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Methane Hydrate Field Program

Project Period (October 1, 2012 - December 31, 2013)

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Office of Fossil Energy

Development of a Scientific Plan for a Methane Hydrate-Focused Marine Drilling, Logging and Coring Program

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Principal Author: Consortium for Ocean Leadership

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Project Title: **Methane Hydrate Field Program: Development of a Scientific Plan for a Methane Hydrate-Focused Marine Drilling, Logging and Coring Program**

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Abstract: This final report document summarizes the activities undertaken and the output from three primary deliverables generated during this project. This fifteen month effort comprised numerous key steps including the creation of an international methane hydrate science team, determining and reporting the current state of marine methane hydrate research, convening an international workshop to collect the ideas needed to write a comprehensive Marine Methane Hydrate Field Research Plan and the development and publication of that plan.

The following documents represent the primary deliverables of this project and are discussed in summary level detail in this final report.

- Historical Methane Hydrate Project Review Report
- Methane Hydrate Workshop Report
- Topical Report: Marine Methane Hydrate Field Research Plan
- Final Scientific/Technical Report

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1 Executive Summary

This fifteen month effort led to the completion of numerous key deliverables including the creation of an international methane hydrate science team, determining and reporting the current state of marine methane hydrate research, convening an international workshop and creating a comprehensive Marine Methane Hydrate Field Research Plan, with all materials being disseminated to the international science community at www.oceanleadership.org/methane. This final report summarizes these activities in the sequence they were completed. This report concludes with a series of recommendations in section 7.5 plan which suggests solutions to address the science and technical challenges including recommended field research locations and recommendations for future actions.

2 Introduction

In 2012, the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL), in partnership with the Consortium for Ocean Leadership (COL), initiated a new field-focused methane hydrate research project that would inform, and potentially lead to, future offshore drilling field expeditions. The primary objective of this project was to conduct planning that would help define and enable future ocean drilling, coring, logging, testing, and analytical activities to assess the geologic occurrence, regional context, and characteristics of methane hydrate deposits along U.S. continental margins. It was also envisioned that this effort would reach out to the international research community to develop a more global vision of methane hydrate research goals and needs. To this end, COL led an effort to identify the range of scientific questions and unknowns that need to be addressed within hydrate science and worked within the methane hydrate research community to solicit input and develop a comprehensive Marine Methane Hydrate Field Research Plan (the Science Plan). This report is the culmination of this effort.

To implement and guide this effort COL carried out several critical steps during the progression of the project. These included:

(1) formation of a Methane Hydrate Project Science Team consisting of representatives from academia, industry, and government who steered this effort from start to completion,
(2) authoring of a Historical Methane Hydrate Project Review Report[1] used as a guide to develop the agenda for a Methane Hydrate Community Workshop and provide the foundation for the Methane Hydrate Field Research Science Plan,
(3) hosting of the Methane Hydrate Community Workshop with the goal of obtaining input from a broad section of the hydrate scientific community to identify and assess specific scientific challenges that must be addressed to advance our understanding of methane hydrates and how these challenges could be resolved with the support of scientific drilling (Workshop results were captured in a report and posted on the COL project website).
(4) development and publication of a comprehensive Marine Methane Hydrate Field Research Plan which considers in detail the critical science and technical challenges associated with marine methane hydrate research, potential solutions to address those challenges and recommendations for potential future field research locations and activities.

These key activities and outputs are used as the framework for this final project scientific and technical report in the sections to follow.

[1] Historical Methane Hydrate Project Review Report, Consortium for Ocean Leadership, http://www.oceanleadership.org/scientific-programs/methane-hydrate-field-program

[2] Methane Hydrate Community Workshop Report, Consortium for Ocean Leadership, http://www.oceanleadership.org/scientific-programs/methane-hydrate-field-program

3 Formation of Methane Hydrate Science Team

The Project Execution Plan established a path to ultimately create the Marine Methane Hydrate Field Research Plan which included several key personnel acquisition steps. One of the most important steps was forming a science team comprised of international experts, each with unique perspectives and skillsets to create a well-rounded team. Attaining objective and accurate input from the team was vital to the success of the project. The all-volunteer team came from academia, government and the oil and gas industry and members possessed expertise including: marine methane hydrate formation and physical properties, production, geohazard, and potential climate impact. All team members participated in biweekly conference calls for many months and also attended the hydrate community workshop and field plan document writing events.

The Methane Hydrate Science Team members are listed below:

Tim Collett – Community Liaison and Team Leader
U.S. Geological Survey

Jang-Jun Bahk
Korea Institute of Geoscience and Mineral Resources

Matt Frye
U.S. Bureau of Ocean Energy Management

Dave Goldberg
Lamont-Doherty Earth Observatory

Jarle Husebø
Statoil ASA

Carolyn Koh
Colorado School of Mines

Mitch Malone
Texas A&M University

Craig Shipp
Shell International Exploration and Production Inc.

Marta Torres
Oregon State University

4 Methane Hydrate Technical Review

The first task of the Methane Hydrate Science Team was to conduct a review of marine methane hydrate research to date. This began with the brief Methane Hydrate Technical Review that states the well-understood fundamentals of methane hydrate.

To aid those who are not familiar with methane hydrate science, the following discussion serves as a primer. Natural methane hydrate is a combination of two common substances, water and natural gas. If gas and water meet under suitable conditions of high pressure and low temperature, they join to form an ice-like solid substance. Beneath Earth's ocean and polar regions are areas conducive to methane hydrate formation. In fact, numerous field studies have shown that natural methane hydrate is widespread in permafrost regions and beneath the sea in sediments of outer continental margins (Figure 1).

Methane hydrates are crystalline compounds that result from the three-dimensional stacking of "cages" of hydrogen-bonded water molecules. Generally, each cage can hold a single gas molecule (Figure 2). Natural methane hydrates are clathrates, meaning that "guest" gas molecules are encaged in a "host" framework of water molecules. The empty cagework is unstable, and requires the presence of encapsulated gas molecules to stabilize the clathrate crystal. The compact nature of the hydrate structure makes for highly effective packing of gas. A volume of methane hydrate expands between 150- and 180-fold when released in gaseous form at standard pressure and temperature (1 kPa, 20°C).

Clathrate hydrates can form in the presence of gas molecules over the size range of 0.48–0.90 nanometers (nm). There are three distinct structural types, and generally the structure that is formed depends on the size of the largest guest molecules. There are considerable complexities in the structure-size relation; however, methane and ethane individually form Structure I (sI) hydrate, but in certain combinations also form Structure II (sII) hydrate (Figure 2). Propane and isobutane form sII hydrate, either individually or in combination with ethane and methane. Normal butane and neopentane form sII hydrate only when methane is present as well, and larger hydrocarbon molecules (C5-C9) form Structure H (sH) hydrate, again where methane is present (Figure 2).

The methane hydrate structures encountered in nature reflect the composition of the gas included in the hydrate, with the abundance of each structural type dependent on the relative amount of each type of hydrocarbon molecule. In sediments that contain only biogenic methane, sI hydrate occurs; this is the predominant type of hydrate in marine environments. Thermogenic gas produced by thermal "cracking" of more deeply buried organic carbon commonly contains a wider range of hydrocarbons in addition to methane. Significant amounts of propane and butane result in sII hydrate being formed. The pressure and temperature stability zone for sII and sH is much greater than for sI hydrate. Incorporation of other non-hydrocarbon gas molecules such as nitrogen, hydrogen sulfide, and carbon dioxide can affect the pressure and temperature stability conditions of all hydrate structures.

On a macroscopic level, many of the mechanical properties of methane hydrates resemble those of ice because hydrates contain about 85% water on a molar basis. Among the exceptions to this heuristic is thermal conductivity, which is relatively low in hydrates—a behavior that can be attributed to the interaction between the guest molecule and the host water framework, an interaction not present in normal ice.

For a complete description of the structure and physical properties of methane hydrates, see the summary by Sloan and Koh (2008).

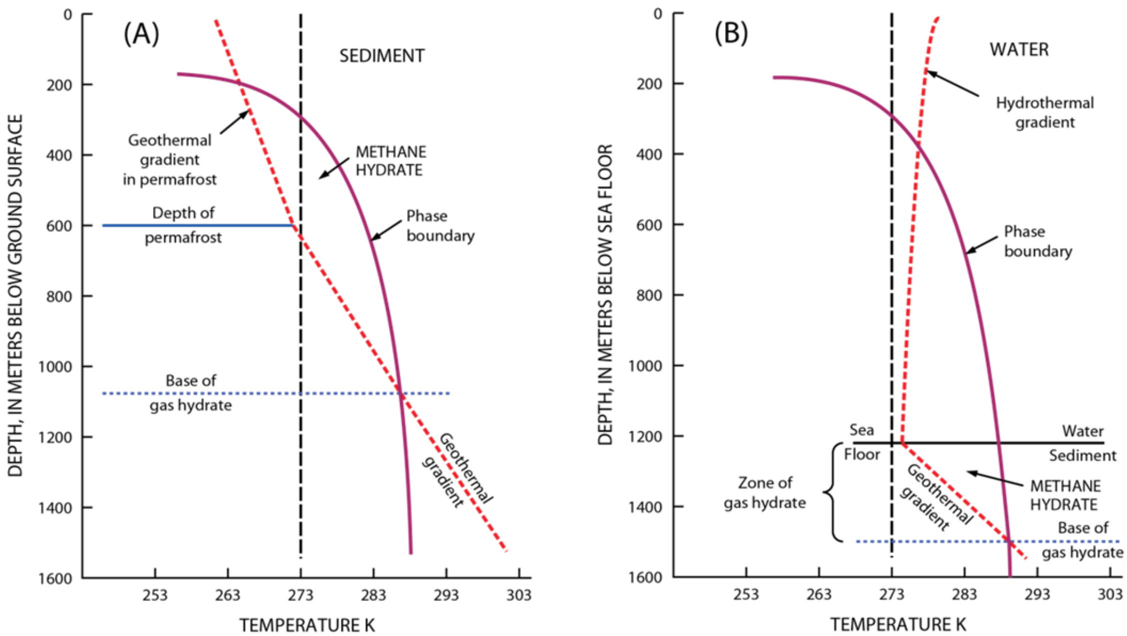

Figure 1. Arbitrary examples of different depth-temperature zones in which methane hydrates are stable: (A), a permafrost region; and (B), an outer continental margin marine setting (modified from Kvenvolden, 1988).

