MARINE METHANE HYDRATE FIELD RESEARCH PLAN

Topical Report – December 2013

DOE Award No.:
DE-FE0010195

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

Project Period Start Date: **October 1, 2012**
Project Period End Date: **December 31, 2013**

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Prepared for:
United States Department of Energy | National Energy Technology Laboratory

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ABSTRACT: This topical report represents a pathway toward better understanding of the impact of marine methane hydrates on safety and seafloor stability and future collection of data that can be used by scientists, engineers, managers and planners to study climate change and to assess the feasibility of marine methane hydrate as a potential future energy resource.

Our understanding of the occurrence, distribution and characteristics of marine methane hydrates is incomplete; therefore, research must continue to expand if methane hydrates are to be used as a future energy source. Exploring basins with methane hydrates has been occurring for over 30 years, but these efforts have been episodic in nature. To further our understanding, these efforts must be more regular and employ new techniques to capture more data.

This plan identifies incomplete areas of methane hydrate research and offers solutions by systematically reviewing known methane hydrate "Science Challenges" and linking them with "Technical Challenges" and potential field program locations.

Table of Contents

1 Executive Summary

The study of methane hydrates in nature has been ongoing for over 40 years. Significant strides have been made in our understanding of the occurrence, distribution, and characteristics of marine methane hydrates, but knowledge of the role they may play as an energy resource, geologic hazard, and possible agent in climate change is incomplete. To advance these issues, methane hydrate related research efforts should be better integrated and critical outstanding research challenges identified.

Recent methane hydrate research has focused mostly on: (1) documenting the geologic parameters that control the occurrence and stability of methane hydrates in nature, (2) assessing the volume of natural gas stored within various methane hydrate accumulations, (3) analyzing the production response and characteristics of methane hydrates, (4) identifying and predicting natural and induced environmental and climate impacts of methane hydrates, and (5) analyzing the effects of methane hydrate on drilling safety.

Recognizing the importance of methane hydrate research and the need for a coordinated effort, the U.S. Congress enacted the Methane Hydrate Research and Development Act of 2000, the Secretary of Energy began a methane hydrate research and development program in consultation with other U.S. federal agencies. At the same time, the Ministry of International Trade and Industry in Japan launched a research program to develop plans for a methane hydrate exploratory drilling project in the Nankai Trough. India, China, Canada, the Republic of Korea, and other nations also have established large methane hydrate research and development programs. Government-funded scientific research drilling expeditions and production test studies have provided a wealth of information on the occurrence of methane hydrates in nature.

In 2012, the U.S. Department of Energy (DOE) and the Consortium for Ocean Leadership (COL) combined their efforts to assess the contributions that scientific drilling has made and could continue to make to advance our understanding of methane hydrates, primarily through the development of a Marine Methane Hydrate Field Research Plan (the Plan). COL assembled a Methane Hydrate Project Science Team with members from academia, industry, and government. This Science Team worked with COL and DOE to develop and host the Methane Hydrate Community Workshop, which surveyed a substantial cross section of the methane hydrate research community for input to the Marine Methane Hydrate Field Research Plan.

This plan is built around the most important outstanding scientific and technical challenges associated with the occurrence of methane hydrates in nature identified by the community. The 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 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 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 Marine Methane Hydrate Field Research 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. Listed below are 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 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.

In closing, 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.

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 Plan). This report is the culmination of this effort.

To implement and help guide this effort, COL assembled a Methane Hydrate Project Science Team consisting of representatives from academia, industry, and government who steered this effort from start to completion. Two of the major elements of this COL-led science planning effort designed to provide the foundation for the Plan was (1) the authoring of a Historical Methane Hydrate Project Review Report[1], and (2) the hosting of a Methane Hydrate Community Workshop. The historical review report was used as a guide to develop the agenda for the Methane Hydrate Community Workshop and provide the foundation for the Marine Methane Hydrate Field Research Plan.

The COL-hosted Methane Hydrate Community Workshop was convened in Washington, D.C., on June 4–6, 2013, with the goal of obtaining input from a broad section of the scientific community. The workshop focused on identifying and assessing 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. One of the key workshop goals was the consideration and the potential proposal of scientific drilling expeditions that would address a particular methane hydrate science challenge or a range of challenges. The results of the Methane Hydrate Community Workshop were also captured in a report and posted on the COL project website[2].This Plan is intended to provide guidance to scientific ocean drilling by identifying drilling targets and expeditions that have the greatest potential for collecting the data and information needed to address outstanding critical methane hydrate related scientific and technical challenges.

The Plan begins (Section 3.0) with a summary of the our present understanding of the geologic controls on the occurrence of methane hydrates in nature and an evaluation of the potential role of methane hydrates as an energy resource, as a geohazard, and as a contributor to global climate change. The main body of the Plan describes the most important scientific and technical challenges (Section 4.0) facing hydrate researchers today. This section is followed by details of scientific drilling programs that address the challenges (Section 5.0). The Plan also outlines educational and public outreach opportunities for supporting the growing public interest in methane hydrates (Section 6.0). The Plan concludes with specific project planning recommendations to advance our understanding of methane hydrates in nature (Section 7.0).

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/methane-hydrate-community-workshop

3 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. See **Appendix A** for a *Methane Hydrate Technical Review.*

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 the India 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.

4 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 Marine Methane Hydrate Field Research 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.

4.1 Methane Hydrate Resource Assessment and Global Carbon Cycle

SCIENCE CHALLENGES

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

4.1.2. How do we construct a robust assessment of methane hydrate occurrence?

4.1.3. How do methane hydrate reservoirs respond to natural and anthropogenic perturbations?

All of the challenges explored in this Plan first require a baseline quantification of the amount of methane hydrate stored in 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 hydrates in nature. This concept has been used to guide site selection 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 hydrates in nature. Much of these efforts 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, the nature and driving mechanisms for flow, and changes in these variables through time (**Figure 1**).

Consequently, there is a growing imperative to develop 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 4.1.1. What controls the inventories and fluxes of methane carbon in the marine system, and how do these change over time?

Methane hydrate is a component of a complex system, with inputs and outputs of methane over time. Ultimately, methane generation is intimately tied to the inputs of organic carbon, although it is not yet clear how to best evaluate the relationship between the amount and type of organic carbon landing on the seafloor and the quantity of methane hydrate generated. We still

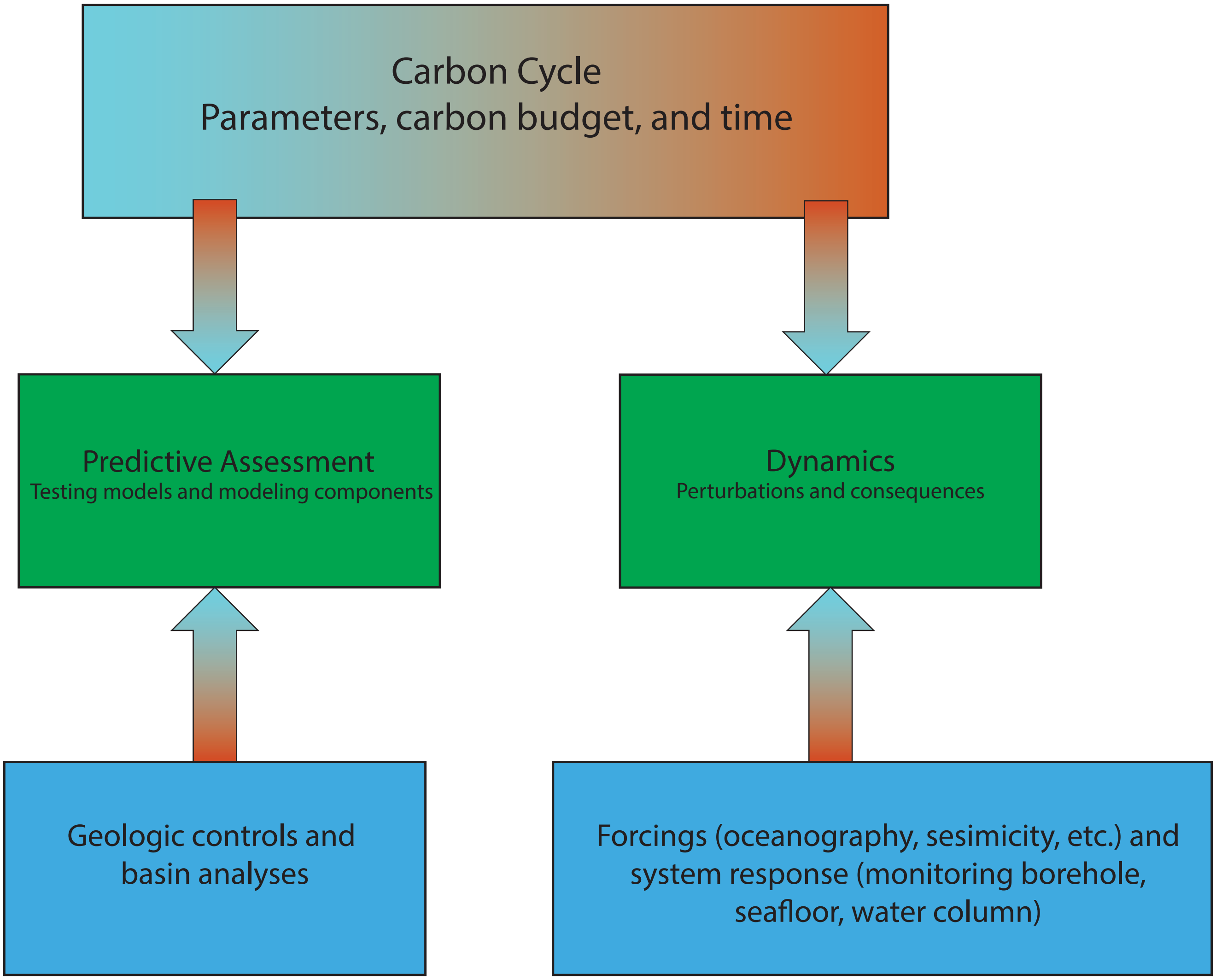

Figure 1. Diagrammatic representation of the role of carbon system dynamics (Science Challenge 4.1.1) on predictive assessment of methane hydrate (Science Challenge 4.1.2) and response of methane hydrate to perturbation (Science Challenge 4.1.3). The predictive assessment necessitates, in addition to parameterization of carbon system dynamics, an understanding of geologic controls commonly used in petroleum system analyses. The more dynamic component of the methane system and its response to natural and anthropogenic perturbations needs to be understood in the context of correlative data that describe forcings and responses of the system.

need to better understand 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 (**Figure 2**).

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). For the latter, how much of the sulfate is consumed by AOM determines how much organic carbon passes into deep sediment and is available for methanogenesis (**Figure 3**).

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, 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 ways 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 observed along global continental margins. These settings include thermogenic versus microbial gas environments, focused flow versus basin-centered accumulations, organic rich versus organic poor sediments, 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, inform global/local assessment models, and increase understanding of 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 topics such as high flux vent/chimney systems, accumulation in sands, and methane hydrate formation in fractured clay-rich sediments. Surface vent locations will be drilled to understand methane flux to the water column, gas flux to the methane hydrate stability zone, methane's impact on microorganisms, the kinetics of rapid formation of hydrate and dissociation, and the spatial variation of shallow sediment's carrying capacity. Drilling in sand reservoirs will further our understanding of the formation mechanism of high concentration methane hydrate in deep marine sand deposits and inform predictive models and assessments. Similarly, targeting locations of methane hydrate accumulation in clay-rich sediments will improve our understanding of where and how methane hydrate accumulates in fracture networks.

Science Challenge 4.1.2. How do we 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 (**Figure 4**). To apply this petroleum system model to a methane hydrate resource system, we not only need to understand conventional reservoir rocks, traps, and seals, but also to incorporate additional parameters that determine methane hydrate stability conditions, including formation temperature and pressure; pore water salinity; water availability; gas source; gas 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 (**Figures 4 and 5**). For example, there are models that quantify localized accumulations to identify potential methane hydrate field size parameters, establish national resource assessments for governmental energy considerations, and assess global methane hydrate distribution. To properly constrain predictive assessment models, it is critical to have a comprehensive understanding of the input parameters, in particular, variables that control inputs and outputs of methane over time. Additionally, while sensitivity studies can identify the most important components in any one model, it remains unclear which of the many critical parameters and conditions are the driving forces in the natural environment at each specific site.

Potential Drilling Strategies

For resource assessment, we focus on the components of the carbon system that lead to methane hydrate accumulations that can be targeted for production. Assessments will be grounded on a comprehensive understanding of the local carbon system, coupled with a geological characterization of the site. Currently, the main focus is hydrate accumulations in deep marine sands, such as those in Gulf of Mexico (OCS Blocks Walker Ridge 313 and Green Canyon 955), on the New Jersey margin, offshore Southwest Taiwan, on the Hikurangi Margin, in the Ulleung Basin, and in the Nankai Trough (**Figure 6**). Proposed strategies begin by verifying assessment models using traditional downhole logging and coring techniques followed by drilling that target reservoirs of interest. Desirable approaches include drilling twins of existing wells and drilling transects to test regional geologic controls.

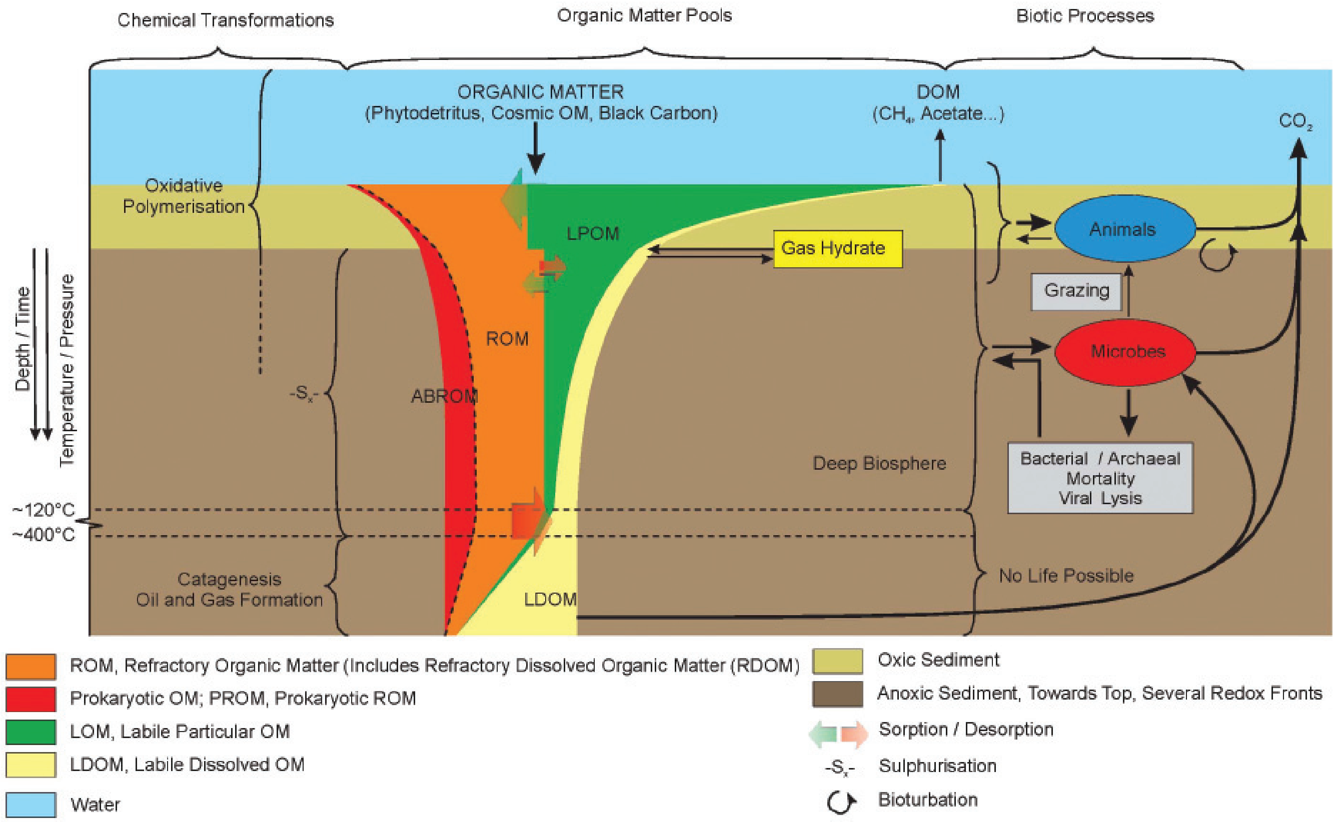

Figure 2. Degradation and transformation of organic matter (OM) in sediments. Left, chemical transformation processes; Center, organic matter pools; Right, biotic processes. The sizes of the organic matter pools and their size reduction with time/depth underestimate the actual degradation, they are not in scale but indicate processes and relative changes (modified from Zonneveld et al., 2010).

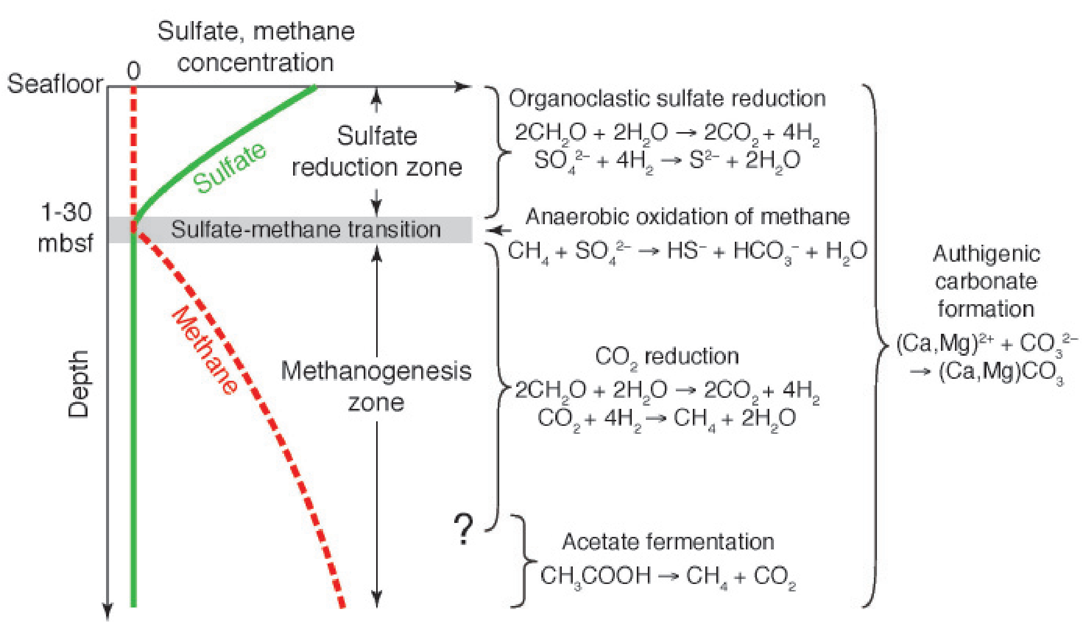

Figure 3. Biochemical pathway reactions for the formation of bacterial methane a marine sediments (Courtesy of WeiLi Hong, Oregon State University, Corvallis, Oregon).

