG), Ghent University, 9000 Gent, Belgium
[5] Geological and Nuclear Science (GNS) 1 FPO Box 31368; Lower Hutt, Avalon, New Zealand
[6] Leibniz-Institute of Marine Sciences at Kiel University (IFM-GEOMAR), 24148 Kiel, Germany

ABSTRACT

Two commercially available methane sensors (METS of Franatech GmbH and HydroC of Contros Systems GmbH, both companies located in Germany) have been deployed for recordings in different oceanic environments and deep-sea tectonic settings for over a decade without a real break through until recently.

Both instruments rely on a gas-selective permeable membrane to create a methane gas phase within a detection chamber. For the METS detection is through a semi-conductor with an active layer that absorbs methane. Absorption leads to an exchange reaction and thus a change in conductivity of the active layer generating an output signal. The reaction is temperature dependent. For the HydroC detection is by optical IR absorption that changes light intensity in generating an output signal. Both companies point to successful applications in off-shore pipeline inspections, exploration of oil and gas deposits, and water and waste water treatment. Detailed specification sheets for each of the sensors are available as well as pricing and other information. We report here on results obtained from two types of METS-sensor (K-series and METS-classic).

In the marine environment, applications have been plagued by great and variable water depth, low methane concentrations, slow response time, instrument drift and memory effects. We have experimented with the METS sensor for over a decade using different modes of deployment, e.g. sensors attached to CTD-casts, deep-tow instruments and most recently sensors attached to ocean bottom seismometers during seismic experiments. Although the output signal in all cases is significant and readily detectable, the conversion to methane concentration sometimes has not been easy using the manufacturer-supplied calibration equations.

Stationary deployment

Our best and most reliable results are derived from stationary deployment over several days at the seafloor with the sensors attached to OBS-units. Hereby ambient temperature and pressure are kept constant, greatly reducing most of the problems encountered with dynamic deployment. Positioning the sensor at water depths within the limits given by the manufacturers, generally not deeper than 2000 m, prevented any pressure related failures that have occurred in the case of deep-towed dynamic deployments exceeding 3000 m. Detectable concentration changes were generally <10 to >100 nM, in rare cases 2 nM of methane, as confirmed by discrete water sampling from CTD casts and subsequent gas stripping or head-space equilibration and gas chromatographic measurements.

The data from stationary deployment were obtained at active cold seeps (700-1200m) from the Hikurangi convergent margin off northern New Zealand during RV SONNEcruises early in 2007. Results from three stations are discussed, 2 from active vent sites, about 9 km apart and recorded simultaneously for 3 days and 1 off-vent site station recorded for 2 days. Data show extreme dynamics in frequency and magnitude of methane emissions. Tidal control as well as spatial coherency, as previously detected by visual recordings between vent sites, is not immediately obvious, although final analysis has yet to be completed.

Dynamic deployment

Equally encouraging results were recorded during deep-towed search for hydrothermal venting along spreading segments of the Indian Ocean Ridge. Both types of METSsensors were deployed with an array of turbidity-sensors attached to the conducting cable of a deep-towed vehicle. A self-contained package, consisting of a sensor and a CTD-unit for data storage and power supply, is positioned at pre-determined depth above the towed vehicle, usually between 250-350 m. As the vehicle follows the bottom morphology closely, the sensor depths vary and often exceed 3000 m when descending the ridge flanks causing instrument failure due to great hydrostatic pressure. The strongest and most reliably calibrated methane signals were observed over the active hydrothermal vent fields EDMOND and KAIREI on the Central Indian Ridge during RV DAYANG YI HAO Cruises in late 2005 and early 2007, respectively. Over the EDMOND field a highly detailed plume structure and rapid sensor response was recorded while transiting the hydrothermal plume (DY-105-17A, Leg IR). However, since the temperature also changed during transit and up-cast of the instrument, the effect on the methane signal had to be corrected and hence calibration became uncertain (70±20 nM). Clearly though, the nature of the methane plume was ascertained and corroborated by simultaneously recorded turbidity anomalies. During a follow-up search for hydrothermal activity in early 2007 (DY-115-19, Leg 3) the same deep-towed set-up with a METSclassic sensor was deployed over the nearby KAIREI field. A clear methane plume was recorded here with maximum methane of 59.5 nM.

Previous successful dynamic deployment of METS was at an active vent site of the Hikurangi margin and recently published by Faure et al. 2006 (New Zealand J. Geol. And Geophys. 49, 503-516). The data were obtained by sensors mounted to a CTD-optical backscatter device that was towed across an active cold seep mound. Methane background concentrations were between 2-4 nM and a plume maximum >8 nM was detected at the flank of the mound coinciding with the increased light scattering. The methane concentrations were verified by discrete CTD-sampling. A 20-minute delay between the METS-signal and CTD-derived methane content is attributed to the slow response time of the sensor. This observation appears to contradict the rapid sensor response observed with the recent models deployed at the Indian Ridge and mounted to the OBS-units, as described above.

The least convincing yet undisputable positive methane recordings were obtained from sensors attached to CTD-casts. Data of four casts obtained by RV SONNE in early 2007 are provided from another active vent site of the Hikurangi margin. Discrete water sampling and gas stripping for GC-detection shows a highly stratified methane plumes with 2 thin layers of maximum methane (>150 nM) around 800 and 1300 m of depth. The corresponding sensor records however show a single broad maximum over that depth whereby the minima are completely wiped out. Broadening of the maxima with little or now structure and suppressing of the minima appears clearly related to the temperature effect on the methane signal as the ambient water temperature changes from <4° to >7° C during up-cast over the methane-containing water strata.

Consideration for methane sensor deployment at ocean observatories

Maintaining an air space in the detector head requires that the membrane be supported to withstand high hydrostatic pressures. The METS K-series sensor provides such a pressure support for depth up to 3500 m, the HydoC-sensor for 4000 m. This feature is not required for their normal commercial use at ambient pressures or shallow ocean margins depths. Our results have shown that water depths of up to 2000m do not pose a problem; even at around 3000m recordings were still possible with METS K-series and classic models. Depending on the depth of planned gas hydrate observatory stations, there might be no limitation at all.

The calibrated and tested range of detection for commercial use (METS = 50 nM to 10 µM; HydroC = 100 nM to50 µM) is higher than what is expected for transient seafloor methane plumes (<10 nM). However, stationary plumes might easily reach high concentration near the seafloor and hence the calibrated versions might directly be deployable at gas hydrate observatory stations or other types of seafloor observatories. An obstacle for the METS-sensor seems to be temperature variations encountered during dynamic deployment in ocean environments. These affect the conductivity of the active layer of the semi-conductor in the heated air-space and thus interfere with methane detection. The temperature of the heated space in the detector head must be accurately known in order to compensate the temperature effect during calibration. CONTROS claims no such limitation exist for the HydoC-sensor. To our knowledge this claim has not been tested. For METS the problem caused by temperature variations can be totally overcome by the stationary deployment as illustrated now for the first time by the OBSmounted sensors. This deployment mode seems closest to that envisioned for gas hydrate observatories.

The successful deployments reported here from OBS-mounted METS-sensors were intended as tests for another important new application currently underway to complement passive seismic recordings for tsunami early warning systems. Fluctuations in methane emissions might be earthquake precursor signals and hence provide critical information of impending seismic events.