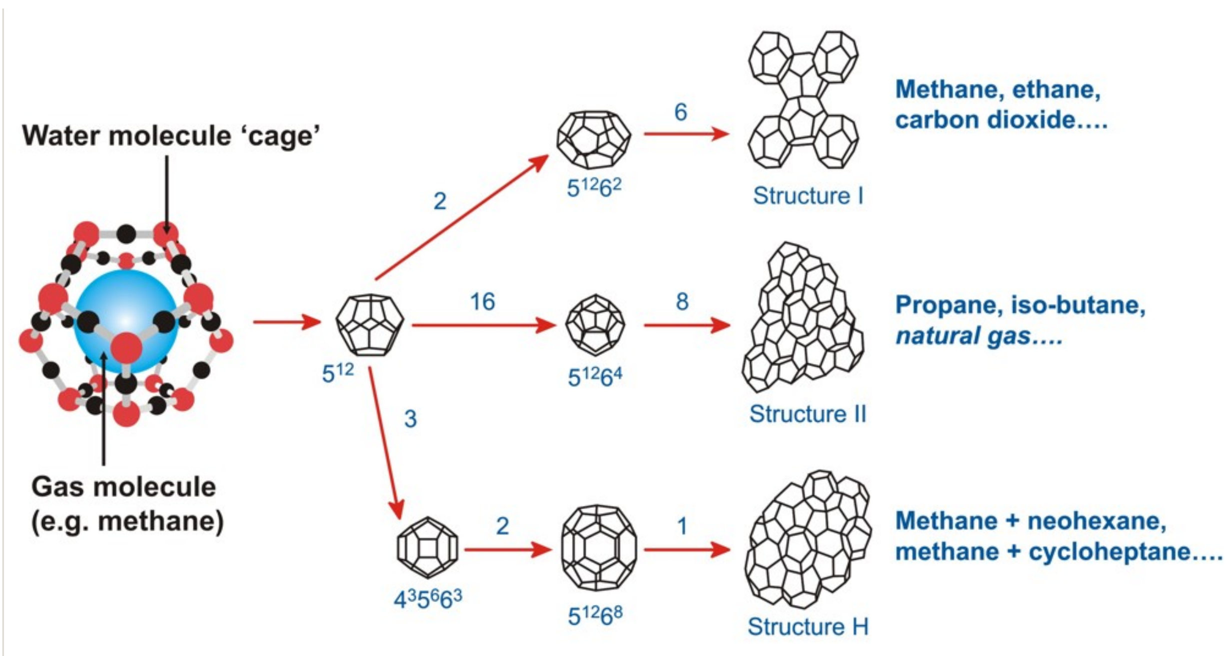

Figure 2. Hydrate crystal structures. The water cages that make-up the hydrate structures are depicted. Also shown are the three structure types that have been observed for hydrates: Structures I, II and H (modified from http://www.pet.hw.ac.uk/research/hydrate/hydrates_what.htm).

5 Historical Methane Hydrate Project Review Report

The development of the Historical Methane Hydrate Project Review Report initiated with performance of an evaluation including a methane hydrate technical review and detailed review of historical methane hydrate research scientific drilling activities throughout the world. This document served as a guide to develop the agenda for the Methane Hydrate Community Workshop (see Section 6) and provided the foundation for the Marine Methane Hydrate Research Plan (see Section 7).

The content included in the section below is a summary of that provided in the full historical review report. The complete technical content of the report can be downloaded in three parts at http://oceanleadership.org/scientific-programs/methane-hydrate-field-program/.

Since 1995, there have been a growing number of marine scientific drilling expeditions dedicated to locating methane hydrates and obtaining a greater understanding of the geologic controls on their occurrence. Some of the most notable projects have been those of the Ocean Drilling Program (ODP) and the Integrated Ocean Drilling Program (IODP), including ODP Legs 164 and 204 and IODP Expedition 311. For the most part, methane hydrate research expeditions carried out by ODP and IODP provided the foundation for our scientific understanding of marine methane hydrates. The methane hydrate research efforts under ODP-IODP have mostly dealt with the assessment of the geologic controls on the occurrence of methane hydrate, with a specific goal to study the role methane hydrates may play in the global carbon cycle.

The map in Figure 3 indicates methane hydrate has been recovered and/or inferred to exist in numerous marine and onshore polar basins. However, as introduced above, only a limited number of accumulations have been examined and delineated with data collected by deep scientific drilling operations. The Historical Methane Hydrate Project Review summarizes the goals and accomplishments of 16 of the more significant methane hydrate research drilling expeditions conducted since the mid-90's.

We have also see the development of strong national led methane hydrate research programs in the United States, Japan, China, Korea, India, and Canada. The most important production land-based field testing programs were conducted at the Mallik site in the Mackenzie River Delta of Canada and in the Eileen methane hydrate accumulation on the North Slope of Alaska. We have also seen the world's first marine methane hydrate production test in the offshore of Japan in the spring of 2013. Industry interest in methane hydrates has also included important projects that have dealt with the assessment of geologic hazards associated with the presence of hydrates. A timeline depicting drilling operations to characterize and produce methane hydrates both on land and at sea is shown in Figure 4.

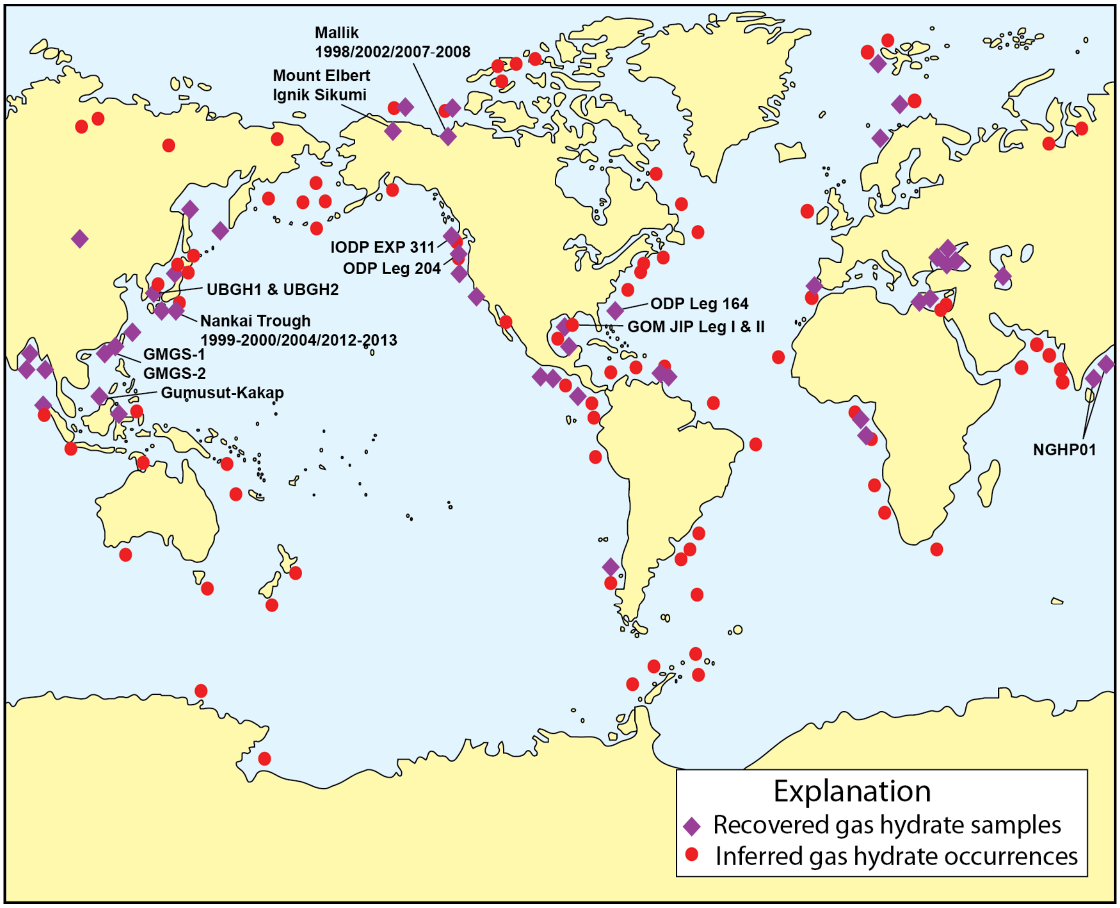

Figure 3. Location of sampled and inferred methane hydrate occurrences in oceanic sediment of outer continental margins and permafrost regions (modified from Kvenvolden, 1993). Most of the recovered methane hydrate samples have been obtained during deep coring projects or shallow seabed coring operations. Most of the inferred methane hydrate occurrences are sites at which bottom simulating reflectors (BSRs) have been observed on available seismic profiles. The methane hydrate research drilling projects and expeditions reviewed in this have also been highlighted on this map.

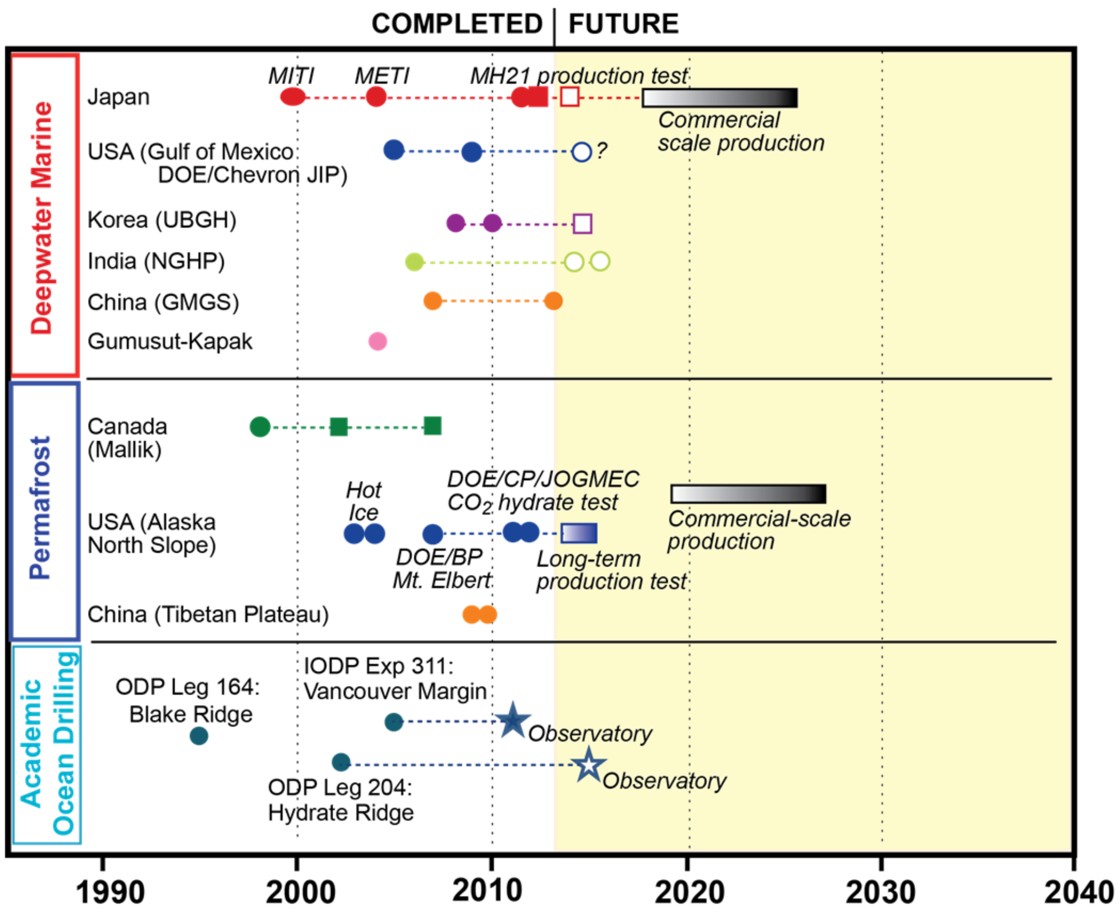

Figure 4. Timeline chart showing the deepwater marine, Arctic permafrost, and academic ocean drilling scientific drilling expeditions dedicated to the research on natural occurring methane hydrates (modified from Ruppel and Collett, 2013).