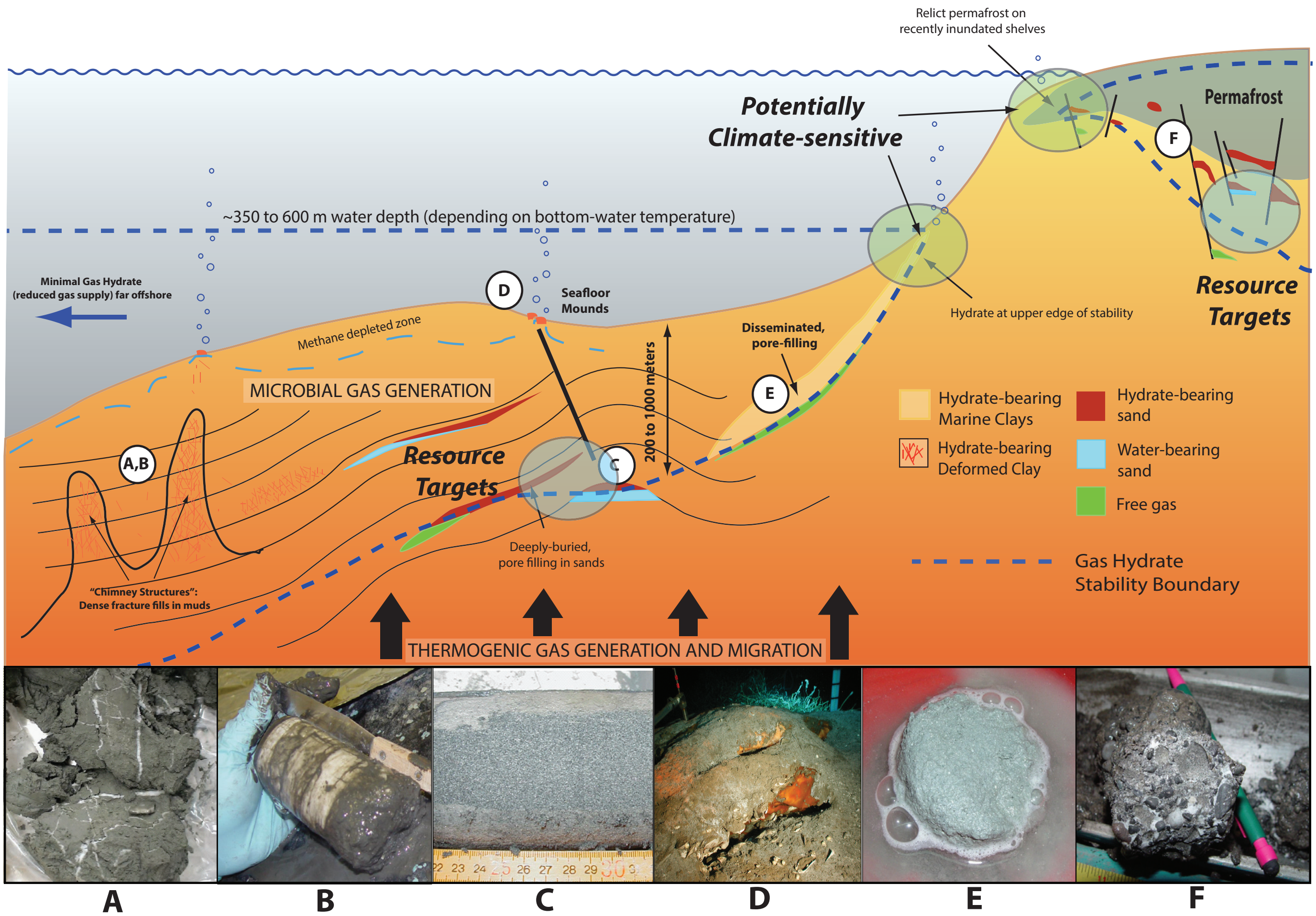

Figure 4. A schematic depiction of the components of various methane hydrate systems. Typical methane hydrate reservoir morphologies including (A) networks of hydrate-filled veins; (B) massive hydrate lenses; (C) grain-filling methane hydrate in marine sands (Japan); (D) massive sea-floor mounds (Gulf of Mexico, USA); (E) grain-filling methane hydrate in marine clays; (F) grain-filling methane hydrate in onshore arctic sands/conglomerates. The general location of the most resource relevant (blue circles) and most climate relevant (green circles) methane hydrate occurrences are also shown. Images as shown are (A) courtesy UBGH-01(Korea); (B) courtesy NGHP-Expedition 01 (India); (E) courtesy GMGS-Expedition 1 (China); (F) courtesy Mallik 2002 Science Program (Canada). Other parts of the methane hydrate system as depicted include the relationship between microbial and thermogenic gas sources and gas migration controls. This depiction was modified from Boswell et al., (in press).

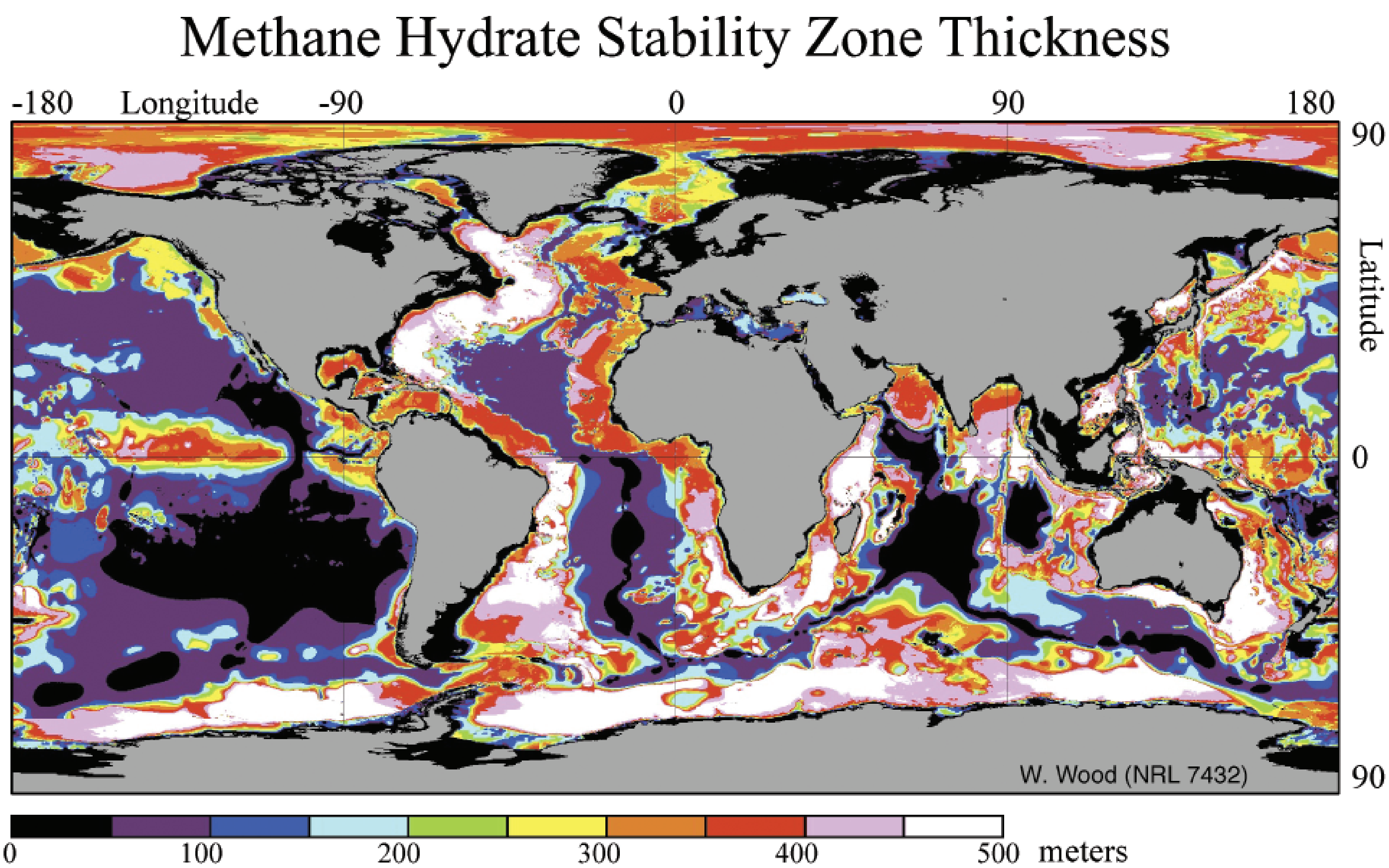

Figure 5. Map of the methane hydrate stability zone thickness used to limit the area assessed for the occurrence of methane hydrate within the worldwide gas hydrate assessment conducted by Wood and Jung (2008).

Science Challenge 4.1.3. How do methane hydrate reservoirs 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 natural and anthropogenic perturbations. Dissociation of methane hydrate due to warming or sea level change can release methane into the ocean-atmosphere system, affecting the ocean's pH (known as "ocean acidification") and, potentially, climate and marine slope stability (**Figure 7**). 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 result in uncertainties in carbon cycle and climate models.

Potential Drilling Strategies

Drilling would most likely target the updip limit of the hydrate stability zone along continental margins where there is evidence of present or past changes of the methane hydrate stability field that led to destabilization and methane discharge (**Figure 7**). These settings are characterized by a well-defined upper limit of methane hydrate stability, evidence of methane hydrate occurrence, fluid venting, temperature changes in the water column (present and past), and an altered methane hydrate stability zone. Sites include the Beaufort shelf, Cascadia margin, Cape Fear, northern Gulf of Mexico, Hikurangi margin, northern Europe (Svalbard), and offshore Cape Hatteras.

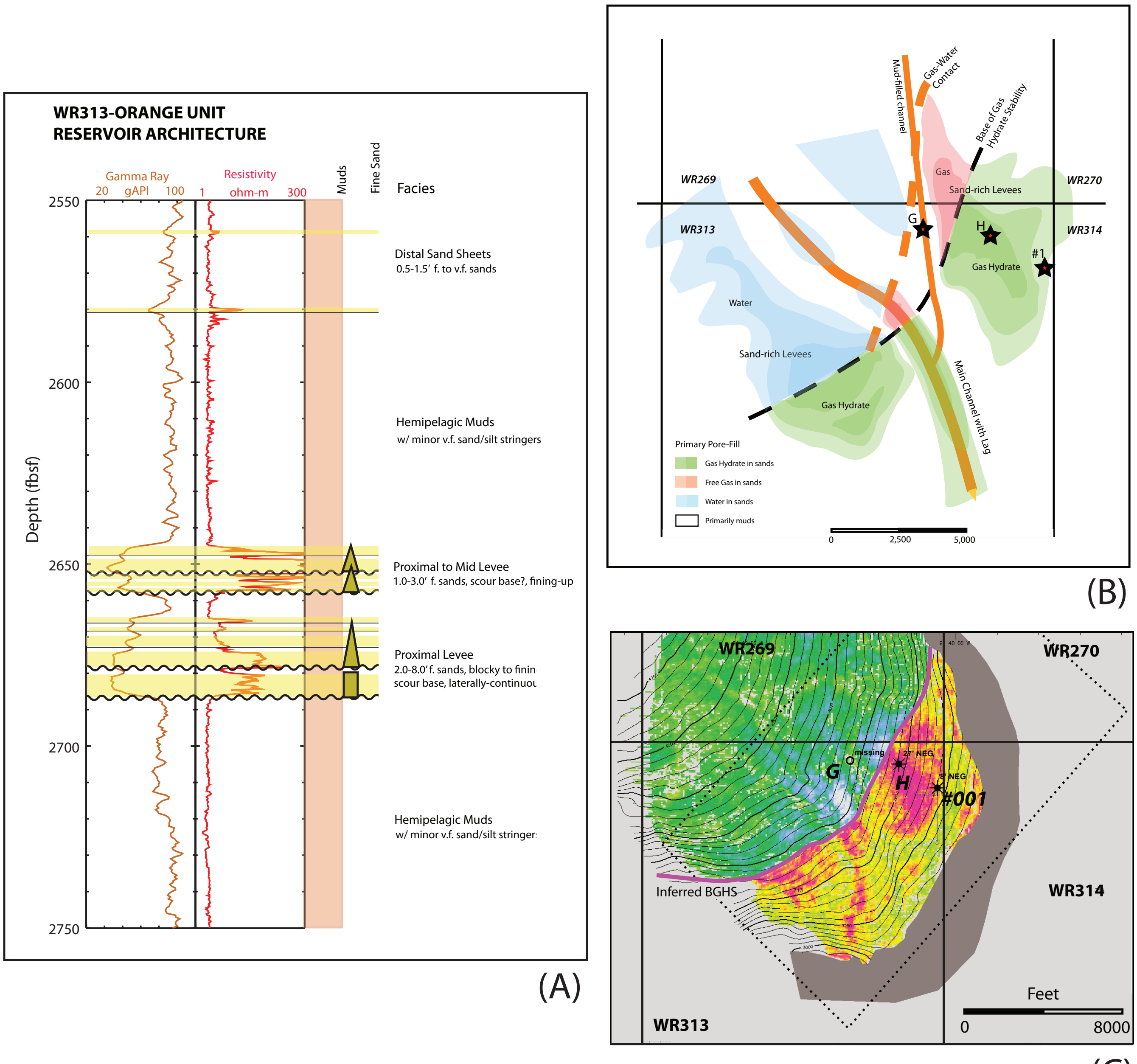

Figure 6. The “Orange” methane hydrate reservoir at the Gulf of Mexico JIP Leg II Walker Ridge 313 drill site (modified from Boswell et al., 2012a). (A) LWD gamma-ray and resistivity data from the “orange” interval in well WR313-H, showing the internal bedding geometry and inferred depositional environments. (B) Cartoon map showing the general areal nature of the lithology and pore fill within the WR313 “orange” unit, showing an axial channel with coarse-channel lag; smaller, mud-filled channels, and bounding sand-rich levees that grade distally into mud-rich facies. Note the lateral change along the base of methane hydrate stability, where sands are present, from methane hydrate over free gas to methane hydrate over water. (C) Amplitude extraction on the high-amplitude seismic horizon corresponding to the “orange” unit drilled in the WR313-G well; the blue and green colors represent areas where amplitude response is negative phase (trough); reds/yellows represent areas of positive amplitude responses (peaks).

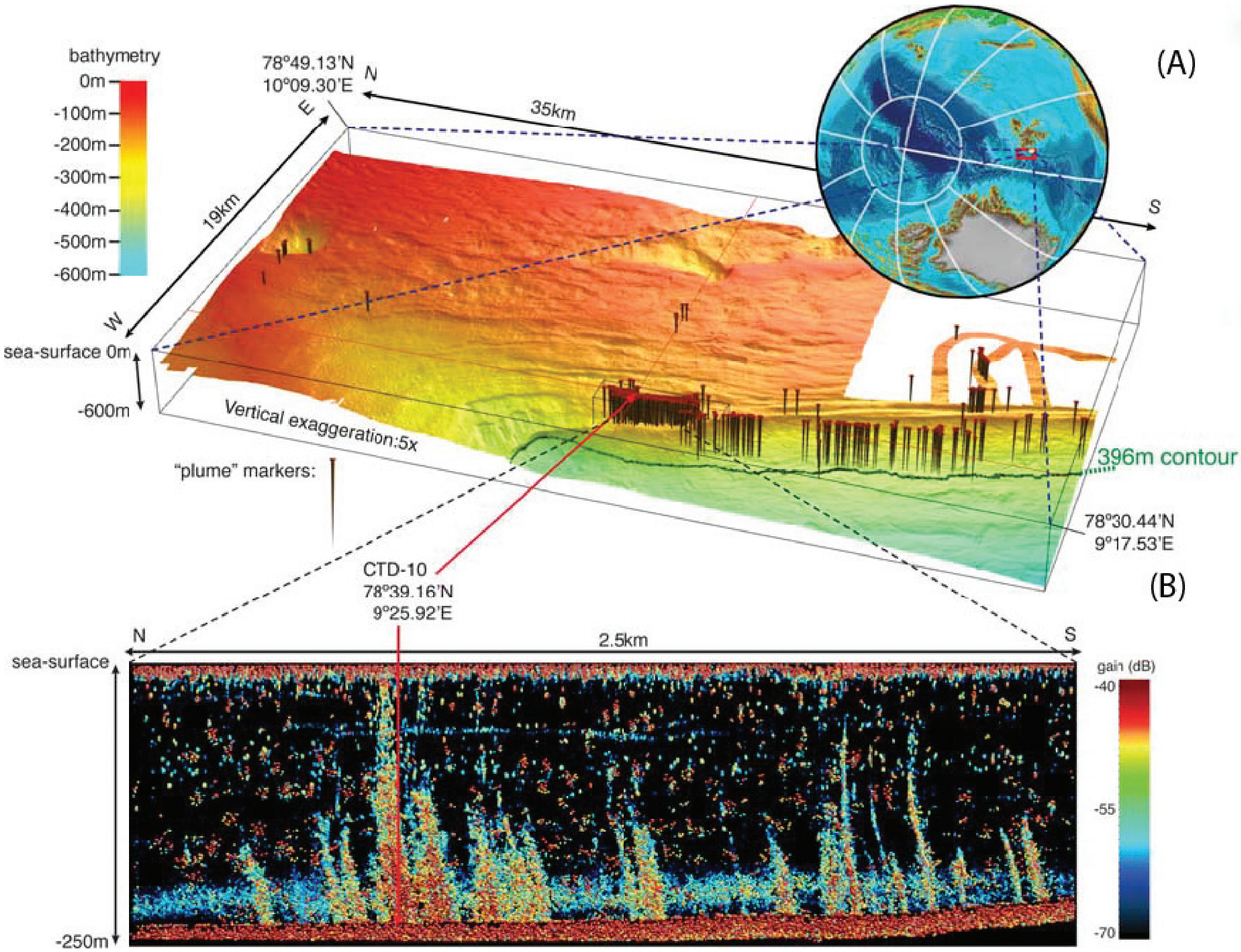

Figure 7. More than 250 plumes of gas bubbles have been discovered emanating from the seabed of the West Spitsbergen continental margin, in a depth range of 150–400 m, at and above the present upper limit of the methane hydrate stability zone. Warming of the northward-flowing West Spitsbergen current by 1°C over the last thirty years has likely lead to an increase in the the release of methane from the seabed by reducing the extent of the methane hydrate stability zone, causing the liberation of methane from decomposing hydrate. (A) Location of survey area west of Svalbard showing the positions of plumes acoustically imaged by sonar, depicted by ''pins'', superimposed on perspective view of the bathymetry of part of the area of plume occurrence. The 396-m isobath is the expected landward limit of the methane hydrate stability zone. (B) Part of a record from an acoustic survey showing examples of observed plumes. Amplitude of acoustic response is given by the color of the ''bubbles''. All plumes show a deflection towards the north caused by the West Svalbard Current. The seabed, at around 240-m depth, is shown by the strong (red) response. This depiction was modified from Westbrook et al., (2009).

A drilling program should enable reconstruction of the system response to change/forcing (gas flux rates, seafloor stability, geomechanics); constrain and quantify the methane hydrate dissociation rate, microbial response to gas release, and the shallow sediment carbon cycle; examine the use of paleo-proxies to identify changes in hydrate layer thinning; and ground truth existing acoustic data. To characterize the full system requires a transect or multiple transects (including a reference site) that cross the stability edge. Drilling should be guided by detailed site surveys that include heat flow, imaging, and seafloor and water column surveys.

4.2 The Challenge of Producing Methane Hydrate

SCIENCE CHALLENGES

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

4.2.2. What key reservoir parameters of offshore methane hydrate reservoirs impact production rate?

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

A number of key parameters must be considered when identifying methane hydrate reservoirs suitable for production. 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 offshore 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. Because conventional production technologies favor sand-dominated reservoirs, they 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.

Methane hydrate field testing (Boswell et al., in press) has shown that there is a need for an 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 simple reservoir configurations, such as hydrates in sand reservoirs bounded by impermeable clay-rich 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 (as reviewed by Collett et al., 2009).

Initial reservoir pressure and temperature conditions can significantly impact methane hydrate production responses and rates. Ideally, a reservoir located in deep water, well below the seabed where temperatures are higher, is more susceptible to temperature and pressure changes that lead to methane hydrate dissociation. This type of 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.

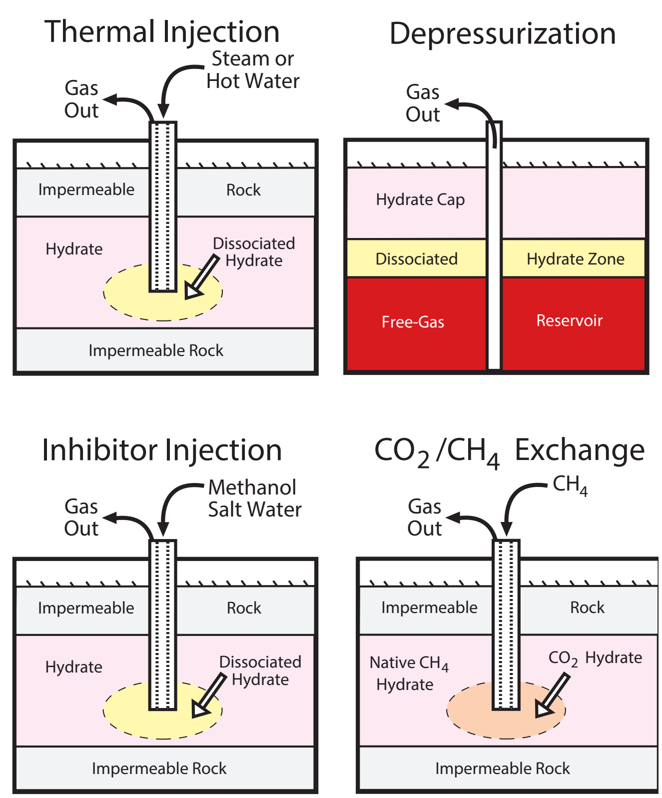

Figure 8. Schematic of proposed methane hydrate production methods.

To prepare for future field production testing, more information is needed on: (1) the geology of the hydrate-bearing formations on a large scale (the distribution of hydrates throughout the world) and on a small scale (their occurrence and distribution in various host sediments), (2) the properties/characteristics of methane hydrate reservoirs, (3) the production response of various methane hydrate accumulations measured in the laboratory and quantified through production modeling, and (4) the environmental and economic issues controlling the ultimate resource potential of methane hydrates. Numerical models that represent observed phenomena in field and laboratory experiments also need to be developed.

Science Challenge 4.2.1. What is the preferred production method for an offshore methane hydrate production test?

To produce methane gas, the methane must be first released from the hydrate structure. Proposed gas recovery methods (**Figure 8**) 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 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 on some of the proposed production methods (see **Appendix B** for *Historical Methane Hydrate Research Scientific Drilling* information on previous hydrate production studies). However, all of these tests have been of limited duration, from six to 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 possesses the suitable reservoir conditions. For example, testing within confined hydrate-bearing, sand-rich reservoirs is preferred to more effectively constrain the test results 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 4.2.2. What key reservoir parameters of offshore methane hydrate reservoirs impact production rate?

Permeability, relative permeability, fluid distribution, porosity, and hydrocarbon saturation typically control fluid flow in conventional gas reservoirs. Methane hydrate adds complexity to reservoir flow. For gas to flow from the reservoir into the producing well, it first has to be released from the hydrate structure. Methane hydrate production by depressurization occurs by lowering reservoir pressures below hydrate stability 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. Key parameters that regulate production rates are the relative permeability of the reservoir, and conduction and convection (how heat is transferred) in the reservoir. Thus, the ideal case for production is to have a highly permeable sand reservoir that is at relatively high temperatures (i.e., deepwater settings and at greater depths below the seafloor).

Potential Drilling Strategy

The main targets for methane hydrate testing and 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, downhole

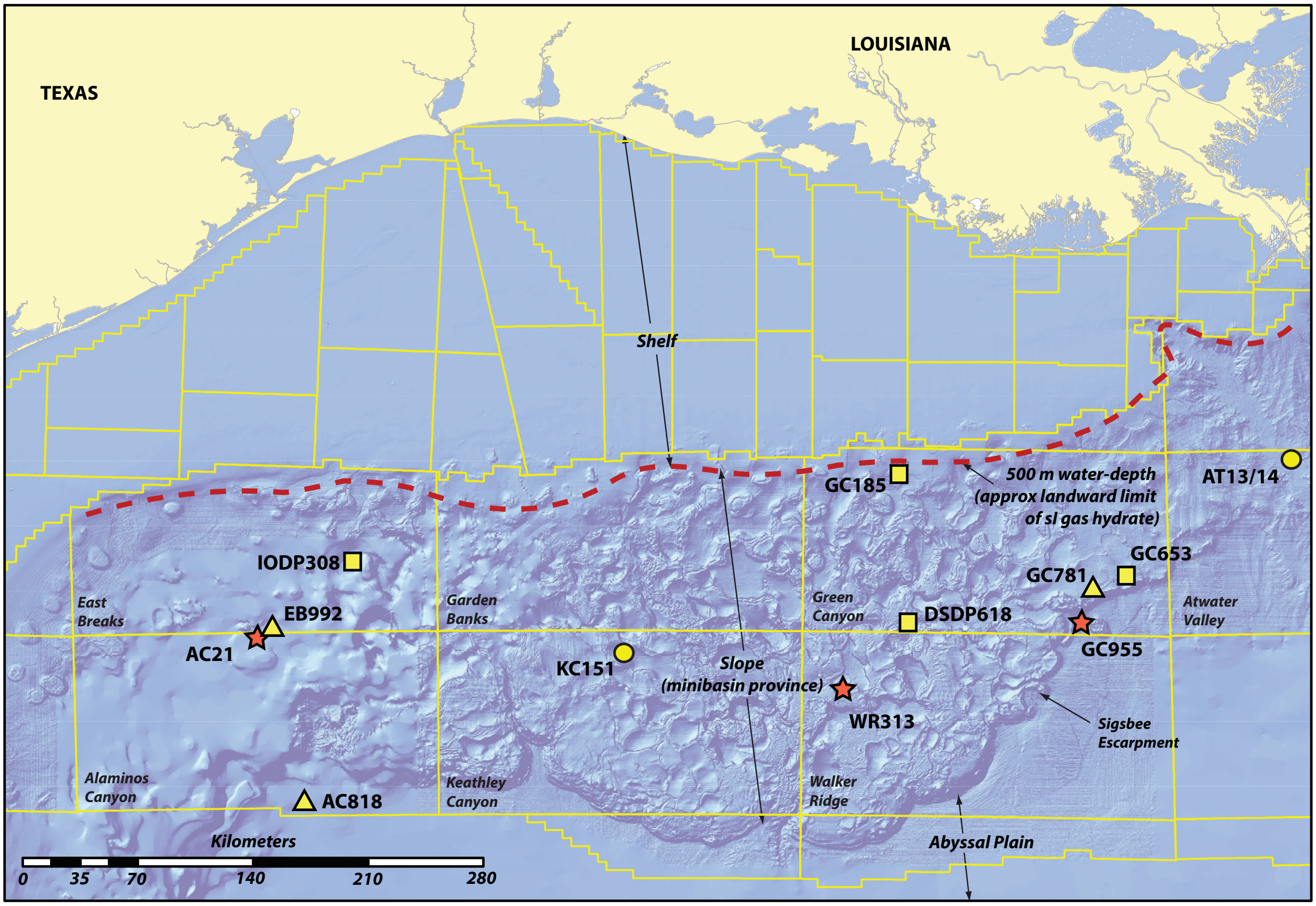

Figure 9. Selected methane-hydrate-related sites in the deepwater Gulf of Mexico. Circles denote Gulf of Mexico JIP Leg I (2005) drilling/coring sites. Stars mark Leg II (2009) LWD sites. Additional sites evaluated but not drilled by the JIP are marked by triangles. Squares mark sites with other methane hydrate research interest (modified from Boswell et al., 2012a).

logging (using both wireline and logging-while-drilling tools) and sediment coring (both conventional and pressure coring) should be conducted 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 deepwater test sites with known hydrate-bearing, sand-rich reservoirs include the Walker Ridge 313 (**Figures 9 and 10**) and Green Canyon 955 (**Figures 9 and 11**) 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 4.2.3. 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

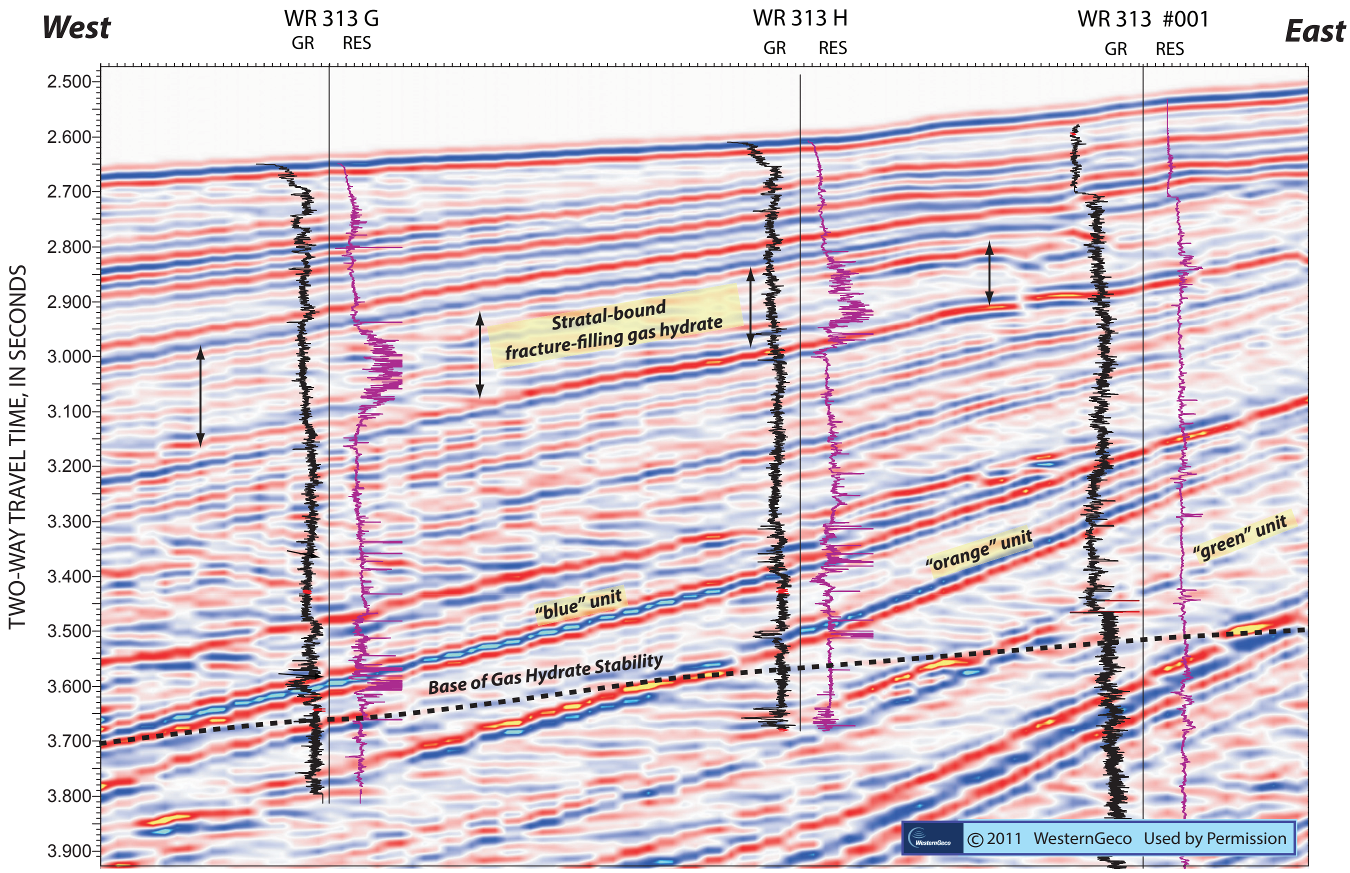

Figure 10. Overlay of select logging while drilling data from Gulf of Mexico JIP Leg II WR313-G and WR313-H wells on regional seismic data showing the major occurrences of methane hydrate, including a shallow, strata-bound zone interpreted to host methane-hydrate filled fractures in fine-grained sediments and deeper occurrences as pore-fill in sand (modified from Boswell et al., 2012a). Seismic data 2011 WesternGeco, used by permission.

magnitude higher. It is important to note 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. Computer simulations indicate that it can take years before the maximum production rate is reached, supporting this observation. Therefore, longer tests (1–5 years in duration) are needed 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 logs and sediment core samples and data. The need to extend the test duration requires locating the test site near existing infrastructure. 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 (**Figure 9**). 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 production.

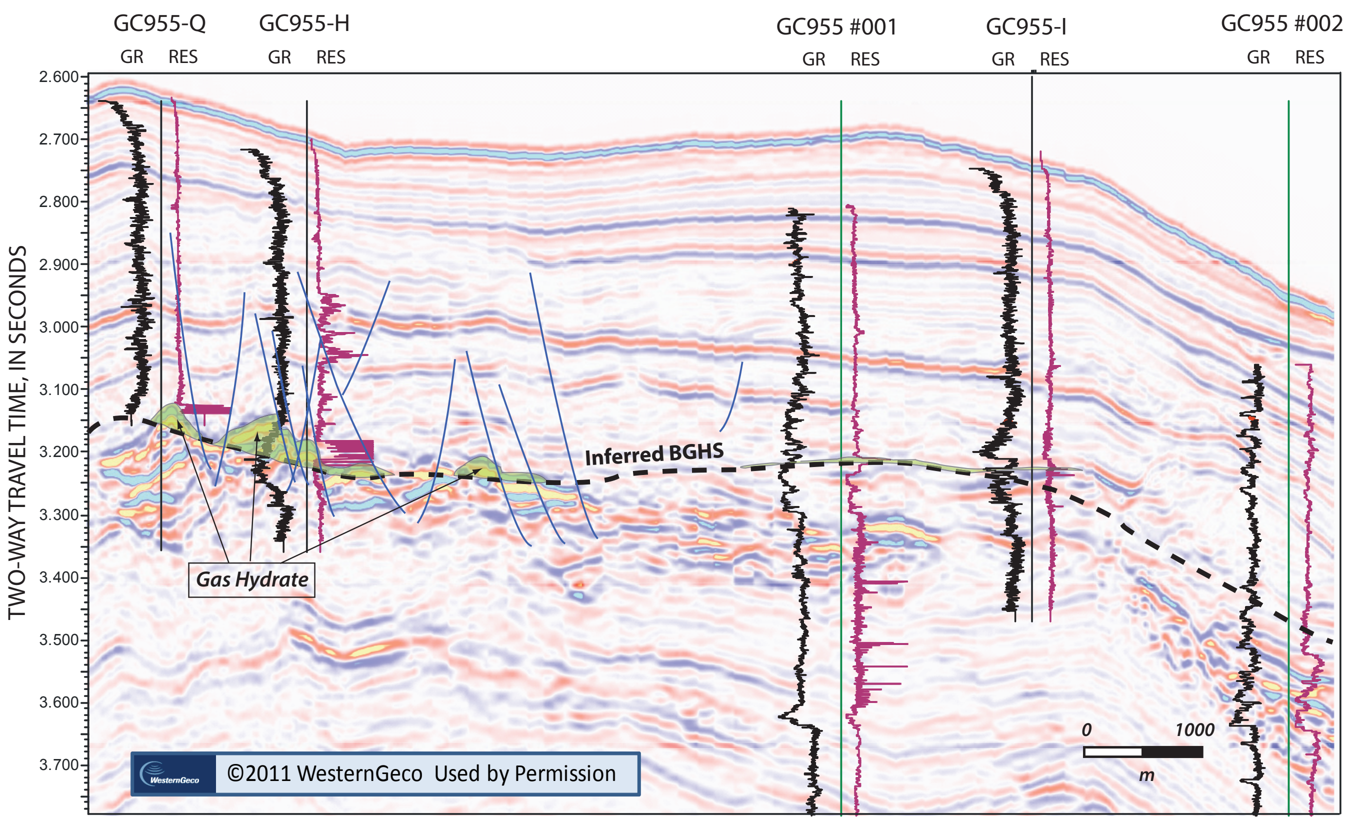

Figure 11. Logging while drilling data for three Gulf of Mexico JIP Leg II wells posted upon an arbitrary display of seismic data at the GC955 site. Green coloration shows the inferred methane hydrate occurrences at the base of methane hydrate stability (dashed line) (modified from Boswell et al., 2012a). Seismic data 2011 WesternGeco, used by permission.

4.3 Methane Hydrate Related Geohazards

SCIENCE CHALLENGES

4.3.1. What operational geohazards affect methane hydrate production?

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

Collective drilling experience to date suggests that the presence of methane hydrate increases the mechanical strength of the surrounding host sediment. Conversely, methane hydrate dissociation releases free gas and excess pore water, substantially reducing the geomechanical stability of the sediment. This reduction in mechanical strength 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, which are hazards triggered by human activities (**Figure 12**). In comparison to most conventional hydrocarbon accumulations, methane hydrates occur at relatively shallow depths. Heating of these shallow reservoirs through, for example, drilling

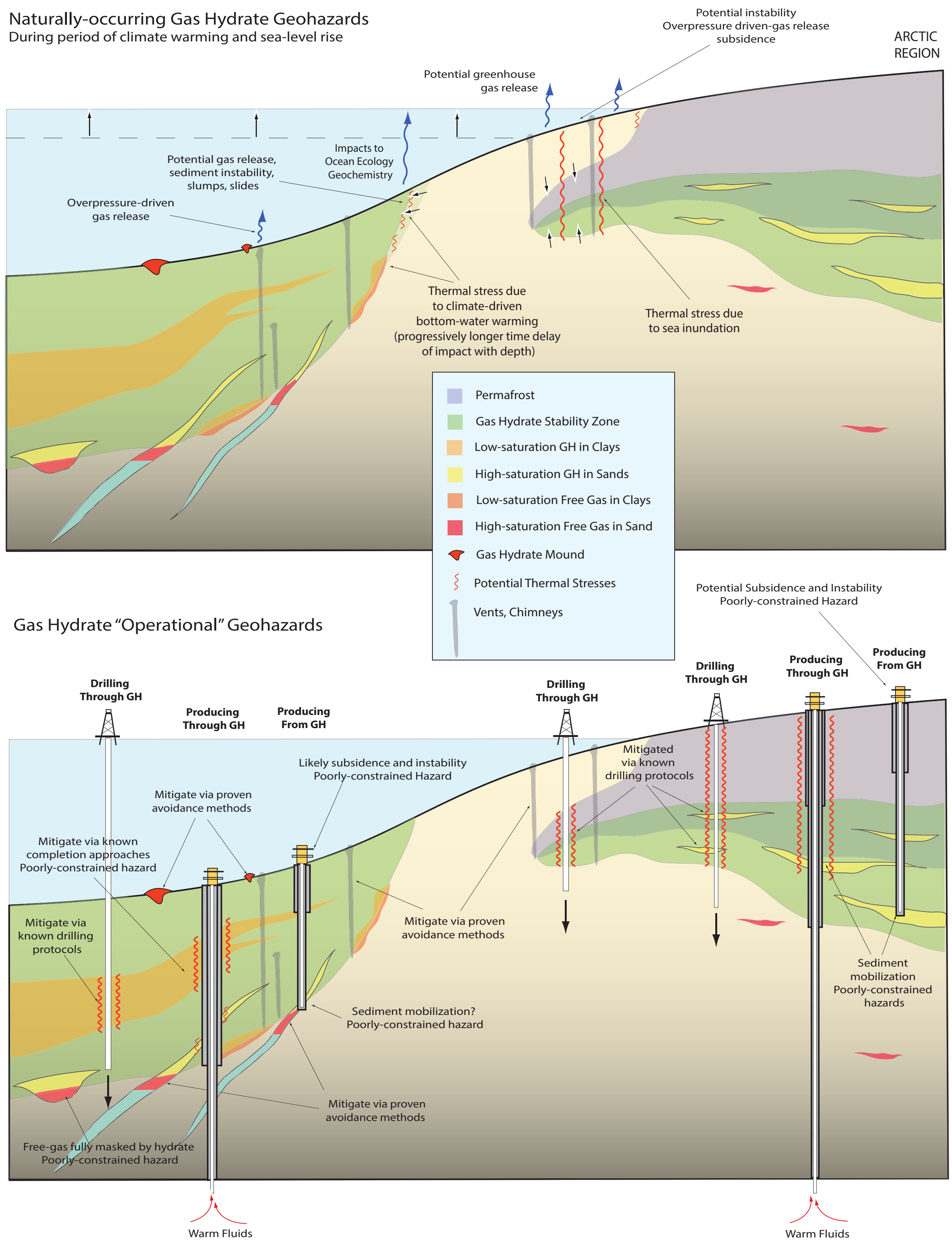

Figure 12. Geohazards associated with the occurrence of methane hydrate encompasses any condition that has the potential to negatively impact any human activity or the natural environment. In this Plan, "natural-occurring" geohazards refer to conditions associated with natural processes. "Operational" geohazards are conditions triggered by human activities (Boswell et al., 2012b).