Historical Perspective

In 1995, the U.S. Geological Survey made the first systematic assessment of the volume of natural gas stored in the hydrate accumulations of the United States. That study, along with numerous other studies, has shown that the amount of gas stored as methane hydrates in the world greatly exceeds the volume of known conventional gas resources. However, gas hydrates represent both a scientific and technical challenge and much remains to be learned about their characteristics and occurrence in nature. Methane hydrate research in recent years has mostly focused on: (1) documenting the geologic parameters that control the occurrence and stability of gas hydrates in nature, (2) assessing the volume of natural gas stored within various gas hydrate accumulations, (3) analyzing the production response and characteristics of methane hydrates, (4) identifying and predicting natural and induced environmental and climate impacts of natural gas hydrates, and (5) analyzing the effects of methane hydrate on drilling safety.

Methane hydrates are naturally occurring crystalline substances composed of water and gas, in which a solid water-lattice holds gas molecules in a cage-like structure. The gas and water becomes a solid under specific temperature and pressure conditions within the Earth, called the hydrate stability zone. Other factors that control the presence of methane hydrate in nature include the source of the gas included within the hydrates, the physical and chemical controls on the migration of gas with a sedimentary basin containing methane hydrates, the availability of the water also included in the hydrate structure, and the presence of a suitable host sediment or “reservoir”. The geologic controls on the occurrence of gas hydrates have become collectively known as the “methane hydrate petroleum system”, which has become the focus of numerous hydrate research programs.

Recognizing the importance of methane hydrate research and the need for a coordinated effort, the U.S. Congress enacted Public Law 106-193, the Methane Hydrate Research and Development Act of 2000. This Act called for the Secretary of Energy to begin a methane hydrate research and development program in consultation with other U.S. federal agencies. At the same time a new methane hydrate research program had been launched in Japan by the Ministry of International Trade and Industry to develop plans for a methane hydrate exploratory drilling project in the Nankai Trough. Since this early start we have seen other countries including India, China, Canada, and the Republic of Korea establish large gas hydrate research and development programs. These national led efforts have also included the investment in a long list of important scientific research drilling expeditions and production test studies that have provided a wealth of information on the occurrence of methane hydrate in nature. The most notable expeditions and projects have including the following:

-Ocean Drilling Program Leg 164 (1995)

-Japan Nankai Trough Project (1999-2000)

-Ocean Drilling Program Leg 204 (2004)

-Japan Toaki-oki to Kumano-nada Project (2004)

-Gulf of Mexico JIP Leg I (2005)

-Integrated Ocean Drilling Program Expedition 311 (2005)

-Malaysia Gumusut-Kakap Project (2006)

-India NGHP Expedition 01 (2006)

-China GMGS Expedition 01 (2007)

-Republic of Korea UBGH Expedition 01 (2007)

-Gulf of Mexico JIP Leg II (2009)

-Republic of Korea UBGH Expedition 02 (2010)

-MH-21 Nankai Trough Pre-Production Expedition (2012-2013)

-Mallik GH Testing Projects (1998/2002/2007-2008)

-Alaska Mount Elbert Stratigraphic Test Well (2007)

-Alaska Iġnik Sikumi Methane Hydrate Production Test Well (2011-2012)

Research coring and seismic programs carried out by the ODP and IODP, starting with the ODP Leg 164 drilling of the Blake Ridge in the Atlantic Ocean in 1995, have also contributed greatly to our understanding of the geologic controls on the formation, occurrence, and stability of gas hydrates in marine environments. For the most part methane hydrate research expeditions carried out by the ODP and IODP provided the foundation for our scientific understanding of gas hydrates. The methane hydrate research efforts under ODP-IODP have mostly dealt with the assessment of the geologic controls on the occurrence of gas hydrate, with a specific goal to study the role methane hydrates may play in the global carbon cycle.

Over the last 10 years, national led methane hydrate research programs, along with industry interest have led to the development and execution of major methane hydrate production field test programs. Two of the most important field testing programs have been conducted at the Mallik site in the Mackenzie River Delta of Canada and in the Eileen methane hydrate accumulation on the North Slope of Alaska. Most recently we have also seen the completion of the world's first marine methane hydrate production test in the Nankai Trough in the offshore of Japan. Industry interest in gas hydrates has also included important projects that have dealt with the assessment of geologic hazards associated with the presence of hydrates.

The scientific drilling and associated coring, logging, and borehole monitoring technologies developed in the long list of methane hydrate related field studies are one of the most important developments and contributions associated with methane hydrate research and development activities. Methane hydrate drilling has been conducted from advanced scientific drilling platforms like the Drilling Vessel (D/V) *JOIDES Resolution* and the *D/V Chikyu*, which feature advanced integrated core laboratories and borehole logging capabilities. Hydrate research drilling has also included the use of a wide array of industry, geotechnical and multi-service ships. All of which have been effectively used to collect invaluable geologic and engineering data on the occurrence of methane hydrates throughout the world. Technologies designed specifically for the collection and analysis of undisturbed methane hydrate samples have included the development of a host of pressure core systems and associated specialty laboratory apparatus. The study and use of both wireline conveyed and logging-while-drilling technologies have also contributed greatly to our understanding of the in-situ nature of hydrate-bearing sediments. Recent developments in borehole instrumentation specifically designed to monitor changes associated with hydrates in nature through time or to evaluate the response of hydrate accumulations to production have also contributed greatly to our understanding of the complex nature and evolution of methane hydrate systems.

The study of methane hydrates in nature has been ongoing for over 40 years but our understanding of how methane hydrates occur in nature is still growing and evolving. Significant strides have been made in our understanding of the occurrence, distribution, and characteristics of marine methane hydrates; but our knowledge related to the role that methane hydrates may play as an energy resource, as a geologic hazard, and as a possible agent in climate change is still incomplete. More work is needed to integrate our methane hydrate related research efforts, while developing a more complete understanding of the critical outstanding research issues to be resolved, to further our understanding of methane hydrates in nature.

6 Methane Hydrate Community Workshop

A three-day international workshop was convened at COL in a concerted effort to solicit the opinions and advice of the methane hydrate community. COL hosted the "Methane Hydrate Community Workshop" in Washington, D.C. on June 4-6, 2013 with the purpose of obtaining input from a broad section of the scientific community. This workshop provided an excellent learning opportunity, as well as a venue for the exchange of ideas among a highly interdisciplinary group of scientists. The workshop was attended by over 60 scientists and engineers from academia, industry and government with the express purpose of working together to develop the content that would be used by the Methane Hydrate Science Team to prepare a Marine Methane Hydrate Field Science Plan.

The workshop focused on the identification and assessment of specific scientific challenges that must be dealt with to advance our understanding of methane hydrates and how these challenges can be resolved with the support of scientific drilling. In preparation for this workshop, the COL-DOE Methane Hydrate Science Team worked with other members of the methane hydrate science community to focus on an initial list of methane hydrate challenges around which the workshop was organized.

The initial challenges prepared by the Methane Hydrate Science Team around which the workshop was organized were:

1. Methane Hydrate Resource Assessment
2. Methane Hydrate Production Analysis
3. Methane Hydrate Related Geohazards
4. Methane Hydrate Role in the Global Carbon Cycle
5. Methane Hydrate Petroleum Systems
6. Methane Hydrate Laboratory and Field Characterization

This list of challenges was not intended to represent the entire range of methane hydrate research interest or limit the scope of the workshop. The initial list of challenges was considered only a starting point to help organize the workshop.

This three-day long event featured a series of plenary presentations to introduce and explore some of the more important methane hydrate research challenges. Most of the workshop, however, was built around three topical breakout sessions developed in tandem with the initial list of methane hydrate research challenges. The breakout sessions strived to further refine our collective understanding of each of the challenges being considered and at the same time explore other challenges and opportunities. One of the key goals of the breakout sessions was the consideration and the potential proposal of specific scientific drilling expeditions that would address a particular methane hydrate science challenge or a range of challenges. The proposed expeditions are listed in section 7.5 below.

The specific outcomes of the workshop were captured in a Workshop Report which can be found at www.oceanleadership.org/methane . This workshop report is a record of the procedures and notes generated as a result of the workshop planning and execution efforts. This report does not attempt to make any final conclusions regarding the science goals or field program targets. The Marine Methane Hydrate Field Science Plan prepared by the science team distilled the output from the workshop and provides a clear path forward for the future methane hydrate research. Output from this Community Workshop served as a basis, in combination with the Historical Hydrate Project Review, for the generation of content included in the Marine Methane Hydrate Field Research Plan (Science Plan) that is discussed in Section 7 below.

7 Marine Methane Hydrate Field Research Plan

Following the methane hydrate workshop, the Marine Methane Hydrate Field Research Plan was built around the most important outstanding scientific and technical challenges associated with the occurrence of methane hydrates as identified by the community. Once completed, the plan was distributed to the community and may be found at www.oceanleadership.org/methane. The plan is summarized below with a culmination of a series of recommendations. The Science Plan also features the development of conceptual plans for scientific drilling expeditions that could yield the data and information needed to address these challenges. The individual challenges identified and described in the Science Plan are grouped under four lead challenges:

-Methane Hydrate Resource Assessment and Global Carbon Cycle
-The Challenge of Producing Methane Hydrate
-Methane Hydrate Related Geohazards
-Modeling, Laboratory, and Field System Requirements and Integration

Broadly, these challenges target understanding geologic controls on the occurrence and stability of methane hydrates in natural systems that impact their potential as an economic energy resource, their role as possible geohazards, and the impact they may have on global climate change. Methane hydrates studies require the development and integration of new modeling, laboratory, and field measurement systems and protocols.

Scientific drilling is an invaluable tool for studying methane hydrate systems in nature. This Science Plan describes and proposes a series of eight topical-based scientific drilling programs, deployed as part of a well-organized, global-based effort to help answer the outstanding methane hydrate scientific and technical challenges:

-Fully Parameterize Global Carbon Cycle Using Wells of Opportunity
-High Methane Hydrate Concentrations in Sand Reservoirs: Resource Assessments and Global Carbon Cycle
-Global Carbon Cycle – High Flux Settings
-Response of Methane Hydrate System to Perturbations at the Upper Edge of Stability
-Preconditioning of Areas for Slope Failure with High Methane Hydrate Saturations
-Characterization of Geohazards Associated with Methane Hydrate Related Features
-Methane Hydrate Production Related Geohazards
-Methane Hydrate Response to Natural Perturbations

This Methane Hydrate Research Science Plan concludes with a series of recommendations concerning the most important methane hydrate research challenges and how scientific drilling can advance our understanding of methane hydrates in nature. Below are listed the most critical program planning recommendations as developed under the COL-led review effort:

-The top priorities for dedicated scientific drilling are: (1) an expedition designed to further our understanding of the highly concentrated sand-rich methane hydrate reservoirs in the Gulf of Mexico and (2) a drilling program designed to characterize the methane hydrate systems along the Atlantic margin of the United States.