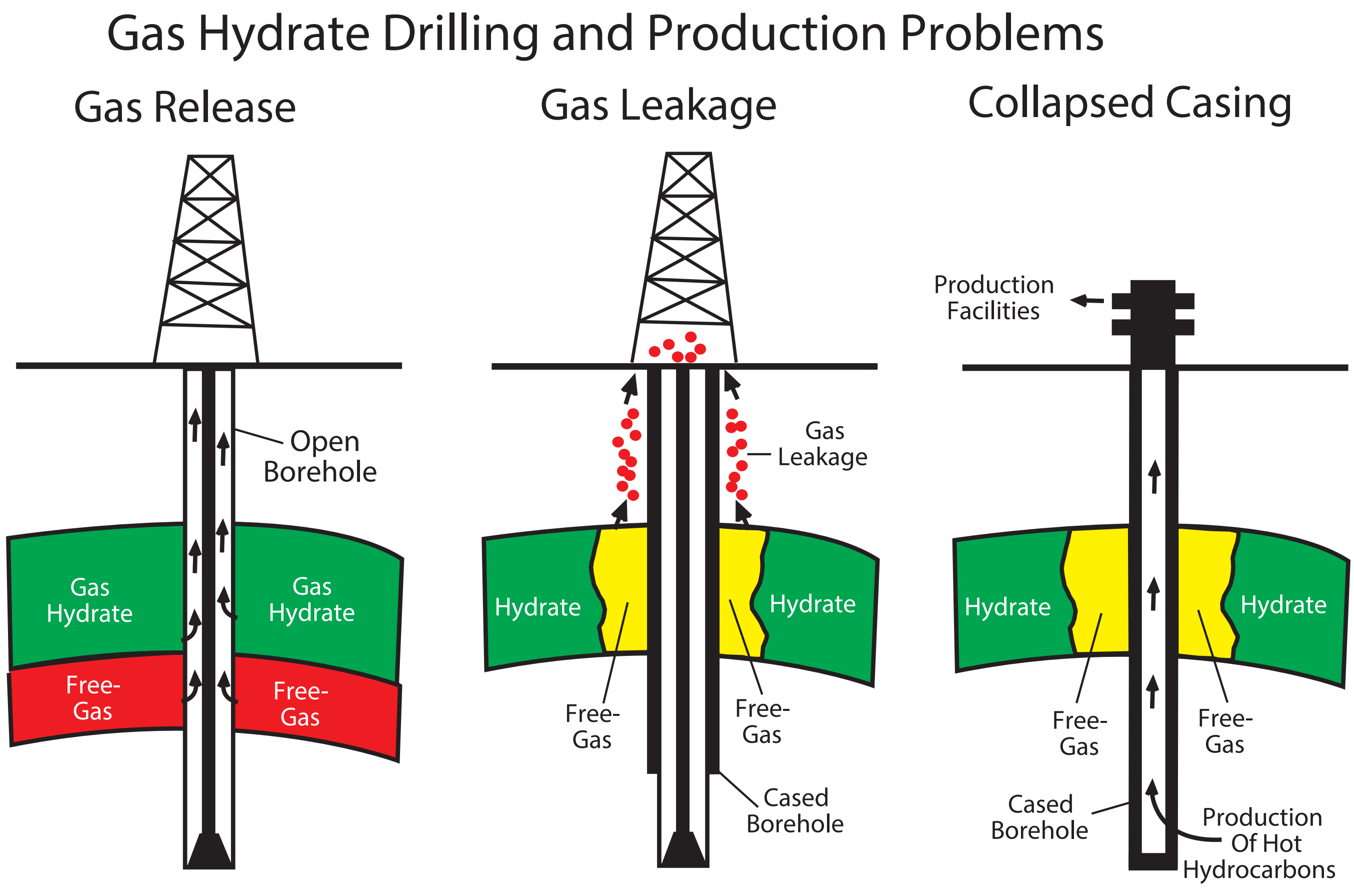

Figure 13. Typical methane hydrate related safety issues associated with the drilling and completion of wells in Arctic terrestrial environments.

or emplacement of seafloor infrastructure such as pipelines can cause the hydrates to dissociate, reduces the host's sediment strength, resulting in seafloor displacement (e.g., a slide).

The second area of interest is naturally occurring geohazards that result solely from geologic processes. The two most important types of naturally occurring methane hydrate geohazards are widespread slope instability and methane gas venting (**Figure 12**). While both of these topics have garnered an unusual amount of interest, particularly, through the Web and television documentaries, it is challenging to provide accurate information when our existing understanding of the geologic controls on the formation, occurrence, and stability of methane hydrates in nature is still evolving.

Science Challenge 4.3.1. What operational geohazards affect methane hydrate production?

Various operational groups (reviewed by Collett and Dallimore, 2002) have reported drilling hazards attributed to the presence of methane hydrate (**Figure 13**). 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 sustained flow of deeper, warmer fluids.

There is a significant lack of quantitative understanding of operational geohazards 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, for example, was formed in 2001 to in part study hazards associated with drilling hydrate-bearing sediments. 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.

The presence of methane hydrates does not appear to be a major issue for the energy industry when drilling exploration and appraisal wells because warm fluid flows through the wellbore for weeks to a few months at most. This short time period is in contrast with the years to a decade or more that warm fluids flow through development wells in an active field. What is difficult to predict over this longer time period is the soil stability profile around heated production casing. Dissociation of methane hydrates around a production casing may fluidize the sediments that in turn would cause the loss of support for the borehole casing.

The hydrate experience gained from conventional oil and gas production is a useful starting point for considering the potential range of geohazards associated with direct exploitation of methane hydrates. We already know of some issues that might be associated with methane hydrate production, but at present we do not know to what extent these issues will impact production operations.

Potential Drilling Strategy

Any drilling and development program that may encounter methane hydrates uses geophysical techniques to identify and mediate potential methane hydrate related geohazards, including exploration 3-D seismic, high-resolution 2-D and 3-D seismic profiles, and multicomponent seismic surveys.

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 permit characterization of the nature of methane hydrate occurrences and associated geohazards.

Hazard assessment drilling must evaluate the full range of methane hydrate settings, from natural seafloor vents to more deeply buried fracture and pore-filling hydrate systems that may trap underlying free-gas accumulations. In addition, geotechnical drilling programs need to assess the potential risk factors. For example, will the project be dealing with foundational designs in the upper several 100 meters below the seafloor or with drilling exploratory and/or production wells through more deeply buried methane hydrate accumulations? It is also possible that the project needs to be designed to directly target methane hydrates to acquire scientific and engineering knowledge.

Science Challenge 4.3.2. 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 that methane hydrate dissociation causes extensive slope instability has been around for over three decades (e.g., McIver, 1982), and it has received further support with the recognition that methane hydrates play an important role in global climate cycles (e.g., Nisbet, 2002; Kennett et al., 2003). Several investigators have since argued that lowering global sea level establishes a new equilibrium for marine methane hydrate stability, which induces seafloor slope instability (e.g., Maslin et al., 2004; Mienert et al., 2005a; 2005b).

Evidence has emerged that methane hydrate dissociation does not cause widespread slope instability. Several large field investigations have addressed this topic with inconclusive results (e.g., Kvalstad et al., 2005; Hornbach et al., 2007). Additional evidence in support of this conclusion include isotopic analysis from methane in ice cores (Sowers, 2006), calculations of methane hydrate contributions to the global carbon budget (Maslin and Thomas, 2003), and models of methane hydrate melting in natural settings (Sultan, 2007). All of these studies suggest that methane hydrate's impact in recent geologic history may be small. Numerous investigations of continental margins and extensive surveys by offshore energy companies clearly show 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.

Continuous methane gas venting occurs in many marine settings, but generally it is not considered a widespread naturally occurring geohazard. Large concentrations of gas chimneys have been documented in certain settings (e.g., Cathles et al., 2010), which may cause widespread catastrophic gas release or even sediment expulsion. Gas venting was initially thought to have caused a collapse feature on the crest of Blake Ridge (Holbrook et al., 2002), but later it was found to have resulted from more gradual processes. Compelling evidence for gas and sediment expulsions was found in the "pingo-like features" observed on the shallow Canadian Beaufort shelf (Paull et al., 2007). They appear to be a result of methane hydrate dissociation associated with the melting of permafrost due to post ice age sea level rise. Again, existing data do not support the case for widespread, catastrophic methane hydrate dissociation-induced gas venting episodes.

Potential Drilling Strategy

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

Additional important scientific drilling targets are regions that exhibit evidence of gas venting from the seafloor. 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 dissociation of methane hydrates is much less clear.

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.

To improve our fundamental understanding of the consequences of methane hydrate dissociation requires the ability to measure the change in sediment strength and fluid properties over time.

4.4 Modeling, Laboratory, and Field System Requirements and Integration

TECHNICAL CHALLENGES

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

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

4.4.3. 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.

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

4.4.5. 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.

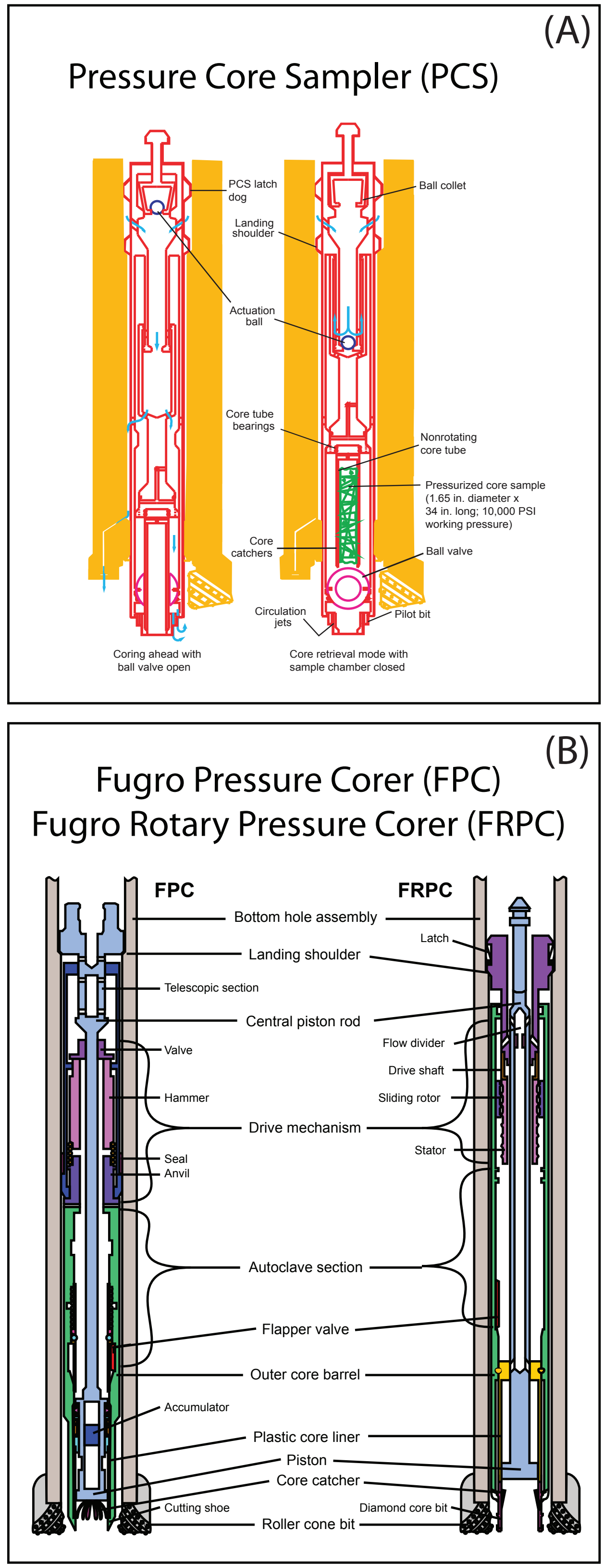

Figure 14. Diagrams of pressure core systems: (A) Pressure Core Sampler (PCS); (B) Fugro Pressure Corer (FPC) and Fugro Rotary Pressure Corer (FRPC).

Technical Challenge 4.4.1. Develop and perform laboratory measurements to help calibrate and interpret field data.

Pressure Core Retrieval and Testing

To assess methane hydrates using field and laboratory systems requires pressure core sample retrieval and analysis to minimize the disturbance of the hydrate-bearing sediment core and provide a samples that are more closely representative of its in situ conditions. One of the first pressure core systems used to study methane hydrates was the pressure core sampler (PCS). The PCS is sealed in an autoclave core barrel that can withstand the hydrostatic pressure at the coring depth and remains sealed as it is brought to the surface. Typically, pressure core systems are used to determine the in situ gas compositions of recovered hydrate-bearing cores and in some configurations, where the autoclave/barrel is constructed of aluminum, the pressurized core can be analyzed using X-rays. Significant advances have been made in the development and implementation of pressure coring tools for hydrate drilling expeditions. Systems include the wireline Hydrate Autoclave Coring Equipment In New Tests on Hydrates (HYACINTH) pressure coring tools, which can cut and recover cores in a wide range of hydrate-bearing lithologies; the Fugro Pressure Corer (FPC) (**Figure 14**), which is suitable for use in unlithified sediments; and the Fugro Rotary Pressure Corer (FRPC) (**Figure 14**), which was designed to sample lithified sediment or rock. A new generation of pressure coring systems has also been developed, including the Pressure-Temperature Coring System (PTCS) and the Hybrid Pressure-Coring System (Hybrid-PCS), which deliver longer cores and feature robust ball valve sealing systems.

Further developments have been made to enable the hydrate-bearing cores retrieved under pressure to be transferred and measured under pressure (without depressurization). These new systems include the HYACINTH Pressure Core Analysis and Transfer System (PCATS) that enables acoustic P-wave velocity, gamma ray attenuation, and X-ray imaging of recovered pressure cores. Pressure Core Characterization Tools (PCCT) have been developed (Santamarina et al., 2012) that include core manipulation tools and characterization chambers to enable hydrological, thermal, chemical, biological, and mechanical properties to be measured under pressure and under effective stress conditions.

Wider use of the existing pressure core sampling technologies is needed to enable hydrate-bearing core retrieval in situ from a more diverse range of geologic conditions. These pressurized cores need to be analyzed using physical property laboratory measurements before, during, and after hydrate production tests. Furthermore, pressure core technologies should be advanced and developed to enable their implementation to be more robust and reliable, as well as to include pressurized triaxial mechanical testing capabilities.

Synthetic Sample Generation and Testing

The limited number and type of available pressure cores from natural systems highlights the need for the synthesis of hydrate-bearing cores in the laboratory. These synthetic hydrate-bearing cores are critical to facilitate calibration and interpretation of valuable field data by providing end members and reference samples. The ability to synthesize hydrate-bearing sediments in the laboratory also enables systematic, well-controlled and well-defined studies that cannot be performed with pressure core samples due to their limited availability and the complex nature of pressure core control systems.

Significant progress has been made in developing synthesis methods for methane hydrate formation in a range of hydrate-bearing sediment systems. These synthesis methods include hydrate formation from dissolved gas, which leads to heterogeneous nucleation and more uniform growth in the pore space; from partial water saturation, which results in preferential formation at grain contacts; and from hydrate particles and ice seeds where the hydrate-bearing sediment properties depend on the relative size of the hydrate particles and sediment grains as well as hydrate saturation (Waite et al., 2009). Hence, the laboratory synthesis methods can have a significant impact on the pore-scale and macro-scale habit of hydrate formation (**Figure 15**). The synthesized hydrate-bearing core samples can then be analyzed using physical property characterization tools (Waite et al., 2009; Kneafsey et al., 2007). To date, only a few studies have been performed to characterize hydrate-bearing sediment samples (both synthetic and a limited natural core samples) using CT-X-ray imaging, porosity-permeability petrophysical analysis, or acoustic measurements for a limited number of samples and conditions. There have also been only a limited number of laboratory studies to investigate gas production from methane hydrate bearing sediments by

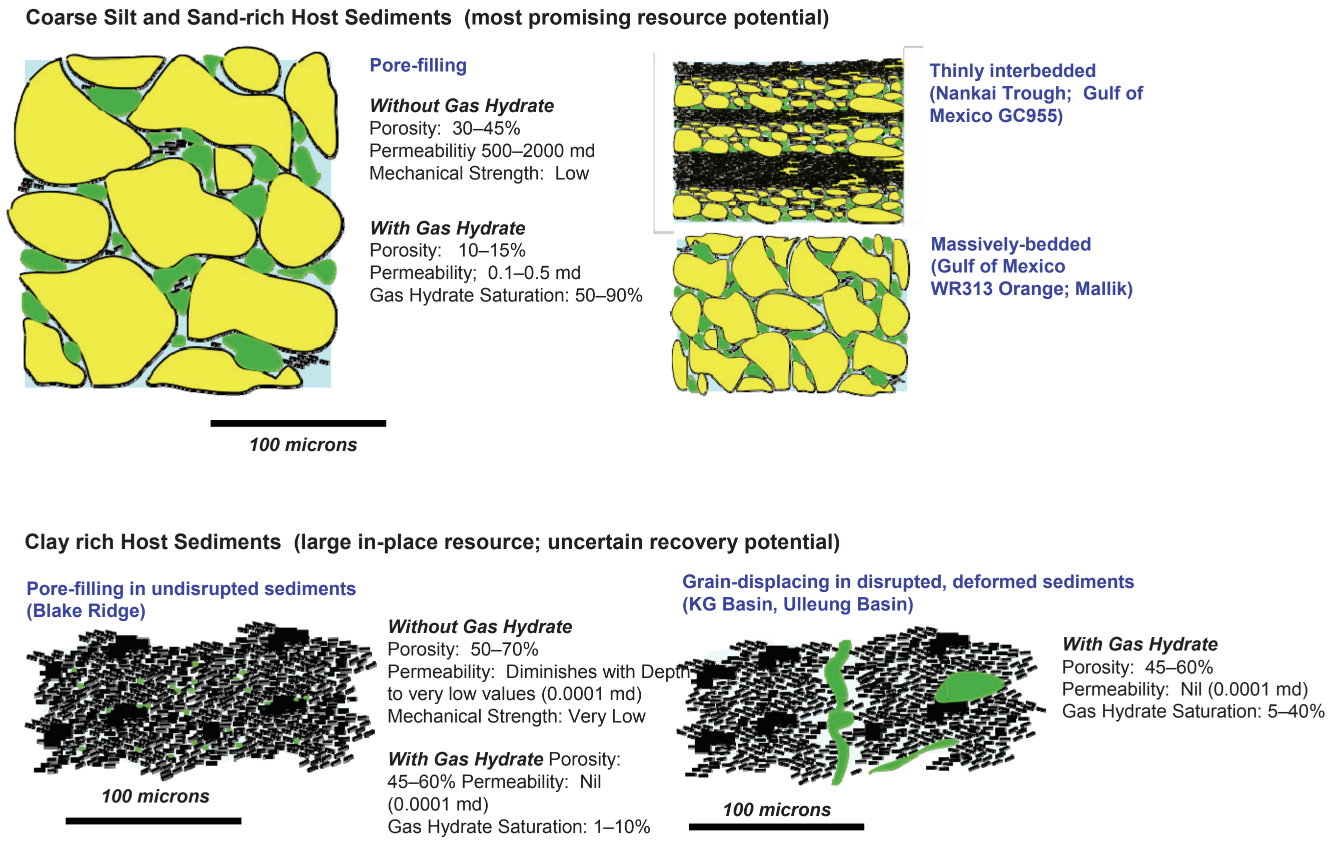

Figure 15. General nature of methane-hydrate-bearing sediments, contrasting the occurrence, abundance and general properties of methane-hydrate-bearing sands (top) with methane-hydrate-bearing clays (below) (modified from Boswell et al., in press)

depressurization, thermal stimulation (Kneafsey et al., 2007), and CO_2 injection (Stevens et al., 2008).