-Establish a high-level international committee to monitor and identify cooperative research and specific scientific drilling opportunities to advance our understanding of methane hydrates in nature.

-Review and update technology and operational requirements for each drilling expedition.

-Include wireline logging and logging while drilling in all future methane hydrate expeditions.

-Further develop downhole geotechnical and scientific tools, and apply them to methane hydrate related research issues.

-Develop and deploy sensors and devices specifically designed to monitor methane systems.

-Continue to test and develop the Hybrid-PCS, and strongly encourage its use in the field.

-Support efforts to coordinate the use and integration of field, laboratory, and model derived data.

-Make use of all available communication channels to disseminate well-vetted data and information on the role that methane hydrates may play as an energy resource, geohazard, or agent of global climate change.

-Monitor the methane hydrate scientific community and deal effectively with misinformation through the peer review process and the judicious use of published reviews and rebuttals.

Of the scientific drilling programs considered in this Science Plan, the community concluded that the first priority would be an expedition targeting the methane hydrate reservoirs in the Gulf of Mexico. The second priority would be a drilling program along the U.S. Atlantic margin. It was also concluded that critical new developments in drilling and measurement technologies are needed to advance the goals and contributions of methane hydrate related scientific drilling opportunities. The use of specialty drilling systems and technologies, such as pressure core systems, downhole measurement tools, borehole instrumentation, advanced wireline logging, and logging-while-drilling, should be continued and expanded. In the end, the appreciation of the contributions scientific drilling makes to our understanding of methane hydrates in nature and as potential energy resource, geohazard, or contributor to global climate change depends on the ability of the research community to communicate the knowledge to the public.

Scientific drilling has made significant contributions to our understanding of the formation and occurrence of methane hydrates in nature and will continue to play a key role in advancing our understanding of the in-situ nature of methane hydrates.

7.1 State of Methane Hydrate Science

The Methane Hydrate Community Workshop provided an excellent venue for the exchange of ideas among a highly interdisciplinary group of scientists. Workshop discussions, as captured in the workshop report and summarized in this section of the Plan, reviewed our current understanding of the geologic controls on the occurrence of methane hydrate in nature and how these factors may impact the energy, hazard, and climate change aspects of methane hydrate research. Numerous studies have shown that the amount of gas stored as methane hydrates greatly exceeds the volume of known conventional gas resources. However, the study of methane hydrates is a scientific and technical challenge, and much remains to be learned about their characteristics and occurrence in nature. Methane hydrate research in recent years has mostly focused on: (1) documenting the geologic parameters that control the occurrence and stability of hydrates in nature—*Methane Hydrate System*, (2) assessing the volume of natural gas stored as hydrates within various geologic settings—*Methane Hydrate Assessments*, (3) analyzing the production response and characteristics of methane hydrates—*Methane Hydrate Production*, (4) identifying and predicting natural and induced environmental and climate impacts of natural methane hydrates—*Methane Hydrate Climate Change Issues*, and (5) analyzing the impact and response of methane hydrates to external forcing—*Methane Hydrate Geohazard Issues*.

Methane Hydrate System

Certain mixtures of gas and water can form solids under specific temperature and pressure conditions within Earth, called the hydrate stability zone. Other factors that control the presence of hydrates in nature are the source of the gas included within the hydrates, the physical and chemical controls on the migration of gas within a sedimentary basin containing hydrates, the availability of the water also included in the hydrate structure, and the presence of a suitable host sediment or "reservoir." The geologic controls on the occurrence of methane hydrates have become collectively known as the "methane hydrate system," which has become the focus of numerous hydrate research programs (as reviewed by Collett et al., 2009).

Methane Hydrate Assessments

Methane hydrate resource assessments that indicate enormous global volumes of methane present within hydrate accumulations have been one of the primary driving forces behind the growing interest in methane hydrates (as reviewed by Boswell and Collett, 2011). For the most part, these estimates range over several orders of magnitude, creating great uncertainty in the role methane hydrates may play as an energy resource or as a factor in global climate change. In recent years, field production tests combined with advanced numerical simulation have shown that hydrates in sand reservoirs are the most feasible initial targets for energy recovery, thus bringing focus to the type of future hydrate assessments to be conducted. It has also been shown that with regard to the climate implications of methane hydrates, there is growing need to accurately assess what portion of the global methane hydrate endowment is most prone to disturbance under future warming scenarios.

Generally, the reported global hydrate assessments include the assessment of a set of minimum source-rock criteria such as organic richness, sediment thickness, and thermal maturity as they apply to both microbial and thermogenic gas sources. In several of the more recent assessments, the hydrate resource volume estimates have also considered the nature of the sediments that host the hydrates. For example, in 2008, the Minerals Management Service (MMS), now known as Bureau of Ocean Energy Management (BOEM), estimated that the Gulf of Mexico (GOM) contains about 190 trillion cubic meters

(~6,710 trillion cubic feet) of gas in highly concentrated hydrate accumulations within sand reservoirs (Frye, 2008). Furthermore, the MMS assessment indicated that reservoir-quality sands may be more common in the shallow sediments of the methane hydrate stability zone than previously thought.

One of the most important emerging goals of methane hydrate research and development activities is the identification and quantification of the amount of technically and economically recoverable natural gas that might be stored within methane hydrate accumulations. A number of new quantitative estimates of in-place methane hydrate volumes (Klauda and Sandler, 2005; Frye, 2008; Wood and Jung, 2008; Bureau of Ocean Energy Management, 2012) and, for the first time, technical recoverable (Collett et al., 2008; Fujii et al., 2008) assessments, have been undertaken using petroleum systems concepts developed for conventional oil and natural gas exploration. For example, in an assessment of methane hydrate resources on the North Slope of Alaska, Collett et al. (2008) indicated that there are about 2.42 trillion cubic meters (~85.4 trillion cubic feet) of technically recoverable methane resources within concentrated, sand-dominated, methane hydrate accumulations in northern Alaska.

Methane Hydrate Production

By all accounts, methane hydrates in both Arctic permafrost regions and deep marine settings can occur at high concentrations in sand-dominated reservoirs. These settings have been the focus of recent methane hydrate exploration and production studies in northern Alaska and Canada, in the Gulf of Mexico, off the southeastern coast of Japan, in the Ulleung Basin off the east coast of the Korean Peninsula, and along the eastern margin of India. Production testing and modeling have shown that concentrated methane hydrate occurrences in sand reservoirs are conducive to existing well-based production technologies. Because conventional production technologies favor sand-dominated methane hydrate reservoirs, sand reservoirs are considered to be the most viable economic target for methane hydrate production and will be the prime focus of most future methane hydrate exploration and development projects.

Over the last 10 years, national methane hydrate research programs, along with industry interest, have led to the development and execution of major methane hydrate production field test programs. Three of the most important production field testing programs have been conducted at the Mallik site in the Mackenzie River Delta of Canada and in the Eileen methane hydrate accumulation (i.e., Mount Elbert and Ignik Sikumi tests) on the North Slope of Alaska. Most recently, we have also seen the completion of the world's first marine methane hydrate production test in the Nankai Trough offshore of Japan. The recent production tests in Alaska, northern Canada, and offshore Japan have collectively shown that natural gas can be produced from methane hydrates with existing conventional oil and gas production technology.

For both Arctic and marine hydrate-bearing sand reservoirs, it is generally accepted there are no apparent technical roadblocks to resource extraction; the remaining resource issues deal mostly with the economics of hydrate extraction.

Methane Hydrates and Climate Change

The atmospheric concentration of methane, like that of carbon dioxide, has increased since the onset of the Industrial Revolution. Methane in the atmosphere comes from many sources, including wetlands, rice cultivation, termites, cows and other ruminants, forest fires, and fossil fuel production. Some researchers have estimated that up to two percent of atmospheric methane may originate through dissociation of global methane hydrates (as reviewed by Ruppel, 2011). It has been shown that methane is an important component of Earth's carbon cycle on geologic timescales. Whether methane once stored as methane hydrate has contributed to past climate change or will play a role in the future global climate remains unclear. A given volume of methane causes 15 to 20 times more greenhouse gas warming than carbon dioxide, so the release of large quantities of methane to the atmosphere could exacerbate atmospheric warming and cause more methane hydrates to destabilize. Extreme warming during the Paleocene-Eocene Thermal Maximum about 55 million years ago may have been related to a large-scale release of global methane hydrates. The impact of modern climate warming on methane hydrate deposits does not appear to have led to catastrophic breakdown of methane hydrates or major leakage of methane to the ocean-atmosphere system from destabilized hydrates. The vast majority of methane hydrates would require a sustained warming over thousands of years to trigger dissociation; however, methane hydrates in some locations are now dissociating in response to longer-term climate processes.

Methane Hydrates as Geohazards

Geohazards associated with the occurrence of methane hydrates in nature are generally classified as "naturally occurring" geohazards that emerge wholly from geologic processes and "operational" geohazards that may be triggered by human activity (Boswell et al., 2012b). As a "naturally occurring" geohazard, the presence of methane hydrate increases the mechanical strength of the sediment within which it resides. However, the dissociation of methane hydrate releases free gas and excess pore water, which may substantially reduce the geomechanical stability of the affected sediment. The potential linkage between large-scale mass wasting events and the dissociation of methane hydrates has been a topic of interest over the past decade. In comparison to most conventional hydrocarbon accumulations, methane hydrates occur at relatively shallow depths, representing a hazard to shallow drilling and well completions. Results from several methane hydrate drilling programs, including Ocean Drilling Program (ODP) Legs 164 and 204, and more recently the Chevron-led Gulf of Mexico Joint Industry Project (GOM-JIP) Legs I and II, Integrated Ocean Drilling Program (IODP) Expedition 311, and National Gas Hydrate Program (NGHP) Expedition 01 have shown that drilling hazards associated with methane hydrate bearing sections can be managed through careful control of drilling parameters.

7.2 **Challenges in Methane Hydrate Research**

The general consensus from the Methane Hydrate Community Workshop was that significant strides have been made in our understanding of the occurrence, distribution, and characteristics of marine methane hydrates, but our knowledge related to the role that methane hydrates may play as an energy resource, as a geologic hazard, and as an agent of climate change remains incomplete. More work is needed to integrate methane hydrate related research efforts, while developing a more complete understanding of the critical outstanding research issues. The Methane Hydrate Community Workshop identified three integrated methane hydrate science challenges and one technical challenge as the central theme for this Methane Hydrate Research Science Plan: (1) Methane Hydrate Resource Assessment and Global Carbon Cycle, (2) The Challenge of Producing Methane Hydrate, and (3) Methane Hydrate Related Geohazards, and (4) Modeling, Laboratory, and Field System Requirements and Integration. Each of these challenges is further reviewed below along with considerations of how scientific drilling can contribute our understanding of these challenges.

7.2.1 Methane Hydrate Resource Assessment and Global Carbon Cycle

SCIENCE CHALLENGES

7.2.1.1 What controls the inventories and fluxes of methane carbon in the marine system, and how do these change over time?