Further advances in the synthesis and analysis of hydrate-bearing sediment samples are critical to advance and validate pore-scale models (i.e., cementing versus pore filling models) and aid in calibrating field data to advance assessment of the geomechanical stability and gas production rates from hydrate-bearing sediments. These advances should also include the development of controlled systematic synthesis of hydrate-bearing sediment samples in a wide range of sediment systems (e.g., grain size, lithologies) and systematic physical property measurements (e.g., permeability, hydrate distribution, shear velocity) as a function of hydrate-bearing sediment conditions, including hydrate saturation, grain size, lithology, pressure, temperature, composition, and hydrate-bearing sediment pore-scale characteristics (generated with different synthetic methods/conditions).

Technical Challenge 4.4.2. To advance and implement field characterization tools to address the critical methane hydrate science challenges.

To address all of the methane hydrate science challenges described in this Plan requires in situ assessment of methane hydrate distribution and hydrate-bearing sediment physical properties. Field characterization tools that have been used in methane hydrate expeditions include 2-D/3-D seismic and electromagnetic (EM) surveying, shallow coring (e.g., geochemical, geotechnical analysis), deep coring for sedimentology, geochemistry, and physical property analysis, and well logging (e.g., wireline logging [WL], logging while drilling [LWD], vertical seismic profiling [VSP]). Key deep sea drilling expeditions that have been dedicated to locating marine hydrates and understanding the geologic controls on the occurrence methane hydrates in nature include ODP Leg 164 on the Blake-Bahama Ridge and ODP Leg 204 on Hydrate Ridge where LWD and pressuring coring were conducted; IODP Expedition 311 across the Northern Cascadia margin, which applied LWD, pressure coring, WL, and VSP; and GOM-JIP, which used scientific drilling, downhole logging, and pressure coring. Production field tests have been conducted at the Mallik wells in the Mackenzie Delta using depressurization and thermal stimulation production methods, at the Ignik Sikumi well in the Alaskan North Slope using CO_2/N_2 injection for CO_2/CH_4 exchange, and in the Nankai Trough off the coast of Japan using depressurization.

It is necessary to widely implement existing advanced field characterization tools to obtain reliable and accurate field data on hydrate-bearing reservoirs during pre-drilling, drilling, and post-drilling phases and production programs (**Figure 16**). More high quality field data are needed to map methane hydrate occurrences and determine the geophysical properties of hydrate-bearing reservoir systems. **Table 1** summarizes the general and overarching field characterization tools and data needed to address the outstanding methane hydrate science challenges described in this Plan. **Table 2** summarizes the field tools and data requirements specific to Science Challenges 4.1, 4.2, and 4.3. In particular, nuclear magnetic resonance (NMR) and wireline formation testing tool (MDT) deployments are needed for detailed reservoir characterization. In addition, downhole tools such as cone penetrometers and in situ formation pressure and temperature measurement devices need to be included in future drilling expeditions to address the outstanding methane hydrate related science challenges.

Technical Challenge 4.4.3. 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.

Multiscale model (pore-scale and reservoir-scale) development and validation are needed to provide reliable assessment of the methane hydrate resource potential, gas production rates, and geomechanical/environmental impacts of methane hydrate systems during production. Hydrate reservoir models that have been developed include TOUGH+HYDRATE/TOUGH, Fx/Hydrate (DOE-LBNL), CMG STARS (Computer Modeling Group), HydrateResSim (DOE-NETL), MH-21 (National Institute of Advanced Industrial Science and Technology, Japan Oil Engineering Company, University of Tokyo), HYDRES, and STOMP-HYD (PNNL, University of Alaska Fairbanks). These reservoir model prediction tools have been applied in numerous resource studies to

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: • "Timing issues" related to dynamic aspects of methane hydrate system • 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

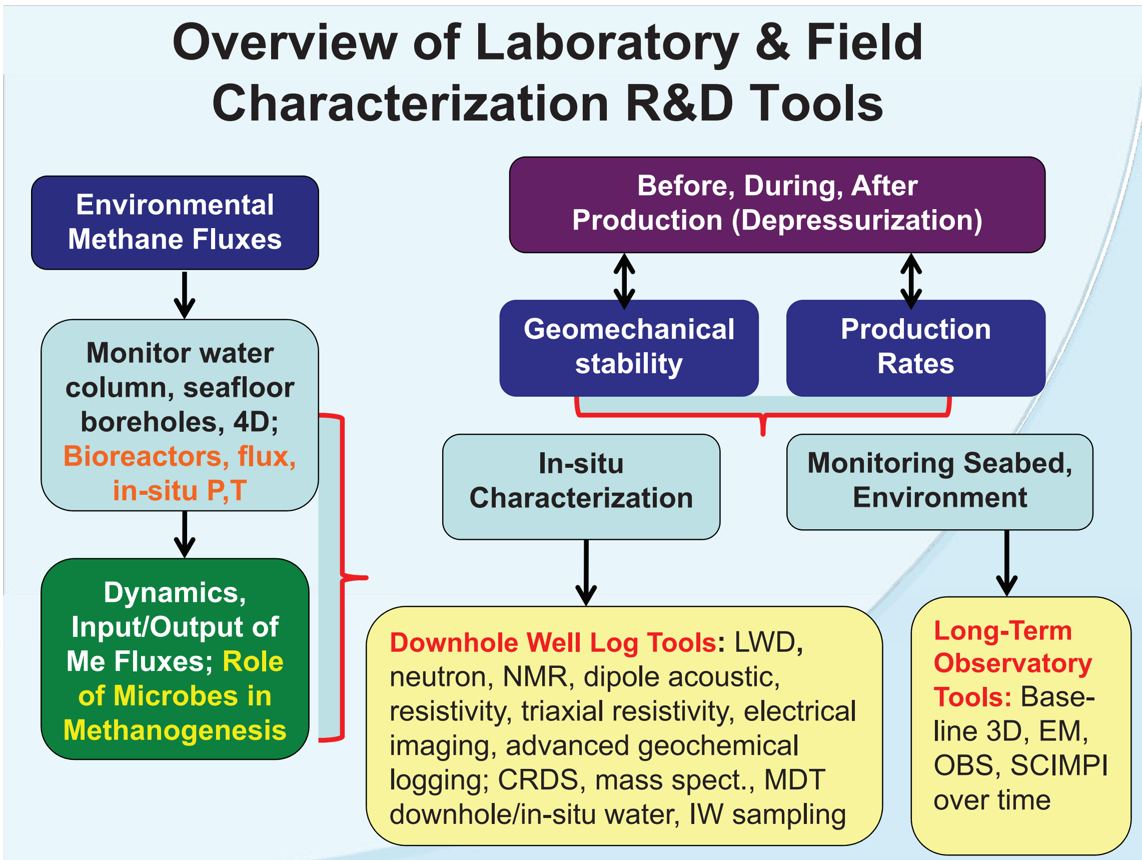

Figure 16. Overview of laboratory and field tools used to characterize the occurrence of methane hydrates associated production and carbon cycle issues.

estimate gas production rates and reservoir response to depressurization, thermal stimulation, and chemical injections (Moridis et al., 2009; Wilder et al., 2008).

International code comparison programs have been/are being performed to compare different methane hydrate reservoir simulators, enable improvements to be made in reservoir simulation by cross comparisons, and build confidence in the models and their applications. The first international code comparison study (Wilder et al., 2008) used different reservoir models to predict hydrate dissociation by thermal stimulation and depressurization, heat transfer across geological media, and changes in thermodynamic and transport properties with changes in pressure and temperature. Simulating methane hydrate production requires solving a complex combination of coupled heat, mass, and fluid transport equations, together with assessment of the formation and dissociation of multiple solid phases in the reservoir. The available simulation models use different approaches to solve the problems, which can lead to discrepancies between some of the models. Reservoir simulators are being further developed to assess gas recoverability from hydrate-bearing sediments in oceanic and arctic environments using different production methods and the geomechanical properties of hydrate-bearing reservoir systems. However, previous predictions and current models (both on pore and reservoir scales) are missing key physics due to the lack of data on various parts of the hydrate-bearing systems. There is also a need for accurate, long-term production field data to validate the models.

Reservoir modeling is needed to guide site selection, experimental design, and data collection for future field tests in support of the science challenges described in this Plan. To ensure the model predictions are accurate and reliable, it is important to incorporate the correct physics into the models, including accurate pore-scale, thermodynamic, and transport information. The correct physics can only be obtained by acquiring more laboratory and field characterization data sets and by conducting more production tests.

Technical Challenge 4.4.4. To determine critical site review and characterization requirements for proposed drilling strategies.

In recent years, there have been important advances in the approaches and data used in pre-drilling site surveys. For example, building on the results of GOM-JIP Leg I, a key objective of JIP Leg II drilling program was to address the hypotheses that methane hydrate occurs in sand reservoirs within the deepwater Gulf of Mexico and that specific methane hydrate-in-sand accumulations can be identified and characterized prior to drilling through an integrated geophysical-geological prospecting approach. This effort began with a review of data from existing wells in the Gulf of Mexico that exhibited evidence for the presence of methane hydrate. The second phase of the JIP Leg II consisted of simultaneously integrating advanced seismic inversion results with the geological-geophysical evaluation to assess the presence of gas sources and sand-rich lithofacies linked by migration pathways. JIP Leg II was launched with a total of 20 drill locations permitted within the Gulf of Mexico. Ultimately, the LWD data acquired during GOM-JIP Leg II confirmed reservoir-quality sands within the methane hydrate stability zone in all seven wells drilled during the expedition, with methane hydrate occurrences closely matching pre-drill predictions in six of the wells. The integrated prospecting approach developed by the JIP to delineate and characterize methane-hydrate-bearing sands prior to drilling has become an integral part of most pre-drill methane hydrate assessment programs.

For most drilling projects, however, not all of the data needed for a comprehensive pre-drill site survey are readily available. It is critical that operation planners consider existing data and critical missing data. COL workshop attendees consider the following data sets as necessary for a thorough pre-drill site review.

Remote characterization methods:

- *Conventional 3-D survey of region to locate target area*
- *High-resolution 3-D survey to focus in on prospect and sites*
- *Multi-component seismic data, OBSs (broadband)*
- *Sub-bottom profiling (chirp)*
- *Multi-beam bathymetry and backscatter*
- *Water column anomalies (echo sounder, multi-frequency systems)*
- *Electromagnetic surveys*
- *Microgravity surveys*
- *Seafloor video coverage*
- *Sea-surface observations (petroleum slicks, gas at surface)*

Near-seafloor sampling and investigations:

- *Fluid flux meters*
- *Gas flux coming out of the system—sniffers, diffusion detectors*
- *Infaunal sampling with spatial resolution—box cores*
- *Shallow piston cores*
- *Tiltmeters and bottom pressure sensors*
- *Heat flow sensor data*
- *Geotechnical coring*
- *Cone penetrometers surveys*
- *Discrete temperature measurements*

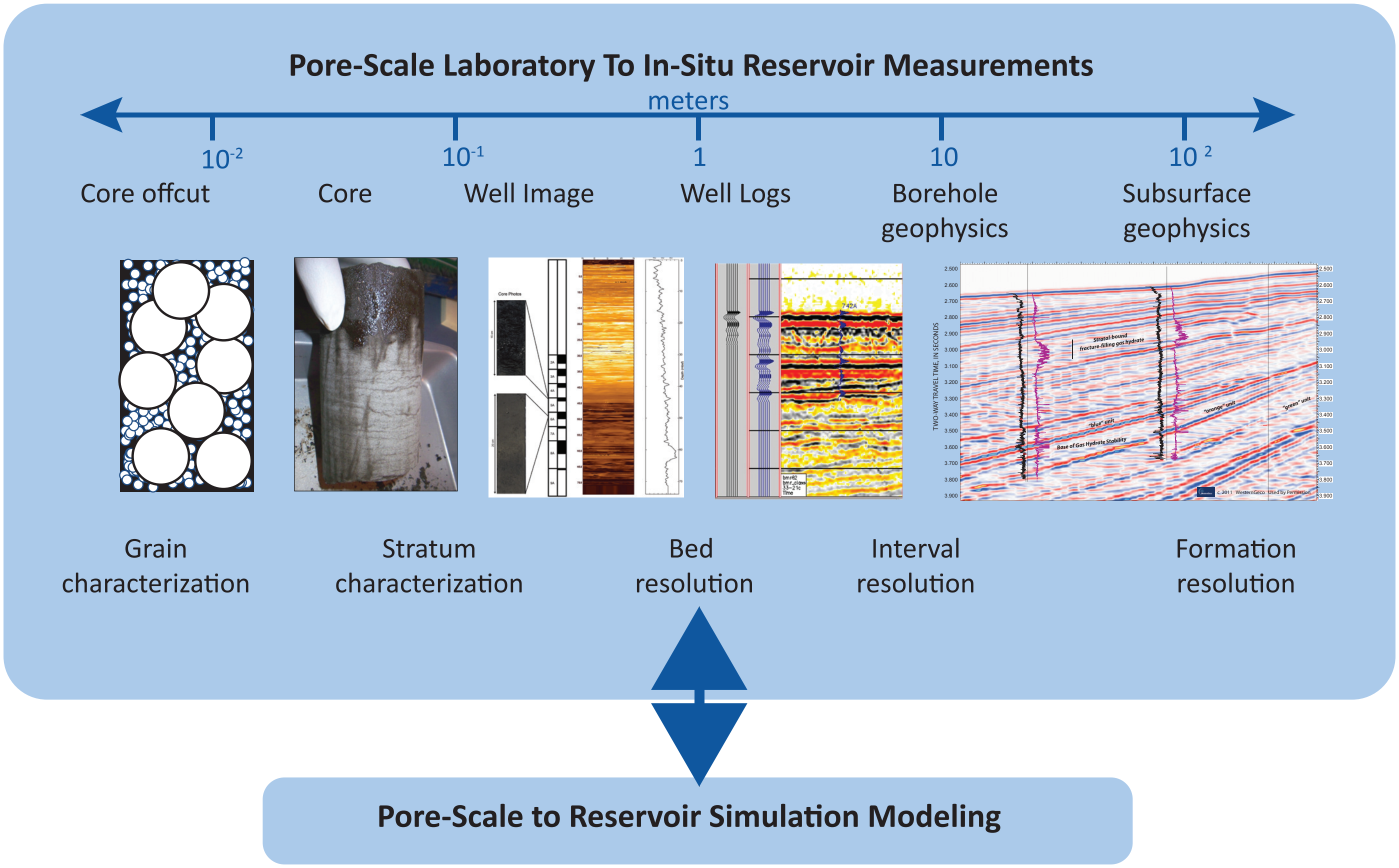

Figure 17. Schematic illustrating the different scales of geophysical measurements (modified from Goldberg, 1997). The scale ratio from core to log may be greater than 2 x 10^3; the ratio from log to seismic may be 10^6 to 10^7 times larger. Interpretation of data from samples (natural and synthetic cores) to intermediate-scale logging and borehole measurements to regional geology coupled with multi-scale modeling enables the science challenges with in the to be addressed.

Technical Challenge 4.4.5. Advance integration and upscaling of model, lab, and field derived data.

"Upscaling" of core and laboratory-scale measurements to the scale of downhole logging and seismic prospecting measurements has long been a challenging endeavor. Upscaling requires integrating core sample measurements (natural and synthetic hydrate-bearing sediment cores) with downhole logs by placing both in the context of regional geophysical and seismic studies, and coupling both sets of measurements with pore-scale and reservoir modeling. Seismic sections enable regional 3-D geologic relationships to be inferred. Downhole logs typically have an intermediate resolution of around 0.5 m, giving continuous information in the region surrounding the borehole. Natural core samples provide detailed information on physical properties and sedimentologic relationships. Laboratory measurements of synthetic cores enable systematic calibration of the downhole log data. Calibration of well logging data, controlled laboratory tests, and seismic analysis, coupled with pore- and reservoir-scale modeling, will help constrain upscaling requirements for studies of methane hydrates in nature (**Figure 17**).

This coupled multi-scale approach is critical to overcoming the limitations of the individual data types. For example, coring (even pressure cores) provides samples by disrupting the in situ hydrate-bearing sediments, synthetic cores while enabling systematic field data calibrations have issues of being comparable to field samples, and logs have much greater vertical resolution than seismic data, but little lateral resolution.

5 Cross-Disciplinary Research Frontiers

5.1 Methane Hydrate Research Challenge Integration

One of the key goals of this plan is to consider the potential overlapping relationships among 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.

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,

Methane Hydrate Research Science Plan

Science Challenges

4.1. Methane Hydrate Resource Assessment and Global Carbon Cycle
4.1.1. What controls the inventories and fluxes of methane carbon in the marine system, and how do these change over time?
4.1.2. How do we construct a robust assessment of methane hydrate occurrence?
4.1.3. How does this reservoir respond to natural and anthropogenic perturbations?
4.2. The Challenge of Producing Methane Hydrate
4.2.1. What is the preferred production method for an offshore methane hydrate production test?
4.2.2. What are the key reservoir parameters of offshore methane hydrate reservoirs impacting the production rate?
4.2.3. What is the minimum production rate and length of test needed from offshore methane hydrate reservoir to indicate economic viability?
4.3. Methane Hydrate Related Geohazards
4.3.1. What are the operational geohazards, triggered by human activities, which will affect methane hydrate production?
4.3.2. Are there methane hydrate geohazards that are induced solely from naturally occurring processes?

Technical Challenges

4.4. Modeling, Laboratory, and Field System Requirements and Integration
4.4.1. Develop and perform laboratory measurements to help calibrate and interpret field data.
4.4.2. Advance and implement field characterization tools to address the critical methane hydrate science challenges.
4.4.3. 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.
4.4.4. Determine critical site review and characterization requirements for proposed drilling strategies.
4.4.5. Advance integration and upscaling of model, lab, and field derived data.

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 this 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 previously in this Plan.

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.

5.2 Scientific Drilling Programs

Field studies have yielded invaluable information on the occurrence of methane hydrates in nature, but more work is needed to characterize the geology of hydrate-bearing formations. Scientific drilling will play a key role in advancing our understanding of methane hydrates by providing a range of geologic and geophysical data on the geologic controls governing the variability among methane hydrate accumulations in different settings. This section describes topical-based scientific drilling programs that would address the outstanding methane hydrate related challenges described in this Plan, including specific operational and scientific details.

5.2.1 Fully Parameterize the Global Carbon Cycle Using Wells of Opportunity

Science Challenges Addressed:

Science Challenge 4.1.1. What controls the inventories and fluxes of methane carbon in the marine system, and how do these change over time?

Science Challenge 4.1.2. How to construct a robust assessment of methane hydrate occurrence?

Science Challenge 4.3.2. Are there methane hydrate geohazards that are induced solely from naturally occurring processes?

To fully account for the sources and sinks within the global carbon cycle requires knowledge of the geologic controls on the formation, occurrence, and stability of methane hydrates in nature. Science Challenge 4.1.1. What controls the inventories and fluxes of methane carbon in the marine system, and how do these change over time establishes the need to assemble a global database of methane hydrate accumulations. Taking advantage of "wells of opportunity," in which the goals and operational aspects of a particular expedition or individual well drilled for non-hydrate related research purposes have been expanded to collect important methane hydrate data, has been a successful approach to assembling a global inventory.

The successor to IODP, the International Ocean Discovery Program, will again use three primary platforms: the multipurpose drillship *JOIDES Resolution*, the riser-drilling-capable Chikyu for ultra-deep drilling, and mission specific platforms chartered on an ad hoc basis for drilling in challenging environments. It is also clear that most of the national-led methane hydrate energy assessment programs will continue to plan and execute complex methane hydrate scientific and production focused expeditions far into the future. We also see industry-led deepwater oil and gas exploration and development drilling interest expanding throughout the world. These programs have already contributed greatly to our understanding of methane hydrates in nature and the hydrate systems that control their presence.

For the proposed "wells of opportunity program" to be successful requires coordination at the highest levels, perhaps though a program management team that will develop protocols, oversee field programs, and maintain a database of industry, IODP, and other wells that may yield the sought after samples and data.