7.2.1.2 How to construct a robust assessment of methane hydrate occurrence?

7.2.1.3 How does this reservoir respond to natural and anthropogenic perturbations?

All of the challenges explored in this science plan first require a baseline quantification of the amount of methane hydrate stored in the Earth's subsurface. In terms of methane hydrate as a potential energy resource, the concept of a methane hydrate system has been developed to systematically assess the geologic controls on the occurrence of methane hydrate in nature. This concept has been used to guide the site selection process for numerous recent national and international methane hydrate scientific drilling programs. At the same time the petroleum system concept has been used to assess geologic variables, such as "reservoir conditions" or the "source" of the gas within a hydrate accumulation, to better understand how they impact the occurrence and physical nature of methane hydrate at various scales.

In recent years significant progress has been made in addressing key issues on the formation, occurrence, and stability of methane hydrate in nature. However, much of these efforts continue to focus on describing hydrates as static deposits, rather than building a better appreciation of them as part of a dynamic system. Fundamental questions remain as to the residence time of methane hydrates near the seafloor and deeper within the sediment column, the sources and pathways of methane transport, nature and driving mechanisms for flow, and changes in these variables through time.

Consequently, there is an obvious and growing imperative for the development of integrated time dependent models to understand the controls on the formation, occurrence, and stability of methane hydrates in nature, as well as the forcing mechanisms that modulate the processes responsible for methane generation, consumption, and potential discharge to the overlying water column.

Science Challenge 7.2.1.1. What controls the inventories and fluxes of methane carbon in the marine system, and how do these change over time?

Methane hydrate must be understood as a component of a complex system with dynamic inputs and outputs of methane over time. Ultimately methane generation is intimately tied to the inputs of organic carbon, although questions remain as to how to best evaluate the relationship between the amount and type of organic carbon landing on the seafloor and the quantity of the methane hydrate generated. We still need a better understanding on how much of this carbon is available for methanogenesis, how to parameterize degradation kinetics as a function of the nature of the organic carbon, temperature and age, as well as the factors that control the amount of organic matter that passes through the sediment oxidative reactors and is buried within the methanogenesis zone.

In terms of outputs, it is important to quantify how much methane is lost from the system via naturally occurring gas seeps and how much is consumed by anaerobic methane oxidation (AOM). How much of the sulfate is consumed by AOM determines how much organic carbon passes into deep sediment for methanogenesis.

It is also important to better understand how methane generated at depth reaches the methane hydrate stability zone, what fraction of the generated gas may remain trapped below the stability zone, and what processes determine whether methane migrates as a dissolved or gas phase, and whether migration is diffused or focused, constant or episodic. Finally, we need a mechanism to validate assumptions and how to scale from local to global models.

Potential Drilling Strategies

To fully understand the methane hydrate system it is critical that we constrain all the variables that control fluxes, inventories, and reactions that govern the changes in the system over time. To parameterize all components in the system we propose a strategy of using “wells of opportunity” and other strategic drilling that will target the full gamut of geologic settings that characterize those observed along global continental margins. These include, among others, thermogenic versus microbial gas environments; focused flow versus basin-centered accumulations, organic rich versus organic poor settings; and active versus passive margins, with the goal of defining metrics that control the carbon budget over time. This comprehensive approach aims to establish thresholds, informing global/local assessment models; understand the life cycle components of carbon to methane over time, and the role of the deep biosphere in formation and consumption of methane. We envision taking advantage of research ship transits and other opportunities to drill and sample wells that will populate a matrix of varying conditions that can then be used to constrain both the resource assessment and system perturbation issues detailed below.

In addition, specific locations need to be targeted to address certain topics such as high flux vent/chimney systems, accumulation in sands, and methane hydrate formation in fractured shale systems. Surface vent locations will be drilled to understand methane flux to the water column, gas flux to the methane hydrate stability zone, impact on microbiology, kinetics of rapid formation of hydrate and dissociation, and spatial variation of shallow sediment carrying capacity. Drilling in sand reservoirs will further our understanding of the mechanism of formation of high concentration methane hydrate in deep marine sand deposits and inform predictive models and assessments. Similarly, targeting locations of methane hydrate accumulation in shales will improve our understanding of where and how methane hydrate accumulates in fracture networks.

Science Challenge 7.2.1.2. How to construct a robust assessment of methane hydrate occurrence?

In conventional petroleum systems analysis, the geologic components and processes necessary to generate and store hydrocarbons are well established. Appropriate relative timing of formation of these elements and the processes of generation, migration, and accumulation are necessary for hydrocarbons to accumulate and be preserved. To apply this model to a methane hydrate resource system, we not only need an understanding of the conventional reservoir rocks, traps, and seals, but also we must understand and incorporate additional parameters that determine methane hydrate stability conditions. These include formation temperature and pressure, pore-water salinity, availability of water, gas source, chemistry, concentration and transport mechanisms, and the time over which the system evolves.

A variety of models have been developed to predict methane hydrate occurrence on local, regional, and global scales. These models are built for various reasons that include quantifying localized accumulations to identify potential methane hydrate field size parameters, establishing a national resource base for governmental energy considerations, and understanding the role of global methane hydrate distribution on a scale that impacts the carbon cycle. However, it has become clear that to properly constrain such predictive assessment models at all of these levels, a comprehensive understanding of the parameters included in these models is critical, in particular a quantification of those variables that control inputs and outputs of methane over time, as described above. Additionally, while sensitivity studies can identify the most important components in any one given model, it remains unclear which of these many critical parameters and conditions are the driving forces in the natural environment at each specific site.

Potential Drilling Strategies

For a resource assessment goal, we need to focus on the components of the carbon system that leads to the formation of methane hydrate accumulations that can be targeted for production. Assessments will be grounded on a comprehensive understanding of the carbon system as described above, coupled with a geological characterization of the site. Currently the main focus here lies in hydrate accumulations in deep marine sands, such as those in Gulf of Mexico (Lease Blocks Walker Ridge 313 and Green Canyon 955), New Jersey Margin, Southwest Taiwan, Hikurangi Margin, Ulleung Basin, and the Nankai Trough. Proposed strategies follow a phase of verifying assessment models using traditional downhole logging and coring techniques, followed by a strategic approach that target the reservoirs of interest. Desirable approaches include drilling twins of existing wells and utilizing transects to test regional geologic controls.

Science Challenge 7.2.1.3. How does this reservoir respond to natural and anthropogenic perturbations?

In addition to understanding the dynamics of carbon flux associated with hydrate systems, strong interest exists in understanding how methane hydrate systems respond to naturally- and anthropogenically-produced perturbations. Dissociation of methane hydrate due to warming or sea level change can release methane into the ocean-atmosphere system, impacting ocean acidification and potentially climate and may also impact slope stability. Past warming has been hypothesized to be responsible for massive methane hydrate dissociation events that have played a critical role in climate change. However, the nature, mechanisms, and extent of methane escape due to perturbations are poorly understood. Moreover, the fate and extent to which methane reaches the atmosphere is not well constrained even in active vents and seeps overlying modern methane hydrate systems. These unknowns limit robust implementation of the effect of perturbations in carbon cycle and climate models.

Potential Drilling Strategies

Within this challenge, drilling would most likely target the updip limit of hydrate stability zone along continental margins, where there is evidence of present or past changes of the methane hydrate stability field, which led to destabilization and methane discharge. These settings are characterized by well-defined upper limit of methane hydrate stability, evidence of methane hydrate occurrence, fluid venting, temperature changes in water column (present and past), and altered methane hydrate stability zone. Sites include Beaufort Shelf, Cascadia Margin, Cape Fear, northern Gulf of Mexico, Hikurangi Margin, Northern Europe (Svalbard), and offshore Cape Hatteras.

To address this challenge, a drilling program should be designed to reconstruct and understand the system response to change/forcing – present and past consequences of change (gas flux rates, seafloor stability, geomechanics), constrain and quantify rate of dissociation, response of microbes, shallow sediment carbon cycle and use of paleo-proxies to identify changes in thinning, and to ground truth existing acoustic data. To characterize the full system, a transect or multiple transects (including a reference site) that crosses the stability edge is needed. Drilling should be guided by detailed site surveys that include heat flow, imaging, seafloor and water column surveys.

7.2.2 The Challenge of Producing Methane Hydrate

SCIENCE CHALLENGES

7.2.2.1 What is the preferred production method for an offshore methane hydrate production test?

7.2.2.2 What are the key reservoir parameters of offshore methane hydrate reservoirs impacting the production rate?

7.2.2.3 What is the minimum production rate and length of test needed from offshore methane hydrate reservoir to indicate economic viability?

When identifying methane hydrate reservoirs suitable for production there are a number of key parameters to be considered. Methane hydrates in both arctic permafrost regions and deep marine settings can occur at high concentrations in sand-dominated reservoirs, which have been the focus of methane hydrate exploration and production studies in northern Alaska and Canada, and offshore in the Gulf of Mexico, off the southeastern coast of Japan, in the Ulleung Basin off the east coast of the Korean Peninsula, and along the eastern margin of India. Because conventional production technologies favor sand-dominated methane hydrate reservoirs, sand reservoirs are considered to be the most viable economic target for methane hydrate production and have been the prime focus of most methane hydrate exploration and development projects.

It has also been shown that there is a need for experimental type of methane hydrate production testing rather than the more traditional industry style of demonstration testing. For example, it is recommended that the initial round of significant methane hydrate production testing needs to be conducted in relatively simply reservoir configurations, such as hydrates in sand reservoirs bounded between impermeable shale layers. Testing within confined reservoirs, not in contact with movable reservoir water or free-gas, will ensure that the gas tested from the well is actually from the hydrate-bearing portion of the reservoir, rather than another part of the reservoir.

It has also been shown that the initial reservoir pressure and temperature conditions can significantly impact methane hydrate production responses and rates. Ideally a reservoir located in deep water conditions, well below the seabed to ensure a hydrate reservoir with the highest temperature possible are more susceptible to temperature and pressure changes leading to methane hydrate dissociation. This type of deeply buried and higher temperature hydrate reservoir will support stronger depressurization and will produce longer without added complexities (e.g., the use of heat or chemical inhibitors). The deeper reservoir conditions will also increase the probability for better reservoir seals and more likely lead to a reservoir with enough geomechanical stability to support both vertical and horizontal drilling.

To prepare for future field production testing it is envisioned that more information is needed in the following areas: (1) the geology of the hydrate-bearing formations, on a large scale - the distribution of hydrates both throughout the world and on small scale – their occurrence and distribution in various host sediments; (2) the reservoir properties/characteristics of methane hydrate reservoirs; (3) the production response of various methane hydrate accumulations at both the lab scale and through production modeling; (4) the environmental and economic issues controlling the ultimate resource potential of methane hydrates; and (5) the development of numerical models that represent observed phenomena in field and laboratory experiments.

Science Challenge 7.2.2.1. What is the preferred production method for an offshore methane hydrate production test?

In order to produce methane from methane hydrate, the methane must be first released from the hydrate structure. As described in the COL “Historical Methane Hydrate Project Review” report, proposed methods of methane gas recovery from hydrates generally deal with dissociating or "melting" in-situ methane hydrates by heating the reservoir above hydrate formation temperatures, injecting a thermodynamic inhibitor such as methanol or glycol into the reservoir to decrease hydrate stability, or decreasing the reservoir pressure below the hydrate equilibrium. Recently, several studies have shown that it is also be possible to produce methane from hydrates by displacing methane molecules in the hydrate structure with carbon dioxide, thus releasing methane and sequestering the carbon dioxide.

Several field scale tests have been performed to test some of the proposed production methods (*See the Historical Methane Hydrate Research Scientific Drilling information box in this Science Plan for more information on previous hydrate production studies*). However, all of these tests have been of limited duration on the order of 6 to as many as 25 days. In general, these tests support the technical proof-of-concept for gas production from hydrate reservoirs, but they fall short of proving the economic viability of the resource. Longer duration production tests, that rigorously test a wide range of production technologies, are needed to investigate the viability of gas production from methane hydrate.

Potential Drilling Strategy

One of the most important aspects of any methane hydrate field production test is the selection of a site or possibly multiple sites that possess the reservoir conditions suitable for testing the available hydrate production concepts and technologies. For example, testing within confined hydrate-bearing sand-rich reservoirs is preferred in order to more effectively constrain the results of the test when considering depressurization production methods. However, production methods that require injecting either a hot fluid or carbon dioxide into the hydrate-bearing section may benefit from more open reservoir conditions. Thus, when considering the wide range of available production technologies it will be important to select drill sites that possess the conditions that would be most suitable for the particular methane hydrate production method being tested.

Science Challenge 7.2.2.2. What are the key reservoir parameters of offshore methane hydrate reservoirs impacting the production rate?

Fluid flow in conventional gas reservoirs is typically controlled by parameters such as permeability, relative permeability, fluid distribution, reservoir porosity, and hydrocarbon saturation. Methane hydrate adds complexity to reservoir flow. In order for gas to flow from the reservoir into the producing well, it has to be first released from the hydrate structure. Methane hydrate production by depressurization occurs by lowering reservoir pressures below hydrate stable conditions. Key factors expected to control the efficiency of hydrate dissociation by depressurization and gas flow to the well include the intrinsic and relative permeability of the hydrate-bearing reservoirs and the nature of heat transfer within a producing hydrate reservoir. It has been shown that the nature of how hydrates occur in the reservoir impacts relative permeability as well as how heat is transferred (conduction and convection) in the reservoir are key parameters regulating production rates. This supports the ideal case for production of having a high permeable sand reservoir at relatively high temperatures (i.e., deep water settings and at greater depths below the seafloor).

Potential Drilling Strategy

It is generally assumed that the main targets for methane hydrate testing and supporting scientific drilling are deeply buried sand-rich reservoirs with high methane hydrate saturations, preferably not in contact with free-water or -gas, and bounded above and below by impermeable layers. As part of the pre-test, scientific drilling phase of the project, there should be downhole logging (both wireline and logging-while-drilling tools) and sediment coring (both conventional and pressure coring) to establish hydrate saturations, reservoir porosity and permeability, grain size distribution, sediment clay content, and the geomechanical, physical, and thermal properties of the hydrate-bearing reservoirs being considered for testing. Potential future deep-water test sites with known hydrate-bearing sand-rich reservoirs include the Walker Ridge 313 and Green Canyon 955 sites in the Gulf of Mexico as well as the sites drilled in the Nankai Trough by the Japan Oil, Gas and Metals National Corporation (JOGMEC).

Science Challenge 7.2.2.3. What is the minimum production rate and length of test needed from offshore methane hydrate reservoir to indicate economic viability?

In March of 2013, JOGMEC conducted a six day methane hydrate production test at a drill site in the Nankai Trough. This test established the technical feasibility of methane gas production from offshore hydrate accumulations. The average production rates were estimated to be about 20,000 cubic meters of gas per day. This kind of production is far from the commercial rate needed for a conventional gas accumulation, which are typically two orders of magnitude higher. It is important to note, however, that initial production rates are expected to be low from a methane hydrate test well. During the initial phase of in-situ hydrate dissociation and production the relative permeability of the reservoir is low due to high methane hydrate saturations. This observation is supported by computer simulation studies that indicate it can take years before the maximum production rate is reached. Therefore, longer tests (1-5 years in duration) are needed in order to establish the commercial viability of methane gas production from hydrate reservoirs. Such a long production test will need to be near existing infrastructure, so that the gas produced can be utilized and not flared.

Potential Drilling Strategy

As discussed above, any pre-test drilling program should include the acquisition of downhole logging and sediment coring data and samples. The additional goal to the extended duration test is the need for a near infrastructure test site. Pre-site survey work in advance of the Second Joint Industry Project Gas Hydrate expedition (JIP Leg II) has already revealed the potential occurrence of hydrate-bearing sand reservoirs in the area of the Green Canyon 781 lease block in the Gulf of Mexico near the Mad Dog Field. For example, a hydrate test well in the area of the Mad Dog Field could be connected to the conventional production systems in the field to allow for continuous long-term uninterrupted production.

7.2.3 Methane Hydrate Related Geohazards

SCIENCE CHALLENGES

7.2.3.1 What are the operational geohazards, triggered by human activities, which will affect methane hydrate production?

7.2.3.2 Are there methane hydrate geohazards that are induced solely from naturally occurring processes?

From the collective drilling experience to date, it is generally accepted that the presence of methane hydrate increases the mechanical strength of the surrounding host sediments. Conversely, the dissociation of that methane hydrate releases free gas and excess pore water, which appears to substantially reduce the geomechanical stability of the impacted sediments. It is this reduction in mechanical strength that is fundamental to many of the issues, associated with methane hydrate as a geohazard. Methane hydrate geohazards in marine settings generally encompass two areas of concern.

The first area is operational geohazards that represent latent natural hazards that may be triggered by human activities. In comparison to most conventional hydrocarbon accumulations, methane hydrates occur at relatively shallow depths, and therefore as potential operational geohazards, could contribute to seafloor displacements over the long-term development of a methane hydrate accumulation. Additionally, methane hydrates in some cases may represent a geohazard to drilling associated with oil and gas exploration and production as well as for drilling and directly producing methane hydrates.

The second area of interest is naturally occurring geohazards that emerge solely from geologic processes. The two most important types of naturally occurring methane hydrate geohazards are widespread slope instability and gas venting of methane, which have become topics of increasing interest over the last decade. Both of these topics have garnered an unusual amount of concern through several avenues of public media, particularly web exposure and television documentaries. Addressing these specific naturally occurring processes with confident scientific information and technical approaches continues to be a challenging goal when considering our existing understanding of the geologic controls on the formation, occurrence, and stability of methane hydrates in nature.

Science Challenge 7.2.3.1. What are the operational geohazards, triggered by human activities, which will affect methane hydrate production?

Various operational groups (reviewed by Collett and Dallimore, 2002) have reported drilling hazards attributed to the presence of methane hydrate. However, a longer-term, and perhaps more difficult to constrain risk is the potential for hydrate dissociation and sediment-wellbore instability caused by the heating of sediment around production wells due to the sustained production of deeper, warmer fluids.

There is a significant lack of quantitative understanding regarding operational geohazards associated with human induced disturbance of natural methane hydrates because of the general lack practical field experience with methane hydrate systems. There is even a greater lack of experience when dealing with operational geohazards associated with the direct exploitation of methane hydrates as a potential resource. With these concerns, several industry projects have focused on collecting field data to identify and assess the potential range of problems associated with human induced methane hydrate related geohazards. The Gulf of Mexico Gas Hydrate Joint Industry Project (GOM-JIP), for example, was formed in 2001 to in part study hazards associated with drilling hydrate-bearing sediments. The GOM-JIP demonstrated that some hazards associated with operations in areas characterized by shallow methane hydrates can be anticipated and avoided when sufficient information is available on the occurrence of methane hydrates. But, more work is needed to understand the complete range of geohazards associated with various types of methane hydrate occurrences in nature.

Overall, the presence of methane hydrates appears not to be a major issue for drilling of exploration and appraisal wells in the energy industry, because the amount of time with warm fluid flowing through the wellbore is measured in weeks to a few months at most. This is in contrast to constant warm fluid flow through development wells in an active field that are designed to be produced on a scale of years to a decade or more. What is difficult to predict over this longer time period is the soil stability profile around a heated production casing in an actively producing field. Dissociation of methane hydrates around a production casing may fluidize the sediments, which may cause the loss of support for the borehole casing.

As we start to consider the potential range of geohazards associated with the direct exploitation of methane hydrates, we will need leverage all the experiences we have gained from our understanding of the impact of conventional oil and gas production on methane hydrate related geohazards. It can be concluded that we have a relatively comprehensive list of possible issues that might be associated with methane hydrate production, but at present we do not know to what extent these issues will impact methane hydrate production operations.

Potential Drilling Strategy

A critical component of both predicting and understanding the potential range of methane hydrate related geohazards associated with any potential drilling and development program deals with the use of geophysical techniques, including exploration 3-D seismic, high resolution 2-D and 3-D seismic, and multi-component seismic surveys to identify and mediate potential geohazards.

The drilling portion of a geohazard assessment project should also include a comprehensive geoscience and geotechnical investigation program that employs downhole logging, pressure coring and other geotechnical methods to characterize subsurface methane hydrates. Integration of logging and core data should allow for the characterization of the nature of methane hydrate occurrences and associated geohazards.

When considering the range of potential geohazards associated with the occurrence of methane hydrates, hazard assessment drilling needs to evaluate the full range of the types of methane hydrate occurrences, including those hydrates associated with seafloor natural vents, to more deeply buried fracture and pore-filling types of occurrences, and hydrate systems that may trap underlying free-gas accumulations. In addition, the overall goal of the geotechnical drilling program also needs to be designed with an appreciation of what potential risk factors need to be assessed. For example, will the project deal with the foundational designs in the upper several 100 meters below the seafloor, or will the project be dealing with drilling exploratory and/or production wells through relatively more deeply buried methane hydrate accumulations. It is also possible that the project needs to be designed to directly target methane hydrate to acquire needed scientific and engineering knowledge.

Science Challenge 7.2.3.2. Are there methane hydrate geohazards that are induced solely from naturally occurring processes?

The two most important naturally occurring geohazards, associated with methane hydrate production, are slope instability and wide-scale gas venting. The concept of extensive slope instability being caused by dissociation of methane hydrates has been a recurring theme for over three decades (e.g., McIver, 1982). Methane hydrate dissociation as a major factor in slope instability has also received further support with the recognition of the importance of methane hydrates in cyclic global climate control (e.g., Nisbet, 2002; Kennett et al., 2003). Several investigators have since proposed arguments for the lowering of global sea level as a control on establishing a new equilibrium for marine methane-hydrate stability, and thus inducing seafloor slope instability (e.g., Maslin et al., 2004; Mienert et al., 2005a; 2005b).