Drill Site and Operational Considerations

1. Geologic Setting: Target all ocean margins and all known variables within the methane hydrate system (including thermogenic and microbial gas systems, low and high organic matter content systems, focused flow and basin-centered accumulations, passive and active margins).

2. Specific Locations: Global, with a diverse range of conditions and settings.

3. Scientific Objectives: Defining metrics that control global carbon cycle budget over time; establish thresholds, inform global/local assessment models, and understand the lifecycle components of methane over time.

4. Site Survey Requirements: The focus of this effort is to link operations with other programs.

5. Drilling Strategy: Wells of opportunity, establishment of a consistent data acquisition protocols and requirements.

6. Required Technology: Conventional wireline coring, pressure coring, specialized sampling/analysis protocols, downhole logging (LWD and wireline), borehole instrumentation.

7. Pre- and Post-Drilling Laboratory and Modeling Requirements: Microbial gas generation models, gas migration models, and systems analysis.

5.2.2 High Methane Hydrate Concentrations in Sand Reservoirs: Resource Assessments and Global Carbon Cycle

Science Challenges Addressed:

Science Challenge 4.1.2. How do we construct a robust assessment of methane hydrate occurrence?

Science Challenge 4.2.1. What is the preferred production method for an offshore methane hydrate production test?

Science Challenge 4.2.2. What are the key reservoir parameters of offshore methane hydrate reservoirs impacting the production rate?

Science Challenge 4.2.3. What is the minimum production rate and length of test needed from offshore methane hydrate reservoir to indicate economic viability?

Methane hydrates have been observed occupying pores of coarse-grained sediment, as nodules disseminated within fine-grained sediment, and as a solid filling in fractures. Field expeditions have led to the conclusion that hydrate grows preferentially in coarse-grained sediments because lower capillary pore pressures in these sediments permit the migration of gas and nucleation of hydrate. Production testing and modeling has further shown that concentrated methane hydrate occurrences in sand reservoirs are conducive to existing well-based production technologies.

Only a limited number of energy assessment studies have focused on the sand-dominated systems. In a study 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 in the sand-dominated accumulations in northern Alaska. No similar assessments exist for other Arctic permafrost settings. In 2008, the MMS (now BOEM) (Frye, 2008) estimated that the Gulf of Mexico contains about 190 trillion cubic meters (~6,710 trillion cubic feet) of gas in highly concentrated hydrate accumulations within sand reservoirs. 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. Fujii et al. (2008) estimated a volume of about 1.1 trillion cubic meters (about 40 trillion cubic feet) of gas exists within the hydrates of the eastern Nankai Trough, with about half concentrated in sand reservoirs.

The results of these resource assessments and the success of recent methane hydrate drilling in the Gulf of Mexico and the Nankai Trough have fueled international interest in methane hydrates as a potential producible energy resource. Before the gas can be economically extracted, more data are required on the occurrence of methane hydrate in sand-rich sediment systems. Additional scientific drilling is critical to advancing our understanding of the geologic controls on the occurrence of methane hydrates in sand-rich systems. Advanced pre-site surveys studies, like those conducted in preparation for the GOM JIP Leg II expedition that led the discovery of extensive sand-rich reservoirs with high methane hydrate saturations, need to be further refined and more widely considered as methane hydrate exploration efforts grow throughout the world. Laboratory and modeling studies need to be expanded to consider the controls on the growth of methane hydrate in porous media.

Drill Site and Operational Considerations

1. Geologic Setting: Target deepwater fans and turbidite systems. In general, deepwater sand deposition is enabled by sharp reductions in depositional gradient, so inferred slope breaks and/or embayments are conducive to the occurrence of sand reservoirs.

2. Specific Locations: Gulf of Mexico (WR313, GC955), Atlantic Margin of the US (New Jersey Margin), Nankai Trough, Southwest Taiwan, Hikurangi Margin, Ulleung Basin, onshore and near-shore Arctic permafrost settings.

3. Scientific Objectives: Understand the mechanism for the formation of methane hydrate in deep marine sand deposits; provide data for predictive models and methane hydrate assessments.

4. Site Survey Requirements: Development of a rigorous methane hydrate systems based site review criteria, focusing on assessing existing industry seismic data and downhole log data from nearby wells. Incorporate advanced geophysical inversion techniques where possible.

5. Drilling Strategy: Drill “twins” of existing wells if available; consider drilling a transect of wells to test migration mechanisms and the evolution of the reservoir systems.

6. Required Technology: Conventional wireline coring and pressure coring is essential, specialized sampling/analysis protocols, downhole logging (LWD and wireline) including advance reservoir logging and testing tools such as nuclear-magnetic logging (NMR) and wireline-conveyed formation testing tools (i.e., MDT) would also be required.

7. Pre- and Post-Drilling Laboratory and Modeling Requirements: Advance physical property analysis of recovered pressure cores (including mechanical, thermal, geophysical, and petrophysical properties).

5.2.3 Global Carbon Cycle – High Flux Settings

Science Challenges Addressed:

Science Challenge 4.1.1. What controls the inventories and fluxes of methane carbon in the marine system, and how these change over time?

Science Challenge 4.3.1. What are the operational geohazards, triggered by human activities that will affect methane hydrate production?

Science Challenge 4.3.2. Are there methane hydrate geohazards that are induced solely from naturally occurring processes?

Many of the marine methane hydrate accumulations studied to date are in fine-grained, clay-dominated sediment (reviewed by Milkov and Sassen, 2002). These deposits are commonly associated with hydrate mounds that are exposed on the seafloor. In many cases, the mounds appear to be dynamic and connected to the deep methane hydrate system through fractures that provide conduits for gas migration from below the hydrate stability zone. Commercial recovery of gas from mound features is unlikely due to economic and technology hurdles, and it is also constrained by the probable destruction of sensitive seafloor ecosystems. However, high flux (gas and water) sites still represent important part of the carbon cycle at both local and global scales.

One of the best-characterized cold vent sites is the Bullesye vent on the Cascadia margin off the west coast of Canada. Downhole logs collected from wells drilled into the Bullesye vent display a near-surface high-resistivity interval interpreted to be steeply dipping fractures filled with methane hydrates. In 2013, IODP installed the Simple Cabled Instrument for Measuring Parameters In situ (SCIMPI) system in a borehole near the Bullesye vent to gather long-term observations. These data will improve understanding of subseafloor dynamics, such as changes in seafloor and subseafloor methane hydrate systems.

Recent seismic studies and scientific drilling in the Ulleung Basin off the east coast of Korea has revealed the existence of numerous vertical chimney structures throughout the basin. Additional climate-focused studies have located extensive plumes of gas bubbles emanating from the seabed along the Atlantic margin near Svalbard, which may be sourced by thermally destabilized in situ methane hydrate (Westbrook et al., 2009).

Recently, a number of researchers have shown that marine coastal settings in the Arctic, where terrestrial permafrost and methane hydrates have been submerged because of sea level rise, may be releasing a significant amount of methane into the water column (Paull et al., 2007). The existence of gas plumes has been hypothesized based on anomalies observed in marine sonar data, but to date there has been little or no field verification of gas release or documentation of the morphological characteristics of the seabed where the gas may be venting.

Further scientific drilling into high fluid flux systems and monitoring of methane release from potentially destabilized hydrates are needed to quantify the future emissions from these systems and evaluate their contributions to the global carbon cycle.

Drill Site and Operational Considerations

1. Geologic Setting: Vent/chimney locations to evaluate mechanism of formation and evolution of high flux systems.

2. Specific Locations: Many examples exist around the globe, and some well-studied examples are in the Gulf of Mexico, Cascadia, Ulleung Basin, Black Sea, and Arctic shelf.

3. Scientific Objectives: Understand mass flux, methane flux to water column, gas flux to the methane hydrate stability zone, impact on the microbiologic system, kinetics of rapid hydrate formation and dissociation, spatial variation of shallow sediment carrying capacity relative to organic carbon.

4. Site Survey Requirements: Leverage existing data sets (multibeam and backscatter acoustic data, water column, seismic data, monitoring stations).

5. Drilling Strategy: Adapt to local conditions; collect an array of correlative data to fully characterize the methane hydrate system and external forcings (e.g. tides, water temperature, seismicity).

6. Required Technology: Conventional wireline coring, pressure coring, downhole logging (LWD and wireline), borehole instrumentation, and observatories.

7. Pre- and Post-Drilling Laboratory and Modeling Requirements: Microbial and thermogenic gas generation models, gas migration modeling, and sediment mechanical and systems analysis.

5.2.4 Response of Methane Hydrate Systems to Perturbations at the Upper Edge of Stability

Science Challenges Addressed:

Science Challenge 4.1.1. What controls the inventories and fluxes of methane carbon in the marine system, and how these change over time?

Science Challenge 4.1.3. How does this reservoir respond to natural and anthropogenic perturbations?

Science Challenge 4.3.1. What are the operational geohazards, triggered by human activities, which will affect methane hydrate production?

Science Challenge 4.3.2. Are there methane hydrate geohazards that are induced solely from naturally occurring processes?

There is considerable interest in understanding the geologic processes associated with methane hydrate formation and decomposition because of the possible role methane hydrate plays in global climate change. Only a portion of Earth's methane hydrate reservoir is prone to dissociation during some future warming scenarios. In many scenarios, methane hydrate accumulations fall well within methane hydrate stability conditions and/or are relatively deeply buried and so are buffered from near-term temperature changes. However, it is reasonable to assume that marine hydrates that occur nearest the landward edge of methane hydrate stability would be the most susceptible to changing conditions, as proposed for the methane hydrate accumulations off the Svalbard margin (Westbrook et al., 2009). Warming of the northward-flowing West Spitsbergen current over the last 30 years has caused the hydrate stability zone along the western margin of Svalbard to contract, contributing to the release of methane into the water column. Further characterization studies and monitoring of methane release are needed to quantify the likely magnitude of these and other similar emissions in the world. It is not known how much of the world's endowment of methane hydrate lies along the landward edges of the continents. There is also little appreciation of the time dependences associated with the thermal driving forces that impact the stability of in situ hydrate deposits.

Drill Site and Operational Considerations

1. Geologic Setting: Target the updip limit of the marine hydrate stability zone, with a focus on areas characterized by subseafloor thermal disturbances associated with changes in regional current patterns and temperature conditions.

2. Specific Locations: Only a few well-documented areas of potential methane disturbance have been studied, including the Beaufort Shelf, Cascadia Margin, Cape Fear, Hikurangi Margin, Northern Europe (Svalbard), and Cape Hatteras.

3. Scientific Objectives: Reconstruct the history of the methane hydrate stability zone along the continental margins of the world; understand the historical and potential future responses of the methane hydrate system to changes and forcing; document and understand the consequences of change (gas flux rates, seafloor stability, geomechanics); interpret present thermodynamic conditions; determine and model rate of methane hydrate dissociation and the response of the in situ biological system; assess impact on global carbon cycle.

4. Site Survey Requirements: Leverage existing data sets (industry and academic 2-D and 3-D seismic data; multibeam and backscatter acoustic data; water column and other monitoring stations).

5. Drilling Strategy: Consider a transect of holes, or multiple transects (including reference sites), to test fluid migration mechanisms and the evolution of thermal conditions and changes in the methane hydrate stability zone along the margin. Collect an array of correlative data to fully characterize the methane hydrate system and external forcings (e.g., tides, water temperature, seismicity).

6. Required Technology: Conventional wireline coring, pressure coring, downhole logging (LWD and wireline), borehole instrumentation, and observatories to ascertain in situ temperature and pore pressure conditions.

7. Pre- and Post-Drilling Laboratory and Modeling Requirements: Reconstruct sea level; tectonics (relative sea level), other external influences/consequences; also consider potential synergies with geohazard challenges.

5.2.5 Preconditioning of Areas for Slope Failure with High Methane Hydrate Saturations

Science Challenges Addressed:

Science Challenge 4.1.3. How does this reservoir respond to natural and anthropogenic perturbations?

Science Challenge 4.3.1. What are the operational geohazards, triggered by human activities, which will affect methane hydrate production?

Science Challenge 4.3.2. Are there methane hydrate geohazards that are induced solely from naturally occurring processes?

In recent years, as industry activities moved into deepwater environments, concerns associated with the controls and evolution of large-scale submarine slope failures are growing. The Storegga slide, off the coast of Norway, is one of the world's largest exposed submarine slides and has been the focus of numerous geomorphical and geotechnical studies. One of the most prominent features of the Storegga slide is series of compression zones, comprised of lobes where the seabed is marked by numerous deformed parallel ridges. Seismic studies and shallow sediment coring have permitted dating of the various failure events within the Storegga slide, but what triggered the failures remains uncertain.

The Storegga slide, like many other submarine slides, is generally classified as a retrogressive failure. These slides are characterized by multiple failure events resulting from the removal of toe support and increased shear strain during the failure events. Retrogressive failures require triggering of the initial slide near the toe of the slope. In the case of the Storegga slide, failure is generally believed to have been the result of excess pore pressures caused by rapid sediment deposition combined with local steeping of the slope and, likely, earthquake loading. It has also been shown that methane hydrate dissociation, particularly after the initial slope failure, could contribute to excess pore pressures and toe slope failures. More work is needed to understand the evolution of pore pressure conditions in large-scale submarine slides. Deep scientific coring, logging, and downhole pressure measurements and monitoring would contribute greatly to our understanding of the controls on slope failures and the potential role of methane hydrates in the formation of the conditions that may trigger large-scale mass wasting events.

Drill Site and Operational Considerations

1. Geologic Setting: Target the toe of the slope associated with large submarine slide features, with the goal to characterize the downdip edge of future retrogressive failures.

2. Specific Locations: The north wall of the Storegga slide, northwest Svalbard, and the Cape Fear slide off the east coast of the United States. Additional features would include local slope dips on the order of 1 to 3 degrees and greater, high methane hydrate saturations in both stable and destabilized settings, and areas with underlying trapped free gas.

3. Scientific Objectives: Understanding sediment strengths and pore pressure conditions at the toe of the slope and potentially what causes retrogressive failure. Also assess the impact of methane hydrate dissociation on the mechanical properties of the sedimentary section.

4. Site Survey Requirements: Leverage existing data sets (industry and academic 2-D and 3-D seismic data; shallow sediment core studies).

5. Drilling Strategy: Consider a transect of holes to test fluid migration mechanism and the evolution of pore pressure conditions and changes in the toe of the slope along the margin. Collect an array of correlative data to fully characterize the methane hydrate system and in situ mechanical properties of the sediments associated with different features within representative slides.

6. Required Technology: Conventional wireline coring, pressure coring, downhole logging (LWD and wireline), borehole instrumentation and observatories to ascertain in situ pore-pressure conditions.

7. Pre- and Post-Drilling Laboratory and Modeling Requirements: Reconstruct the geologic history of the features associated with the slope failure event(s). Consider other external influences/consequences. Model the evolution of pore pressure conditions with the geologic history of the slope failure event(s).

5.2.6 Characterization of Geohazards Associated with Methane Hydrate Related Features

Science Challenges Addressed:

Science Challenge 4.1.1. What controls the inventories and fluxes of methane carbon in the marine system, and how do these change over time?

Science Challenge 4.3.1. What are the operational geohazards, triggered by human activities, which will affect methane hydrate production?

Science Challenge 4.3.2. Are there methane hydrate geohazards that are induced solely from naturally occurring processes?

An operational drilling hazard assessment consists mostly of a geological and geophysical review of proposed drill sites so that problems that can affect the safe drilling and completion activities can be avoided or effectively mitigated (as reviewed by McConnell et al., 2012). When considering the potential impact of methane hydrates on drilling and marine infrastructure development, the primary seafloor hazards are often associated with active fluid venting, such as seafloor mounds, chemosynthetic communities, and in some Arctic shelf environments, pingo-like features. Below the seafloor, methane hydrates are found at low concentrations in clay-rich sediments and at high concentrations in sand-rich layers and in fracture systems where "chimneys" can be conduits for gas migration through the hydrate stability zone. Below the methane hydrate stability zone, at the depth of the seismic-inferred bottom simulating reflector (BSR), we also see evidence of free gas potentially trapped by the overlying hydrate-bearing sedimentary section.

The primary goal of a pre-drill hazard assessment is to identify potential hazards to operations, some of which can be simply avoided by moving the proposed drill site. Recent studies have shown that the automatic avoidance of an area with any indications of methane hydrate is not prudent; it adds unnecessary costs and complications to the well plans. Consequently, improved methodologies that go beyond the simple recognition of the presence or absence of methane hydrate to a more robust assessment of the nature and significance of methane hydrate deposits and related gas hazards are needed. A more rigorous investigation of soil strength and stability is needed, as well as an appraisal of site conditions to address its suitability for drilling, well completion, and potential field development.

Drill Site and Operational Considerations

1. Geologic Setting: Target specific methane related features for further study (i.e., seafloor vents and mounds, chemosynthetic communities, Arctic pingo-like features, hydrates in sand-rich layers and in fracture systems, and free gas associated with BSRs and deeper free-gas accumulations and conduits).

2. Specific Locations: Global with a diverse range of conditions and settings.

3. Scientific Objectives: Define the metrics that control the formation, occurrence, and stability of in situ methane hydrates. Obtain data required to assess the risk associated with drilling and completion operations through methane hydrate related features.

4. Site Survey Requirements: Leverage existing data sets (industry and academic 2-D and 3-D seismic data; shallow sediment core studies). Make use of downhole log data from existing industry and research wells.

5. Drilling Strategy: Consider a transect of holes to test fluid migration mechanism and the evolution of pore pressure conditions and changes associated with various parts of the methane hydrate system.

6. Required Technology: Conventional wireline coring, pressure coring, downhole logging (LWD and wireline), borehole instrumentation, and observatories. Downhole in situ foundational testing tools (e.g., fluid pressure, resistivity, strength, fluid sampling, temperature).

7. Pre and Post Drilling Laboratory and Modeling Requirements: Microbial and thermogenic gas generation models; gas migration modeling, and sediment mechanical and systems analysis.

5.2.7 Methane Hydrate Production Related Geohazards

Science Challenges Addressed:

Science Challenge 4.1.3. How does this reservoir respond to natural and anthropogenic perturbations?

Science Challenge 4.2.1. What is the preferred production method for an offshore methane hydrate production test?

Science Challenge 4.2.2. What are the key reservoir parameters of offshore methane hydrate reservoirs impacting the production rate?

Science Challenge 4.2.3. What is the minimum production rate and length of test needed from offshore methane hydrate reservoir to indicate economic viability?

Science Challenge 4.3.1. What are the operational geohazards, triggered by human activities, which will affect methane hydrate production?

Science Challenge 4.3.2. Are there methane hydrate geohazards that are induced solely from naturally occurring processes?

We have limited knowledge of the safety issues concerned with drilling and extracting methane from hydrates. Current knowledge is mostly anecdotal. There have been only a few focused studies that are relevant and there has not yet been sustained production of hydrates in any geologic setting. Some of the greatest operational concerns surrounding the production of methane hydrates are thought to be associated with well completion, such as wellbore casing installation difficulties, gas leakage outside the casing, and casing collapse during production. It is also possible that gas and fluid migration to the surface outside of the casing could impact the ability of the casing to support itself. The casing may collapse within the reservoir section of the well if the casing loads have not been adequately addressed in the well design plan.

A potential unique production hazard associated with marine methane hydrates is linked to the relatively shallow occurrence of the producing horizons. These reservoirs will typically be unconsolidated in their native state (i.e., without methane hydrate) and overlain by relatively soft, unconsolidated, mud-dominated sediments. It possible that sediment subsidence associated with production could lead to seafloor instability and surface subsidence. Work is ongoing to better understand these issues, but more is needed. Baseline surveys and monitoring programs associated with the recent hydrate production test in the Nankia Trough are being conducted as well as experimental efforts and coupling of the leading methane hydrate production simulators with geomechanical computer codes.

Drill Site and Operational Considerations

1. Geologic Setting: Linked to proposed methane hydrate production testing programs with an initial focus on deeply buried sand-rich reservoirs that are considered more conducive to production.

2. Specific Locations: Gulf of Mexico (WR313, GC955) and the Mad Dog Field area (GC781), US Atlantic margin (New Jersey margin), Nankai Trough, Southwest Taiwan, Hikurangi margin, Ulleung Basin, and onshore and nearshore Arctic permafrost settings.

3. Scientific Objectives: Understand how strength and stress state around the producing interval (reservoir and seal) change with production of methane hydrate; subsidence issues, brittle or plastic deformation, fluid flow changes in reservoir and seal; associated benthic and seafloor geomorphology changes.

4. Site Survey Requirements: Leverage existing data sets (industry and academic 2-D and 3-D seismic data; shallow sediment core studies). Pre-drill site survey data collection, including seafloor imaging, coring, and geotechnical surveys. Also make use of downhole log data from existing industry and research wells.

5. Drilling Strategy: Consider a transect of holes to test fluid migration mechanism and the evolution of pore pressure conditions and changes associated with various parts of the system. Collect an array of correlative data to fully characterize the methane hydrate system. Consider controlled experiments designed to monitor response of methane hydrate system to external perturbations.

6. Required Technology: Conventional wireline coring, pressure coring, downhole logging (LWD and wireline), borehole instrumentation, and monitoring wells. Downhole in situ foundational testing tools (e.g., fluid pressure, resistivity, strength, fluid sampling, temperature).

7. Pre- and Post-Drilling Laboratory and Modeling Requirements: Advance physical property analysis of recovered pressure cores (including mechanical, thermal, geophysical, and petrophysical properties). Sediment mechanical and systems analysis modeling.

5.2.8 Methane Hydrate Response to Natural Perturbations

Science Challenges Addressed:

Science Challenge 4.1.3. How does this reservoir respond to natural and anthropogenic perturbations?

Science Challenge 4.2.3. What is the minimum production rate and length of test needed from offshore methane hydrate reservoir to indicate economic viability?

Science Challenge 4.3.1. What are the operational geohazards, triggered by human activities, which will affect methane hydrate production?

Science Challenge 4.3.2. Are there methane hydrate geohazards that are induced solely from naturally occurring processes?

Methane hydrates are found in geologic settings associated with slope failure and active seafloor gas venting, but it is not clear whether or how much they contribute to these processes. It has been shown that changes in pore pressure conditions (ie., rise or fall of sea level) and temperatures (ie., changes in bottom water currents) could possibly impact the stability of methane hydrates along the outer continental margin, but there is no clear evidence in the modern or geologic record linking hydrates to sediment instabilities and gas releases.

It is expected that evidence for contemporary and future methane hydrate degradation may be found primarily on the Arctic Ocean continental shelves and possibly along the upper landward edge of marine hydrate stability. In these settings, it is possible that methane hydrate dissociation has been triggered by sea level rise since the Late Pleistocene and by warming at the upper edge of the methane hydrate stability zone on continental slopes. Proof is still lacking that methane hydrate dissociation currently contributes to gas seepage along the upper continental slopes or to elevated seawater methane concentrations on circum-Arctic Ocean shelves. Scientific drilling can provide the data needed to better understand the complex process associated with interrelationship between natural perturbations and methane hydrate stability.

Drill Site and Operational Considerations

1. Geologic Setting: Target the updip limit of the marine hydrate stability zone, with a focus on areas characterized by subseafloor thermal disturbances associated with changes in regional current patterns and temperature conditions. Also consider locations with the potential of earthquake related driving forces.

2. Specific Locations: Areas of potential methane disturbance have included the Beaufort Shelf, Cape Fear, Hikurangi Margin, Northern Europe (Svalbard), and Cape Hatteras. Additional areas associated with the know occurrence of methane hydrates and tectonic activity include the Cascadia Margin, Nankia Trough, and the Chile Triple Junction.

3. Scientific Objectives: Characterize the history of the methane hydrate stability relative to natural perturbations.

4. Site Survey Requirements: Leverage existing data sets (industry and academic 2-D and 3-D seismic data; shallow sediment core studies). Collect pre-drill site survey data, including seafloor images, cores, and geotechnical information. Make use of downhole log data from existing industry and research wells.

5. Drilling Strategy: Consider a transect of holes to test fluid migration mechanism and the evolution of pore pressure conditions and changes associated with various parts of the system. Collect an array of correlative data to fully characterize the methane hydrate system. Consider controlled experiments designed to monitor the response of methane hydrate system to external perturbations.

6. Required Technology: Conventional wireline coring, pressure coring, downhole logging (LWD and wireline), borehole instrumentation and monitoring wells. Downhole in situ foundational testing tools (e.g., fluid pressure, resistivity, strength, fluid sampling, temperature).

7. Pre- and Post-Drilling Laboratory and Modeling Requirements: Advance physical property analysis of recovered pressure cores (including mechanical, thermal, geophysical, and petrophysical properties). Sediment mechanical and systems analysis modeling.

6 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 Recommendations

The methane research community drove the development of this Methane Hydrate 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. This section of the Plan lists both general and specific project planning recommendations 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 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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Appendix A

Methane Hydrate Technical Review

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 MH 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 MH 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 MH 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 (C_{5}-C_{9}) form Structure H (sH) hydrate, again where methane is present (**Figure MH 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).

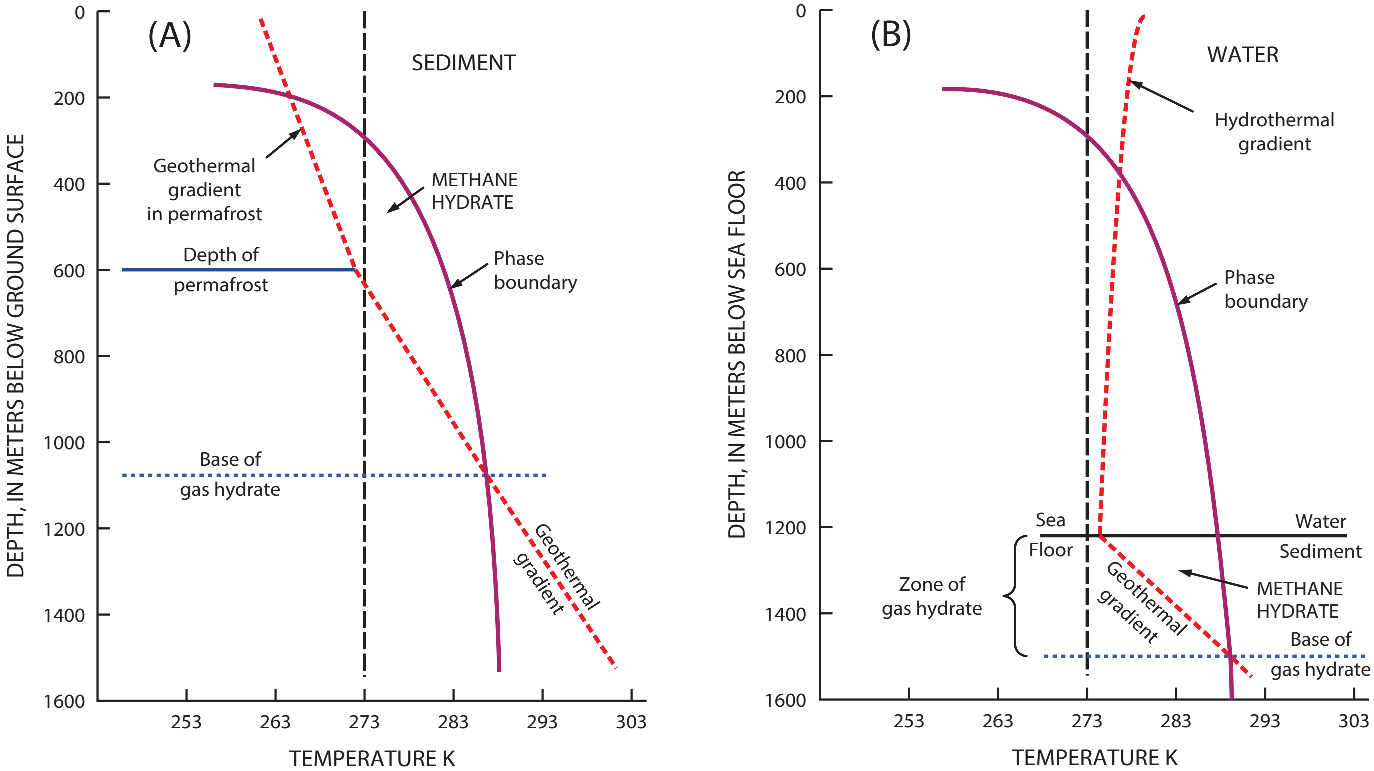

Figure MH 1. Arbitrary examples of different depth-temperature zones in which methane hydrates are stable: (A), a permafrost region; and (B), an outer continental margin marine setting (modified from Kvenvolden, 1988).

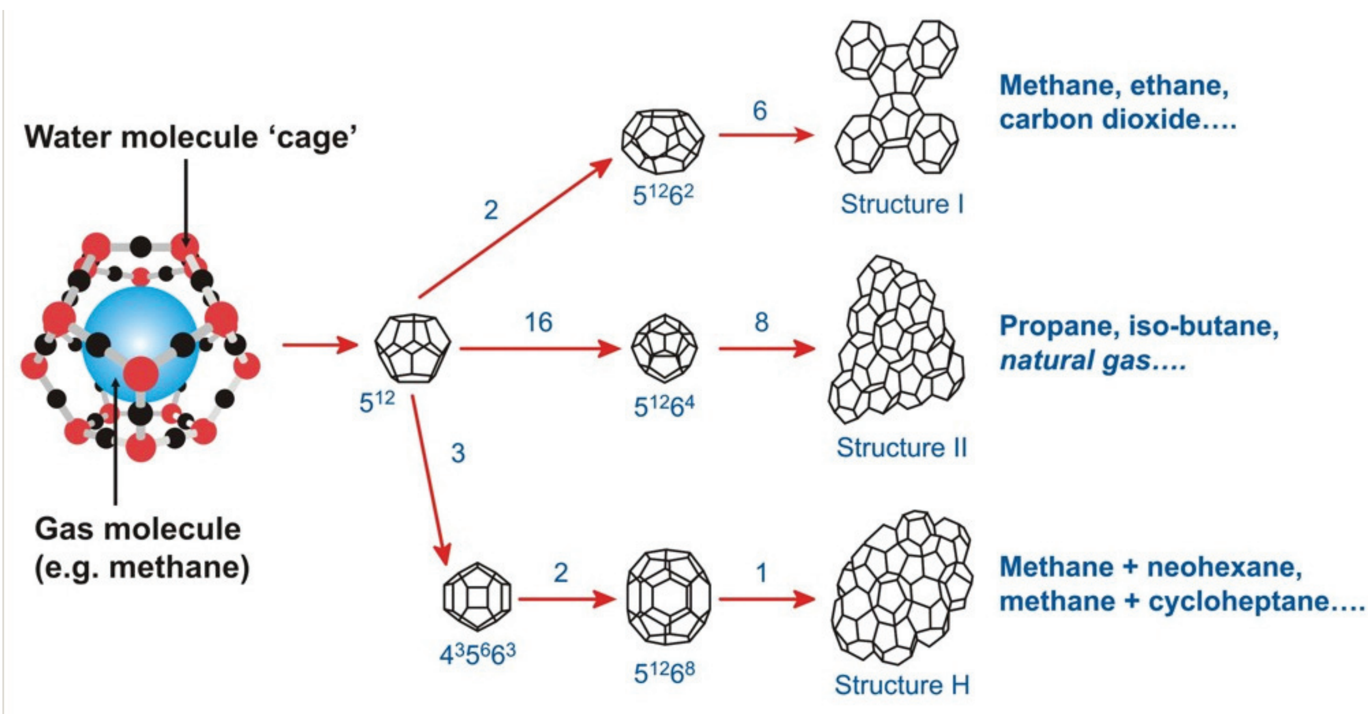

Figure MH 2. Hydrate crystal structures. The water cages that make-up the hydrate structures are depicted. Also shown are the three structure types that have been observed for hydrates: Structures I, II and H (modified from http://www.pet.hw.ac.uk/research/hydrate/hydrates_what.htm).

Appendix B

Historical Methane Hydrate Research Scientific Drilling

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. 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 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.

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 field testing programs

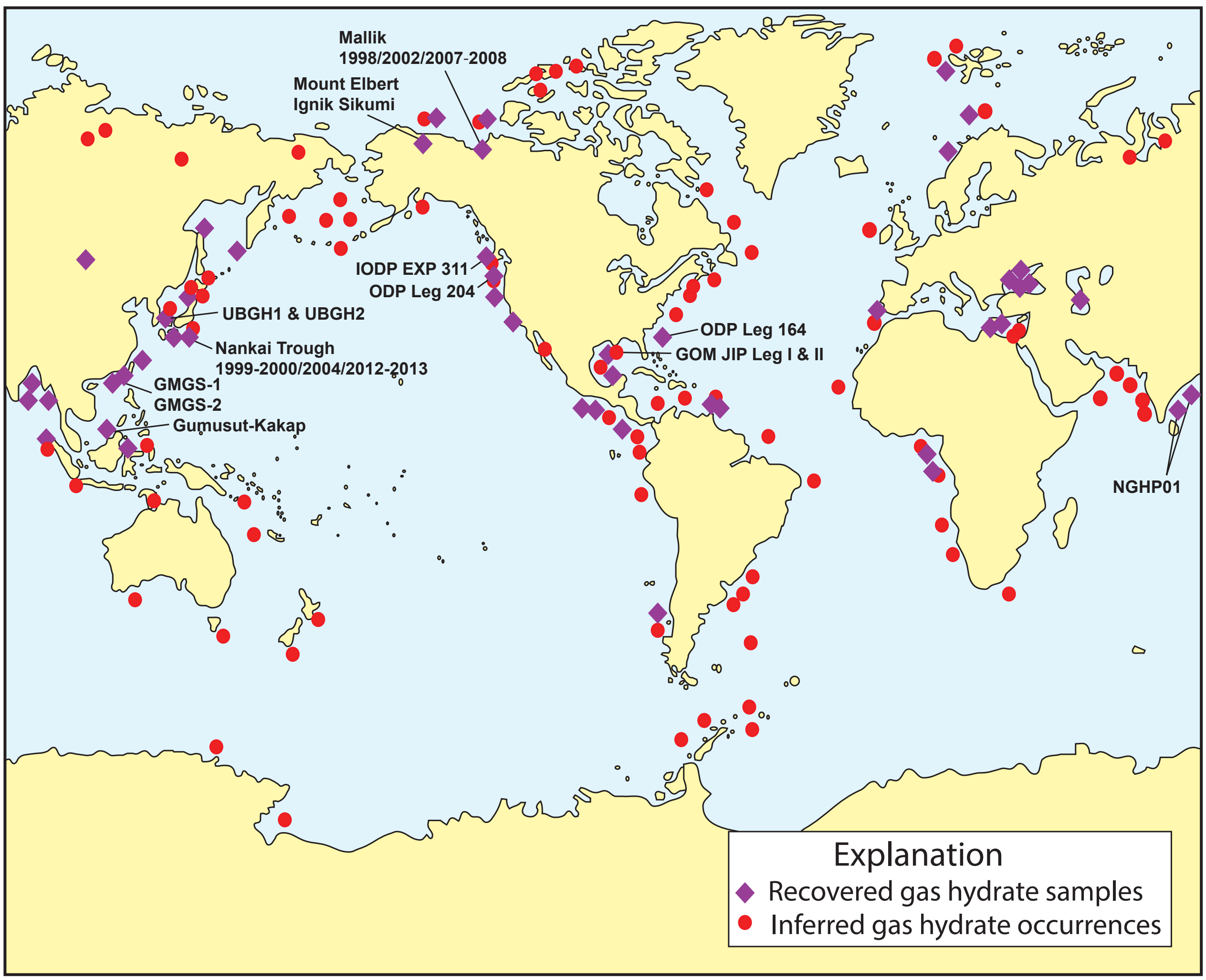

Figure MH Drilling 1. Location of sampled and inferred methane hydrate occurrences in oceanic sediment of outer continental margins and permafrost regions (modified from Kvenvolden, 1993). Most of the recovered methane hydrate samples have been obtained during deep coring projects or shallow seabed coring 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.

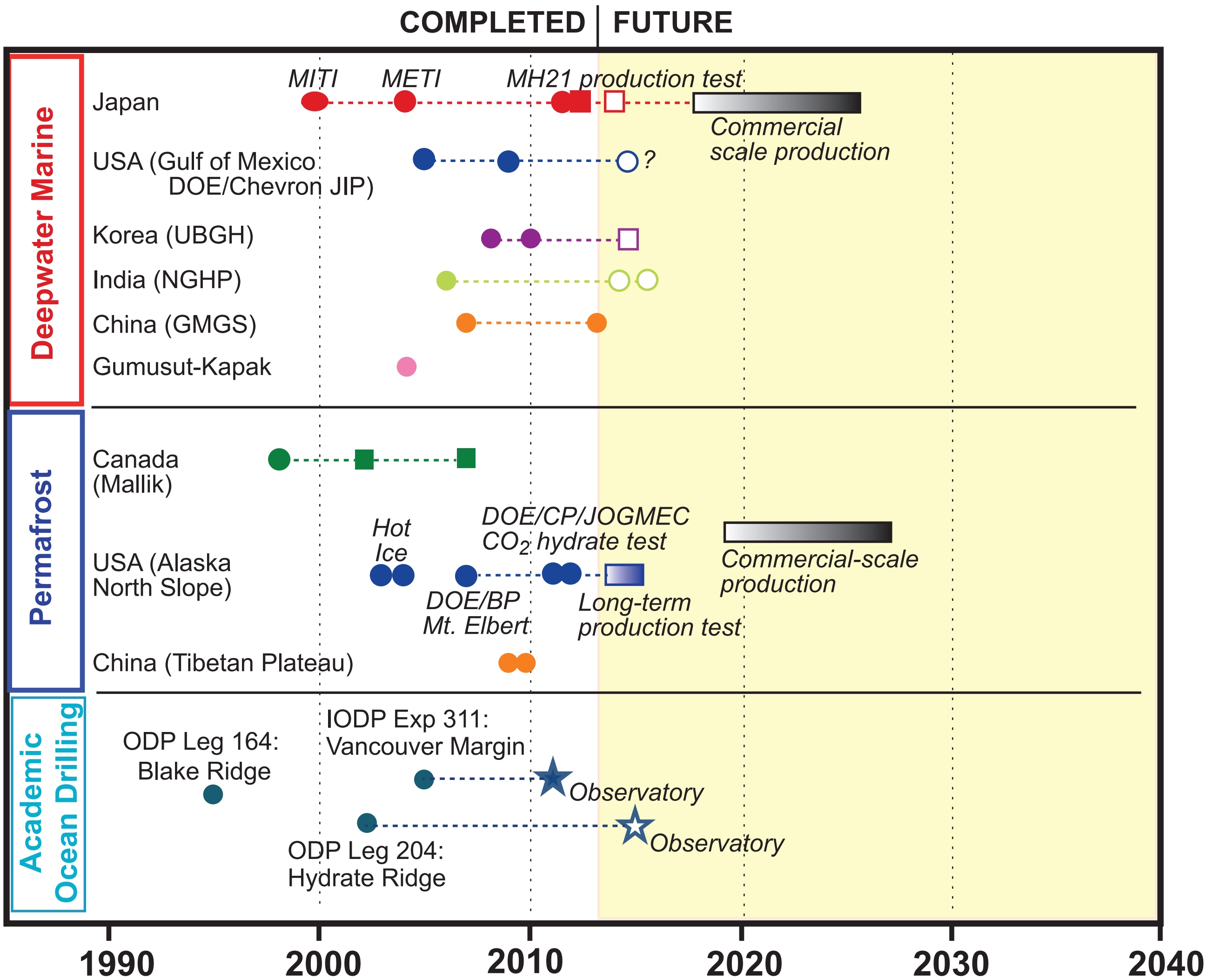

Figure MH Drilling 2. Timeline chart showing the deepwater marine, Arctic permafrost, and academic ocean drilling scientific drilling expeditions dedicated to the research on natural occurring methane hydrates (modified from Ruppel and Collett, 2013).