Contrary evidence has emerged, which counters the feasibility of widespread slope instability induced by methane-hydrate dissociation. Specifically, at least several large field investigations have addressed this specific topic (e.g., Kvalstad et al., 2005; Hornbach et al., 2007) with inconclusive results. Additional contrary evidence includes isotopic analysis from methane in ice cores (Sowers, 2006), budget calculation determining the role of methane hydrates in the global carbon cycle (Maslin and Thomas, 2003), and modeling the melting of methane hydrates in natural settings (Sultan, 2007). All these studies suggest the impact of methane hydrate in recent geologic history may be of minor importance. It is clear from the numerous investigations of continental margins and the extensive survey by offshore energy companies that there was substantial seafloor instability, associated with sea-level fluctuations at the end of the Pleistocene to early Holocene. However, there is no compelling evidence to date that this instability was induced by widespread dissociation of methane hydrates. Presently, the case for large methane-hydrate, dissociation-induced failures remains elusive with the existing data.

Continuous methane gas venting occurs in many marine settings, but is generally is not considered a widespread naturally occurring geohazard. However, investigators have documented large concentrations of gas chimneys in certain settings (e.g., Cathles et al., 2010), which some investigators have suggested could cause widespread catastrophic gas release or even sediment expulsion (*reference – 2003 Geology article – What is this???*). Expulsive gas venting initially was credited with forming a collapse feature on the crest of the Blake Ridge (Holbrook et al., 2002), but the cause was later found to be more gradual processes. A rare documentation of compelling evidence for gas and sediment expulsions are found in the "pingo like features" observed on the shallow Canadian Beaufort shelf (Paull et al., 2007). These features appear to be a result of methane hydrate dissociation, associated with the melting of permafrost, due to post ice-age rising sea level. Again, the case for widespread, catastrophic, methane-hydrate dissociation-induced gas venting episodes is poorly documented with existing data available on this topic.

Potential Drilling Strategy

Seafloor focused and deeper stratigraphic coring has been shown to be effective tools for understanding naturally occurring processes throughout the marine environment. Much can be done with existing data and data integration to understand potential hazards associated with methane hydrates as acted upon by natural processes. Additional field surveys and focused scientific drilling of known submarine slide features, such as the Storegga submarine slide and similar by smaller scale features off the Grand Banks, would also contribute to our understanding of the formation and evolution of these types features.

Another important scientific drilling target are regions that exhibited evidence of gas venting from the seafloor. Features such as cold vents, pockmark fields and pingo-like-features on Arctic shelves have been shown to be closely related to the occurrence of methane hydrate. But the relationship between these potential geohazards and the dissociations of methane hydrates is much less clear.

It has also been shown that the monitoring of methane hydrate systems in accretionary prisms and earthquake-prone regions may provide the ability to observe firsthand the impact of natural perturbations on methane hydrates.

It is clear that an improved fundamental understanding of the actual consequence of methane hydrate dissociation is needed. The key parameters in understanding the natural response to hydrate dissociation are being able to measure the change in sediment strength and fluid properties over time.

7.2.4 Modeling, Laboratory, and Field System Requirements and Integration

TECHNICAL CHALLENGES

7.2.4.1 Develop and perform laboratory measurements to help calibrate and interpret field data.

7.2.4.2 Advance and implement field characterization tools to address the critical methane hydrate science challenges.

7.2.4.3 Increase the accuracy and reliability of reservoir models to assess the energy resource potential of methane hydrate and the role methane hydrate plays as a geohazard and as an agent of climate change.

7.2.4.4 Determine critical site review and characterization requirements for proposed drilling strategies.

7.2.4.5 Advance integration and upscaling of model, lab, and field derived data.

Discussions during the Methane Hydrate Community Workshop identified three integrated science challenges: (1) Methane Hydrate Resource Assessment and Global Carbon Cycle, (2) The Challenge of Producing Methane Hydrate, and (3) Methane Hydrate Related Geohazards. To address these challenges requires accurate laboratory and field data and the development of advanced laboratory and field measurement tools to make critical measurements before, during, and after drilling activities. These data and tools are critical to the development of accurate and reliable pore-scale and transport models, physical property and geochemical field and laboratory measurements, and reservoir prediction models. The technical challenges below describe both routine and specialized needs for laboratory and field measurements and modeling developments in the support of methane hydrate drilling plans.

Table 1. General and Overarching Field Characterization Tools and Data.

Science Objective	Measurement/Tools
To characterize the physical properties of hydrate-bearing sediment systems	Seismic tools: more 3-D seismic data; more complete records of complementary data, such as CSEM, multi-component seismic data (shear velocity). S-wave logs
To estimate methane hydrate content (i.e., methane hydrate pore volume saturation) in various types of reservoirs	Downhole logging tools, including advanced wireline and LWD tools to measure electrical resistivity and acoustic velocity data (both compressional- and shear-wave data)
To analyze highly interbedded and fracture-dominated methane-hydrate reservoirs	Directionally oriented acoustic and propagation resistivity log measurements to provide acoustic and electrical anisotropic data
To characterize hydrate-bearing sediments at the pore-scale; To determine hydrate-bearing sediment porosities and permeabilities	Advanced nuclear magnetic resonance (NMR) logging and wireline formation testing

Table 2. Field Measurements and Tools to Address Specific Science Challenges.

Science Challenge 3.1: Methane Hydrate Resource Assessment and Global Carbon Cycle	
Science Objective	**Measurement/Tools**
To quantify & improve understanding on: o "Timing issues" related to dynamic aspects of methane hydrate system o Input/output fluxes of methane	Water column, seafloor, boreholes and 4-D seismic surveys
To improve understanding of the role of microbes on methanogenesis	Bioreactors with different substratum, flux, in-situ pressure and temperature conditions
To monitor seabed environmental and biological systems	EM, seabed cable, water column, sea-surface (radar sat.), camera survey around well at control site far away from drilling site
To assess stability and environmental effects for shallow (150 mbsf) vs. deep (1,000 mbsf) targets?	Monitoring for subsidence around well before, during, and after perturbation
Science Challenge 3.2: The Challenge of Producing Methane Hydrate	
Science Objective	**Measurement/Tools**
To monitor the gas production rates from HBS during depressurization, thermal stimulation, or chemical injection	(i) Downhole tools and sampling: e.g. downhole tools for mass spec/CH_4, geochemical sensors (ii) NMR and MDT for downhole fluid sampling and in-situ water sampling, and reservoir testing
Science Challenge 3.3: Methane Hydrate Related Geohazards (Before, During, and After Production)	
Science Objective	**Measurement/Tools**
To characterize in-situ geochemistry, lithology, and physical properties	(i) Downhole tools and sampling: downhole tools for mass spec/CH_4, geochemical sensors, MDT for downhole fluid sampling and in-situ water sampling of shallow parts (ii) In-situ water sampling and vertical flux meter for pressure cores
To test geohazard hypotheses; potential environmental seabed changes	*(i)* Measure pressure, temperature, conductivity, strain, fluids geochemistry, water column, sonar and seismicity with spatial and temporal coverage (4-D) *(ii)* Extensive pre-/post-drilling remotely operated vehicle (ROV)/Autonomous Operated Vehicle (AUV) surveying *(iii)* Routine core index property measurements *(iv)* Exploit existing and near-complete data sets
To assess the effect of natural geohazards	Long-term monitoring

7.3 Cross-Disciplinary Research Frontiers

7.3.1 Methane Hydrate Research Challenge Integration

One of the key goals of the Science Plan is to consider the potential overlapping relationships between the various methane hydrate related scientific and technical challenges described in the previous section and summarized in the box below. Any one particular methane hydrate expedition or study can contribute to multiple methane hydrate research challenges. All three science challenges are fundamentally linked in that they each require an understanding of the geologic controls on the formation, occurrence, and stability of methane hydrates— the components of the methane hydrate system. Basic and applied research is needed to further understand the geologic controls governing the formation of methane hydrate in both deep marine and permafrost environments.

Methane Hydrate Field Research Plan

Science Challenges

Methane Hydrate Resource Assessment and Global Carbon Cycle

- *What controls the inventories and fluxes of methane carbon in the marine system, and how do these change over time?*
- *How do we construct a robust assessment of methane hydrate occurrence?*
- *How does this reservoir respond to natural and anthropogenic perturbations?*

The Challenge of Producing Methane Hydrate

- *What is the preferred production method for an offshore methane hydrate production test?*
- *What are the key reservoir parameters of offshore methane hydrate reservoirs impacting the production rate?*
- *What is the minimum production rate and length of test needed from offshore methane hydrate reservoir to indicate economic viability?*

Methane Hydrate Related Geohazards

- *What are the operational geohazards, triggered by human activities, which will affect methane hydrate production?*
- *Are there methane hydrate geohazards that are induced solely from naturally occurring processes?*

Technical Challenges

Modeling, Laboratory, and Field System Requirements and Integration

- *Develop and perform laboratory measurements to help calibrate and interpret field data.*
- *Advance and implement field characterization tools to address the critical methane hydrate science challenges.*
- *Increase the accuracy and reliability of reservoir models to assess the energy resource potential of methane hydrate and the role of methane hydrate as a geohazard and an agent of climate change.*
- *Determine critical site review and characterization requirements for proposed drilling strategies.*
- *Advance integration and upscaling of model, lab, and field derived data.*

In recent years, the concept of a methane hydrate system, similar to the concept that guides conventional oil and gas exploration, has gained acceptance. In a methane hydrate system, the individual factors that contribute to the formation of methane hydrate can be identified and assessed, similar to geologic elements used to define a petroleum system: hydrocarbon source rocks (source-rock type and maturation and hydrocarbon generation and migration), reservoir rocks (sequence stratigraphy, petrophysical properties, seismic attribute development, and prospecting), and hydrocarbon traps (trap formation and timing). A deeper appreciation of the geologic controls on the occurrence of methane hydrate in nature through the study of the geologic, geochemistry, and geophysical properties of known methane hydrate accumulations will allow improved assessment of the energy resource potential of methane hydrates, the analysis of the role of methane hydrates in global climate change, and the rational assessment of the geologic and environmental hazards associated with the occurrence of methane hydrate.

To meet the primary science challenges that underpin the Science Plan, a host of specific and integrated modeling, laboratory, and field experiments and measurements are required to advance our understanding of methane hydrates in nature. These studies require the development of geologic, geophysical, geochemical and other tools needed to identify and characterize the controls on the occurrence methane hydrates. The analysis of geophysical, well log, and sediment core data have yielded critical information on the location, extent, sedimentary relationships, and the physical characteristics of methane hydrate deposits. The key outcome of the Methane Hydrate Community Workshop included the identification and compilation of field and laboratory measurements needed to characterize the occurrence methane hydrates in nature as reviewed in previously in the Science Plan.

Methane Hydrate Community Workshop participants concluded that the development of mathematical/numerical models that represent the observed phenomena in laboratory experiments and field tests is a complementary step in understanding the behavior of hydrate bearing sediments. Methane hydrate system models that predict the formation/dissociation of hydrates and fluid flow in porous media can be used to further understand the occurrence and evolution of methane hydrate deposits in nature and to better define the role of methane hydrates as a resource, a potential geohazard, and as a contributor to climate change. Such models should address the scalability between lab-scale experiments and field tests, and must include a detailed characterization of the hydrate bearing sediments in terms of its in-situ physical, mechanical, geologic, geochemical, and geophysical properties. The coupled modeling of fluid flow and geomechanics is also an important subject to be considered, since the dissociation of hydrates could affect the geomechanical integrity of the reservoir, changing the in-situ stress distribution along with the reservoir properties (e.g., porosity and permeability), which have implications on production potential and safety hazards.