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. 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.

As the map in **Figure MH Drilling 1** shows, methane hydrate has been recovered and/or inferred to exist in numerous marine and onshore polar basins. However, as introduced below and listed in **Appendix C,** 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.

Appendix C

Methane Hydrates Scientific and Industry Drilling Programs

Methane hydrate scientific and industry drilling programs, including a listing of 16 of the more significant methane hydrate research drilling expeditions. Information on each expedition includes the (1) report section and name of the expedition, (2) project management, (3) operational technical developments in the type of core systems, downhole logging tools, borehole instrumentation, and other technologies as deployed on each expedition, (4) primary operational/scientific objectives, and (5) primary operational/ scientific results.

Expedition	Management	Operational Technology Developments	Primary Operational/Scientific Objectives	Primary Operational/Scientific Results
ODP Leg 164 (1995)	Ocean Drilling Program	Extensive use of the pressure core sampler. First use of downhole wireline logs to characterize the distribution and concentration of methane hydrates. First VSP (zero-offset and walk-away) survey conducted to examine occurrence of hydrates.	To safely core and wireline log hydrate-bearing sediments and deliberately penetrate a BSR for the first time. Understand lateral variability in methane hydrate abundance. Understand the relationship between BSRs and methane hydrate development.	Analysis core and well log data from Leg 164 drill sites on the Blake Ridge indicates that methane hydrate occupies 1-2% of a mostly clay-rich sediment volume in a zone that is about 200-250 m thick. The BSR on the Blake Ridge is the product of the change of velocity from hydrate bearing sediments above the BSR to the presence of free-gas below. Completed the first systematic assessment of the volume of gas trapped within hydrates in any offshore setting, included the analysis of pressure cores, well log, and water chemistry data. Proved that hydrate-bearing sediment and BSR's could be safely cored and logged with appropriate drilling considerations.
Japan Nankai Trough Project (1999-2000)	Ministry of International Trade and Industry (presently the Ministry of Economy, Trade and Industry); Japan National Oil Corporation (presently the Japan Oil, Gas and Metals National Corporation)	First use of pressure and temperature controlled coring system (PTCS) in a marine environment.	Assess the resource potential of methane hydrates in the Nankai Trough through the identification of BSRs and characterization by coring and downhole wireline logging.	Extensive BSRs in this area of the Nankai Trough were confirmed to be linked to the occurrence of methane hydrate. Confirmed the existence of methane hydrate within intergranular pores of turbiditic sands, reaching saturations as high as 80% in some layers. Led to the proposal of a new methane hydrate program in Japan.
ODP Leg 204 (2004)	Ocean Drilling Program	First use of infrared core scanning to identify and characterize the presence of methane hydrate. Featured for the first time the acquisition of logging-while-drilling data prior to coring to identify potential hydrate occurrences and to guide coring and other project activities. Deployment of the new HYACINTH pressure coring system.	Obtain better estimates of methane hydrate and free gas volumes. Constrain models for the formation of methane hydrates on convergent margins. Understand the formation of massive hydrate deposits near the seafloor and characterize the mechanism(s) for transporting methane-rich fluids to the seafloor.	When averaged over the entire methane hydrate stability zone on Hydrate Ridge, the amount of hydrate is generally estimated to be about 2% of the sediment pore space. Hydrate concentrations increase to about 10% near methane vents, where massive methane hydrate forms in the upper 20–30 mbsf and occupies 20%–30% of the total sediment volume. Two models were proposed for the occurrence of methane hydrate: (1) Most of the gas that forms the summit hydrate deposit has migrated from greater depth and has either a microbial or microbially altered thermogenic character. (2) Regionally pervasive methane hydrate, at relatively low concentrations, forms from gas produced locally through microbial activity, exsolved from pore waters in response to tectonic uplift and upward migration, and transported advective fluid flow.

Expedition	Management	Operational Technology Developments	Primary Operational/Scientific Objectives	Primary Operational/Scientific Results
Japan Tokai-oki to Kumano-nada Project (2004)	Ministry of Economy, Trade and Industry; Japan Oil, Gas and Metals National Corporation	First "extensive" use of pressure and temperature controlled coring system (PTCS). First offshore deployment of MDT tools to study methane hydrate reservoir properties and response to pressure testing. Deployment of the first downhole offshore temperature monitoring system (DST system). First industrial test of horizontal drilling technology in a methane hydrate deposit.	Verify the seismic indicators for the presence of methane hydrate within the zone of methane hydrate stability (i.e., above BSRs). Obtain high quality methane hydrate samples for laboratory analysis of physical and reservoir properties. Conduct coring to visually observe the growth habit and in-situ nature of methane hydrates	Downhole log data and core observations verified three different types of methane hydrate occurrences: (1) sand with pore-filling hydrate, (2) silt with pore-filling hydrate, and (3) nodular or fracture-filling massive hydrate in fine-grained sediments. The gross thickness of the hydrate-bearing sand layers at one site was greater than 100 m. Methane hydrate saturations in cored sand layers ranged from 55 to 68%. BSRs were shown not to be good indicators of concentrated methane hydrate accumulations. Data from the expedition allowed for the probabilistic estimate of the amount of gas resources associated with methane hydrates in the Nankai Trough.
Gulf of Mexico JIP Leg I (2005)	Gulf of Mexico Gas Hydrate Joint Industry Project; U.S. Department of Energy	Integration of ROV deployed push core deployment with deep coring operations. Continued development of the new HYACINTH pressure coring systems. First time deployment of the Georgia Institute of Technology Instrumented Pressure Testing Chamber (IPTC) for the examination of pressure cores. Development hydrate borehole stability models.	Study hazards associated with drilling and producing through hydrate-bearing sediments. Further calibrate geological/geophysical tools to characterize in-situ methane hydrate. Sample hydrate-bearing sediments to obtain physical data needed to analyze marine methane hydrate resource and production issues.	Drilling, coring, and downhole logging operations were safely conducted in the presence of BSRs and other methane hydrate related features without any significant technical problems. Logging-while-drilling and core data revealed for the first time evidence of "strata-bound" fracture dominated hydrate occurrences. Developed techniques for processing industry 3D seismic data to constrain hydrate saturations. Core data from fluid expulsion mounds show only limited area of thermal and salinity influence on hydrate stability. Seismic, electrical, and strength property measurements of sediment cores were made for the first time on cores that had been retrieved and maintained at in-situ pressures.
IODP Expedition 311 (2005)	Integrated Ocean Drilling Program	Established the concept of drilling a transect of holes to characterize the evolution of methane hydrate across a continental margin. Developed the concept of the three hole test site: Hole-A for logging while drilling, Hole-B for continuous coring, Hole-C for pressure coring, wireline logging, and other tools. Deployment of the a the first generation integrated PCATS pressure core lab van system.	Understand the formation of methane hydrates in accretionary settings. Test and constrain model parameters that account for the formation of concentrated methane hydrate occurrences through upward transport of methane-bearing fluids. Assess the vertical fluid advection and methane fluxes along the expedition transect.	Along the expedition transect, hydrate occurs within the sand-rich reservoir-quality formations and is virtually absent in the fine-grained and clay-rich sediments. All sites drilled showed a high degree of heterogeneity in methane hydrate occurrence. Models that predict the highest concentrations hydrate near the base of the methane hydrate stability zone did not conform with the findings from this expedition. Methane hydrates within the cold vent site drilled during the expedition is the result of focused fluid and gas migrating upward along a underlying fault system. Pressure core analysis document the role of local methane gas solubility controls on the occurrence of hydrate and the undersaturated section from the seafloor to the upper most hydrate occurrence at each non-vent site.

Expedition	Management	Operational Technology Developments	Primary Operational/Scientific Objectives	Primary Operational/Scientific Results
Malaysia Gumusut-Kakap Project (2006)	Shell (Fugro-McCelland Marine Geosciences)	Implementation of a complex integrated geoscience and geotechnical program, including shallow geotechnical coring, pressure coring, logging-while-drilling and wireline logging, and acquisition of shallow piston and box cores, to assess potential drilling and completion problems associated with the development of conventional resources in the Gumusut-Kakap field area.	Assess geohazards, including issues associated with the widespread occurrence of methane hydrates on the development of petroleum resources in the Gumusut-Kakap field area.	Geochemical, geomechanical, and sedimentologic analyses of core samples confirmed the widespread occurrence of disseminated hydrate occurrences and sub-vertical hydrate-bearing fractures throughout the study area. First-time integration of pressure core, pore-water chemistry, and multi-azimuthal resistivity well log data to accurately assess anisotropic properties of hydrate-bearing fracture dominated systems. Geochemical evidence of structure I and structure II hydrates. Tension leg platforms and spar development concepts were abandoned from the Gumusut-Kakap development plan in favor of subsea development with semi-submersible floating production system hosts.
India NGHP Expedition 01 (2006)	Indian National Gas Hydrate Program	The NGHP01 pre-drill site review process initially focused on the what had become the traditional assessment of BSR relations, but as the site review process progressed over the duration of the expedition special attention was given to identifying high amplitude stratigraphic and/or structurally controlled features within the hydrate stability zone. The site review process also incorporated the consideration of conventional and methane hydrate petroleum systems processes for the first time.	Assess the geologic controls on the occurrence of methane hydrates along the west and east coast of the Indian Peninsula and in the Andaman convergent margin. Identify candidate methane hydrate production test sites.	Most of the hydrate occurrences along the eastern margin of India are characterized as mostly fracture-filling material in clay dominated sediments and in several cases as pore-filling particles in coarser grained sediments. The occurrence of methane hydrate in the offshore of India appears to be closely associated with large scale structural features, especially in the Krishna-Godavari Basin, which contributed the development of fracture related gas migration and reservoir systems. Established the existence of fully defined methane hydrate petroleum systems in the Mahanadi and Krishna-Godavari basins. Drilling results has led to the development of a more rigorous and modern regional analysis of additional potentially sand-rich drilling targets and methane hydrate prospects along the eastern margin of the Indian Peninsula.
China GMGS Expedition 01 (2007)	Guangzhou Marine Geological Survey; China Geological Survey; Ministry of Land and Resources of China (Fugro-McCelland Marine Geosciences)	Operated as a fully turnkey project by Fugro, with the inclusion of specialized technical services including drilling, wireline logging, in-situ temperature measurement, pore-water sampling, and pressurized and non-pressurized coring.	The primary objective of this project was to conduct field investigations of methane hydrate in the South China Sea with the goal to more accurately delineate the occurrence, nature, and resource potential of hydrates.	Methane hydrate was detected at three of the five core sites established during this expedition. Pressure coring confirmed the presence of fine-grained sediment layers rich in methane hydrate just overlying the base of the methane hydrate stability zone; it was proposed that foraminifera and other silt-size grains may provide the void space for hydrate to grow in these sediments. The presence of methane hydrate just above the base of the stability zone is the type of accumulation predicted from regional vertical fluid flux models and compares favorably with the nature of hydrate occurrence on the Blake Ridge.

Expedition	Management	Operational Technology Developments	Primary Operational/Scientific Objectives	Primary Operational/Scientific Results
Republic of Korea UBGH Expedition 02 (2010)	Korea Gas Hydrate Development Organization (Fugro)	This project featured a comprehensive pre-drill site review effort, which included input from an external expert panel. Operated as a partial turnkey project by Fugro, with the inclusion of specialized technical services (wireline logging, in-situ temperature measurement, pressurized and non-pressurized coring) and logging-while-drilling operations supported by Schlumberger. A remotely operated vehicle was used to conduct site surveys, to obtain shallow sediment push cores, and to monitor the well head for fluid and/or gas expulsions. The laboratories established on the ship for this expedition were one of the more advanced integrated core analysis laboratories yet deployed for the examination of conventional and pressure cores. Featured the deployment of a new generation PCATS system, which included the ability to cut cores into various lengths and to transfer the core sub-samples while under pressure.	Collect geologic, geochemical, and geophysical data needed to understand the distribution of methane hydrate in the Ulleung Basin. Find a promising candidate site (sand-rich prospect) for production testing. Several sites were selected to acquire data in support of developing a regional geologic framework for the Ulleung Basin.	Drilled and logged 13 sites during a pre-coring logging-while-drilling leg, a total of 10 sites were cored during Leg 2, with two of the cored sites being wireline logged. Integrated seismic, well log, and core analysis indicate that hydrates in the Ulleung Basin occur as "pore-filling" substances in discrete turbidite sand and/or ash layers, or as "fracture-filling" veins and nodules in pelagic/hemipelagic mud. Log data and coring activities at four of the UBGH2 sites have confirmed the chimney structures in the Ulleung Basin contain fracture-filling methane hydrate. Chimney structures in the basin were interpreted to be a product of rapid sedimentation and clay dehydration that led to fluid overpressures and associated fracturing of the formation. Several of the sites established during UBGH2 are being considered as candidates for future hydrate production testing.
MH-21 Nankai Trough Pre-Production Expedition (2012-2013)	Ministry of Economy, Trade and Industry; Japan Oil, Gas and Metals National Corporation	Deployed the new Hybrid Pressure Coring System and the next generation PCATS pressure core processing and laboratory system. Used conventional natural gas exploitation technologies as modified for testing the production response of hydrates to depressurization.	Define and characterize offshore methane hydrate accumulations suitable for production testing. Conduct production testing of a selected methane hydrate accumulation. Test technologies that will enable the safe and economic production of methane gas from hydrates. Further evaluate the resource potential of methane hydrates in the offshore of Japan. Assess the environmental impacts of hydrate testing and production.	The location for the test site was selected through the analysis of 3D seismic data and were calibrated with field data collected during the 2004 Tokai-oki to Kumano-nada drilling project. The test site was established with one production well, two monitoring wells, and one core well. Well logs from the test site revealed the presence of a 60-m-thick section characterized by thinly bedded turbidite sands measuring from a few tens of centimeters to a few meters thick. On 19 March 2013, JOGMEC and MITI reported that they had completed a production test of methane hydrates off Aichi Prefecture, with gas being produced to the drillship during the test.

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Expedition	Management	Operational Technology Developments	Primary Operational/Scientific Objectives	Primary Operational/Scientific Results
Mallik GH Testing Projects (1998/2002/2007-2008)	Natural Resources Canada; Japan National Oil Corporation (presently the Japan Oil, Gas and Metals National Corporation), and others	During the Mallik 1998 and 2002 drilling programs, numerous coring systems were tested, including the pressure-temperature coring device (PTCS) for the first time, conventional wireline core systems, and conventional drill-string-deployed core barrels. The Mallik 2002 test included the first deployment of MDT tools to study methane hydrate reservoir properties and response to pressure testing. The Mallik 2002 and 2007-2008 gas hydrate production test well projects included a number of borehole monitoring studies, including the deployment of distributed temperature sensing (DTS) systems to monitor formation temperatures and their response to production.	Conduct a drilling, coring and logging program(s) to collect geologic and engineering data on in-situ methane hydrates. Conduct research pertaining to methane hydrate production and to assess the environmental implications of terrestrial methane hydrates, including geohazard and climate change considerations. Project partners from Japan sought to undertake a variety of verification studies in preparation for exploration drilling and production testing of hydrates in the Nankai Trough. The Mallik 2007-2008 research well program was designed to establish sustained production from a hydrate reservoir by applying depressurization and to obtain the data needed to simulate hydrate production.	The Mallik 1998 drilling program featured the recovery of 37 m of high quality core, with methane hydrate occurred primarily in sandy sediments. Well logs from the Mallik 2L-38 well confirm the occurrence of in-situ methane hydrate at the Mallik site within the subsurface depth interval from 888.8 to 1101.1 m, with well log derived methane hydrate saturations as high as 90%. The Mallik 2002 drilling and testing program included open hole well logging and continuous wireline coring of the entire hydrate-bearing section at the Mallik site. Small scale production tests, consisting of pressure drawdown experiments, were completed in isolated methane-hydrate-bearing intervals. A longer duration thermal stimulation production test was also conducted. During the Mallik 2002 Gas Hydrate Production Research Well Program gas was produced from methane hydrates with a series of well constrained and controlled production experiments. All three phases of the Mallik project contributed to the quantification of the geologic, geophysical, and geomechanical properties of hydrate-bearing reservoirs. During the Mallik 2007-2008 test well program, gas was continuously produced to the surface over a six day period by reservoir depressurization; thus, established proof of concept that sustained gas production can be achieved by depressurization of methane hydrate reservoirs.
Alaska Mount Elbert Stratigraphic Test Well (2007)	BP Alaska Inc; U.S. Department of Energy; U.S. Geological Survey	The Mount Elbert site review and selection process featured the development and use of specialized seismic based methane hydrate prospecting techniques for the identification and characterization of methane hydrate prospects. The Mount Elbert test included the acquisition of pressure transient data from four relatively long duration open-hole MDT tests. To investigate the petrophysical properties of the hydrate-bearing reservoirs, each MDT test began with a "pre-flow test".	Acquire geologic and engineering data from methane hydrate accumulations in northern Alaska. Obtain geologic data to further constrain estimates of methane hydrate resources in northern Alaska. Confirm pre-drill seismic predictions for the occurrence of methane hydrate with the drilling results and data from Mount Elbert test well. Obtain reservoir engineering data to further develop existing methane hydrate production numerical simulators. Identify and characterize potential sites for extended hydrate production testing.	Methane hydrates were expected and found in two stratigraphic zones, ranging in thickness from about 14 to 16 m. NMR-density porosity derived saturations and other log analyses as well as pore water studies indicate methane hydrate saturations area clearly linked to reservoir quality. It was determined that the Mount Elbert hydrate-bearing reservoirs likely represent pre-existing gas accumulations that have been converted to hydrates. Analysis of initial pre-flow phase MDT tests and NMR wireline log data confirmed the presence of a mobile water phase in the hydrate-bearing sand reservoirs in the Mount Elbert well; analysis of the same data yielded reservoir permeabilites in the presence of a hydrate phase of 0.12-0.17 mD. Reservoir data acquired from the Mount Elbert well enabled reservoir simulation of gas production from hydrates at both field- and pore-scales. Reservoir simulations based on an idealized Mount Elbert geologic model indicate that hydrate-bearing reservoirs may be capable of gas production through sustained dissociation by depressurization.

Expedition	Management	Operational Technology Developments	Primary Operational/Scientific Objectives	Primary Operational/Scientific Results
Alaska Ignik Sikumi Methane Hydrate Production Test Well (2011-2012)	ConcoPhillips; U.S. Department of Energy; Ministry of Economy, Trade and Industry; Japan Oil, Gas and Metals National Corporation	Pre-field testing laboratory experiments demonstrated the effectiveness of exchanging CO_2 for CH_4 in the hydrate structure. In order to design the Ignik Sikumi CO_2-CH_4 hydrate exchange test this project required the development of hydrate reservoir modeling capabilities to simulate the in-situ CO_2-CH_4 hydrate exchange process.	Conduct field test to evaluate the role of free-water on hydrate reformation and reservoir permeability and to determine the effect of N_2 injection on the CO_2-CH_4 exchange process. Test the injectivity of CO_2 into a hydrate-filled, water-bearing reservoir, followed by CH_4 production, to test viability of CO_2/CH_4 exchange technology. Develop methane hydrate production completion technologies. Obtain the engineering data required for the design of a long-term deprsssurization production tests.	The drilling of the Iġnik Sikumi well established a hydrate test site in the westend of the Prudhoe Bay Unit in an area with three hydrate-bearing test intervals. NMR log analysis within the targeted test interval yielded hydrate saturations averaging 75%, with the remaining pore volume filled with a combination of clay bound, capillary-bound, and movable water. The trial yielded a specific mixture of N_2/CO_2 gas that minimizes the loss of injectivity due to the growth of additional CO_2 hydrate in the reservoir. After successfully injecting 210,000 scf of a mixture of CO_2/N_2 in 13 days, the backflow from the well produced nearly 1,000,000 scf of gas over a five-week period with rates as high as 175,000 scf/day. Most of the injected N_2 was collected during the backflow stage of the test, but about half of the of injected CO_2 remained in the formation. Completed initial analysis of both the injection and production phases of the test along with the release of a fully integrated production database.

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