7.4 **Education and Public Outreach**

Today, outreach refers to activities that target the general public through mostly social media or various news outlets. Educational outreach is generally aimed at students in undergraduate and graduate school programs. IODP has had a long and very successful history in both outreach and education. Recent history has also shown that branding is important to ensure ongoing public recognition of the scientific discoveries and technological achievements of scientific ocean drilling. Successful public outreach in support of funding agencies' goals and objectives have also become a vital part of science.

The DOE methane hydrate research program has had similar outreach and education successes. Information outlets such at the DOE-NETL websites on methane hydrates and *Fire In the Ice* newsletters are recognized as important and highly successful sources of public information on methane hydrates throughout the world. The DOE National Methane Hydrates Research and Development Program – Graduate Fellowship Program is a good example of an integrated outreach and educational program that has greatly contributed to the methane hydrate research community and the public appreciation of the role of methane hydrates in nature.

Outreach will be needed to raise the profile of future scientific drilling in support of methane hydrate research described in this Plan. Program managers and scientists engaged in methane hydrate research must effectively communicate the goals and results of their scientific endeavors to other scientists and non-scientists. It is imperative that we all become “methane hydrate educators” to make our science accessible and defendable to the public.

Participants at the COL-led Methane Hydrate Community Workshop recognized the need to better coordinate and manage the scientific accuracy of information released through social media and popular news outlets. In recent years, we have seen a rapid growth of news stories on methane hydrates in which some aspect of methane hydrates as a potential energy resource, geohazard, or agent of climate change have been sensationalized, with eye-catching story titles that suggest looming global disaster. In many cases, these stories have little to no scientific foundation or merit. During the workshop, participants discussed several examples of media stories on methane hydrates where it appears that particular science issues were possibly over-dramatized. In each case, the journalists appeared to lack a critical understanding of the issues they were trying to address. These situations show the need for the methane hydrate research community to make available and widely circulate accurate information on methane hydrate science issues that can be easily used and understood by the general public. It is also appropriate for informed scientists to contribute to public debate on science issues that are not so well defined so the limits of our understanding of a particular phenomenon are accurately portrayed.

Specific recommendations for the continued growth of the public understanding of methane hydrates in nature include: (1) develop and disseminate basic fact sheets that can be easily distributed through social media, (2) encourage science educators, students, and media representatives to participate in field studies and projects to provide a deeper appreciation of complex science issues, (3) provide scientists with the tools, skills, and resources to more effectively interact with the public, (4) offer topical-based workshops focused on attracting representatives from science news outlets and early carrier scientists, and (5) develop a mentoring plan for young career scientists.

7.5 Recommendations

The methane research community drove the development of the Marine Methane Hydrate Field Research Science Plan. The COL-supported Methane Hydrate Project Science Team and the Methane Hydrate Community Workshop contributed greatly to defining the specific scientific and technical challenges that must be addressed to advance our understanding of methane hydrates in nature and their potential role as an energy resource, a geohazard, and as an agent of global climate change. The following are both general and specific project planning recommendations from the Science Plan concerning the most important methane hydrate research challenges and opportunities, with a focus on how scientific drilling can advance our understanding of the geologic controls on the formation, occurrence, and stability of gas hydrates in nature.

Drilling Programs

The top priorities for dedicated scientific drilling are: (1) an expedition designed to further our understanding of the highly concentrated sand-rich methane hydrate reservoirs in the Gulf of Mexico and (2) a drilling program designed to characterize the methane hydrate systems along the Atlantic margin of the United States. The main goal of the proposed Gulf of Mexico expedition would be coring (mostly pressure coring) and formation testing of the hydrate-bearing sand reservoirs discovered during JIP Leg II at the GC955 and WR313 sites. Scientific drilling along the U.S. Atlantic margin primarily would collect fully integrated and comprehensive cores, downhole logs, and seismic data needed to assess the geologic controls on the occurrence of gas hydrate. It is also critical that the pre-drill site review and planning effort are rigorous and make use of all of the available data from the area of interest and from other successful site review efforts.

Wells of Opportunity

Establish a high-level international committee to monitor and identify cooperative research and specific scientific drilling opportunities to advance our understanding of methane hydrates in nature. This committee would work with organizations such as the International Ocean Discovery Program, national-led methane hydrate research and development programs, oil and gas companies involved in deepwater exploration and development, and governmental regulatory agencies to develop cooperative data collection efforts. It is also important for the committee leading this effort to have the technical capability and financial support required to develop and support the methane hydrate research component of these cooperative opportunities.

Required Drilling and Measurement Technology Developments

Review and update technology and operational requirements for each drilling expedition. As methane hydrate research and development activities move into deeper waters and more complex geologic settings, new and emerging technologies and operational procedures need to be incorporated. For example, the continuous use of drilling muds below certain critical depths during the GOM JIP Leg II permitted the safe and efficient drilling of what was at that time abnormally deep holes. Concepts like the use of riser systems or special mud recovery systems also need to be considered.

Include wireline logging and logging while drilling in all future methane hydrate expeditions. Additional research is needed on the acquisition and use of the logging while drilling acoustic log data, with a particular focus on obtaining high-quality shear wave velocity data. Nuclear magnetic resonance logging and wireline formation testing have made important contributions to our understanding of methane hydrate reservoir properties in Arctic permafrost environments; however, the use of these tools in marine environments have been limited because they cannot be deployed through drill pipe commonly used in riserless scientific drilling. Procedures that would allow the use of the more complex downhole logging systems need to be developed.

Further develop geotechnical tools, such as cone penetrometers and thermal conductivity probes, along with downhole scientific tools such as formation temperature probes, pressure measurement systems, and pore water samplers, and apply them to methane hydrate related research issues. Other downhole measurement tools, most often used for industrial site surveys in support facilities and foundation designs, could contribute directly to the analysis and quantification of methane hydrate related geohazards.

Develop and deploy sensors and devices specifically designed to monitor methane systems. Another area where downhole measurements require greater consideration is the use of borehole instrumentation and observatories. We have seen only a limited number of borehole monitoring systems designed to provide some information on dynamic processes associate with the occurrence of methane hydrate.

Continue to test and develop the Hybrid-PCS, and strongly encourage its use in the field. Specifically developed pressure coring and associated laboratory equipment have contributed greatly to our understanding of methane hydrate occurrence and physical properties of hydrates. The Hybrid-PCS has recently shown a great deal of promise. When possible, the Hybrid-PCS should be made available to both domestic and international methane hydrate research expeditions. It is also important to see the continued develop of the laboratory systems required to analyze recovered pressure cores. The use of systems such as the HYACINTH Pressure Core Analysis and Transfer System (PCATS) and Georgia Institute of Technology Pressure Core Characterization Tool (PCCT) are essential to the success of any future pressure coring program.

Data and Science Integration

Support efforts to coordinate the use and integration of field, laboratory, and model derived data. The integration of field, laboratory, and modeling studies is essential to furthering our understanding of the geologic factors controlling methane hydrate systems in nature. For example, methane hydrate reservoir modeling can aid in predicting gas flow rates and the response of the hydrate-bearing sediments to production, as well as in interpreting impact of natural perturbations on methane hydrate systems dynamics. These numerical models also make use of complex coupled equations that account for heat transfer, fluid flow, and kinetic mechanisms that govern the in situ response of hydrate to internal forcing. In most cases, the equations and various physical properties of the methane hydrate system being modeled have been derived through laboratory analyses of natural and synthetic hydrate samples. The ongoing cooperative work in the methane hydrate community that has shown the method of hydrate formation (e.g., out of solution, from free gas phase, ice seeding) will have a significant effect on the resulting physical properties is an important contribution. This effort is also a good example of a grass-root effort being led by key methane hydrate research laboratories throughout the world, and is the type of effort that needs to be supported and duplicated to deal with other fundamental methane hydrate research problems.

Information and Technology Transfer

Make use of all available communication channels to disseminate well-vetted data and information on the role that methane hydrates may play as an energy resource, geohazard, or agent of global climate change. To effectively deal with the outstanding methane hydrate science and technical challenges, the public must be accurately and honestly informed of the potential benefits and impacts associated methane hydrate research. There is a need to standardize the use of common hydrate related research terms and concepts. It is also important to identify the issues and factors that influence the perception of methane hydrate research into the future.

Monitor the methane hydrate scientific community and deal effectively with misinformation through the peer review process and the judicious use of published reviews and rebuttals.

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9 List of Acronyms and Abbreviations

AOM – Anaerobic Methane Oxidation
AUV – Autonomous Underwater Vehicle
BOEM – Bureau of Ocean Energy Management
BSR – Bottom Simulating-Reflector
cm – centimeters
COL – Consortium for Ocean Leadership
CPP – Complementary Project Proposal
CPT – Cone penetrometers
CSEM – Controled source electromagnetic
DOE – Department of Energy
DSDP – Deep Sea Drilling Project
DWOP – Deepwater Operations Plan
FPC – Fugro Pressure Corer
FPRC – Fugro Rotary Pressure Corer
GHSZ – Gas Hydrate Stability Zone
GOM – Gulf of Mexico
HAZID – Hazard Identification
HBS – Hydrate Bearing Sediment
HYACINTH – HYACE In New Tests on Hydrates
HYACE – Hydrate Autoclave Coring Equipment
HYDRES – Hydrate Reservoir Simulator
IODP – Integrated Ocean Drilling Program
JIP – Joint Industry Project
JOGMEC – Japan Oil, Gas and Metals National Corporation
LCL – Lead Community Liaison
LDEO – Lamont-Doherty Earth Observatory
LWC – Logging While Coring
LWD – Logging While Drilling
m – meters
mbsf – meters below sea floor
MDT – Modular Dynamic Tester
MMS – Minerals Management Service
MPa – megapascal
MTDC – Modified Total Direct Costs
MWD – Measurement While Drilling
NEP – National Energy Policy
NETL – National Energy Technology Laboratory
NGDC – National Geophysical Data Center
NGHP – National Gas Hydrate Program
NMR – Nuclear Magnetic Resonance
ODP – Ocean Drilling Program
OBS – Ocean bottom seismograph
PCATS – Pressure Core Analysis and Transfer Systems
PCCT – Pressure Core Characterization Tools
PCS – Pressure Coring System
PI – Principal Investigator

PNNL – Pacific Northwest National Laboratory
PTCS – Pressure Temperature Coring System
ROV – Remotely Operated Vehicle
SMTZ – Sulfate-methane transition zone
STOMP-HYD – Subsurface Transport Over Multiple Phases Natural Gas Hydrate Simulator
TAMU – Texas A&M University
TOUGH+HYDRATE – Transport Of Unsaturated Groundwater and Heat Natural Gas Hydrate Simulator
USGS – United States Geological Survey
VSP – Vertical Seismic Profile

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