Historical Methane Hydrate Project Review

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Executive Summary:

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

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

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

-Ocean Drilling Program Leg 164 (1995)

-Japan Nankai Trough Project (1999-2000)

-Ocean Drilling Program *Leg 204 (2004)*

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

-Gulf of Mexico JIP Leg I (2005)

-Integrated Ocean Drilling Program Expedition 311 (2005)

-Malaysia Gumusut-Kakap Project (2006)

-India NGHP Expedition 01 (2006)

-China GMGS Expedition 01 (2007)

-Republic of Korea UBGH Expedition 01 (2007)

-Gulf of Mexico JIP Leg II (2009)

-Republic of Korea UBGH Expedition 02 (2010)

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

-Mallik Gas Hydrate Testing Projects (1998/2002/2007-2008)

-Alaska Mount Elbert Stratigraphic Test Well (2007)

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

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

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

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

Our understanding of how methane hydrates occur and behave in nature is still growing and evolving – we do not yet know if methane hydrates can be economically produced, nor do we know fully the role of hydrates as an agent of climate change or as a geologic hazard. But it is known for certain that scientific drilling has contributed greatly to our understanding of hydrates in nature and will continue to be a critical source of the information to advance our understanding of methane hydrates.

1. Introduction

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 our knowledge related to the role that methane hydrates may play as an energy resource, as a geologic hazard, and as a possible agent in climate change is still incomplete. More work is needed to integrate our methane hydrate related research efforts, while developing a more complete understanding of the critical outstanding research issues to be resolved, to further our understanding of methane hydrates in nature.

The United States Department of Energy's (DOE) National Energy Technology Laboratory in partnership with the Consortium for Ocean Leadership (COL) has initiated a new field-focused methane hydrate research project. This project was proposed as a planning effort that could inform, and potentially lead to future projects ultimately including an offshore drilling field expedition. The DOE press release for this project can be found at the following web site http://energy.gov/node/387289 (viewed March, 2013). The primary objective of this project is to conduct planning that will 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 the continental margins of the United States. It is also envisioned that this effort will reach out to the international research community to develop a more global vision of methane hydrate research goals and needs. To this end, COL is leading an effort to identify the range of scientific questions and unknowns that need to be addressed within hydrate science and working inclusively within the greater hydrate research community to solicit input and develop a comprehensive "Marine Hydrate Research Expedition Science Plan" (Science Plan). The COL has assembled a "Hydrate Project Science Team" consisting of representatives from academia, industry, and government who will work to steer this effort from start to completion.

Two of the major elements within this effort, designed to provide the foundation for the Science Plan, are (1) a "Historical Methane Hydrate Project Review" report, and (2) a "Hydrate Community Workshop". This document represents the "Historical Methane Hydrate Project Review" report. This report includes a systematic review of the objectives and accomplishments of past ODP-IODP, industry, and nationally sponsored historical methane hydrate research drilling expeditions. This review includes the analysis of both technical concerns that are related to the universal occurrence of methane hydrates and specific regional concerns that are unique to a given region or hydrate accumulation. This report also reviews our present 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. Also summarized in this report are some of the more important drilling related operational understandings and technology developments, such as pressure coring, downhole logging, and borehole instrumentation, which have contributed to our growing understanding of methane hydrates. This report concludes with a systematic review of planning documents for major methane hydrate research projects, national/international assessment reports on methane hydrate research issues and opportunities, and program peer review reports. This synthesis of existing planning and review documents contributes directly to the goal of identifying the most critical unknowns relative to our understanding of methane hydrates in nature.

It is envisioned that this report will be used as a guide to develop the agenda for the "Hydrate Community Workshop" and provide the foundation for the "Marine Hydrate Research Expedition Science Plan".

Within in this report the terms methane hydrate, gas hydrate, and hydrate are considered interchangeable for discussion purposes.

2. Background

Methane hydrates have the potential to provide an immense resource of natural gas from the world's oceans and polar regions. Methane hydrates are known to be widespread in permafrost regions and beneath the sea in sediments of outer continental margins. It is generally accepted that the volume of natural gas contained in the world's methane hydrate accumulations greatly exceeds that of known conventional gas reserves. Recent production tests in Alaska, northern Canada, and offshore Japan have also shown that natural gas can be produced from methane hydrates with existing conventional oil and gas production technology. Beyond a future energy resource, methane hydrates may in some cases represent a significant drilling and production hazard. Russian, Canadian, and American researchers have described problems associated with the occurrence of methane hydrate in the Arctic, including well control difficulties and casing failures. Other studies also indicate that naturally destabilized methane hydrates may be contributing to the build-up of atmospheric methane, a significant greenhouse gas.

With the growing interest in natural methane hydrates as a source of energy, a geologic hazard, and a potential agent of climate change, it is becoming increasingly important to be able to understand the physical nature and the geologic controls on the formation and stability of methane hydrate in nature. Our knowledge of naturally occurring methane hydrates is growing and it can be concluded that: (1) a large volume of natural gas is stored in methane hydrates; (2) production of natural gas from methane hydrates is technically feasible with existing technology; (3) methane hydrates hold the potential for natural hazards associated with seafloor stability and release of methane to the oceans and atmosphere; and (4) methane hydrates disturbed during drilling and petroleum production pose a potential safety problem.

3. Geologic Controls on the Occurrence of Methane Hydrate in Nature

In recent years significant progress has been made in addressing key issues on the formation, occurrence, and stability of methane hydrate in nature. The concept of a methane hydrate petroleum system, similar to the concept that guides conventional oil and gas exploration, has been developed to systematically assess the geologic controls on the occurrence of methane hydrate in nature (Collett et al., 2009). In a methane hydrate petroleum system, the individual factors that contribute to the formation of methane hydrate can be identified and assessed; the most important include (1) methane hydrate pressure-temperature stability conditions, (2) gas source, (3) gas migration, (4) availability of water, and (5) suitable host sediment or "reservoir". In the following discussion, these geologic controls on the formation and stability of methane hydrate in nature will be reviewed and evaluated.

3.1. Methane Hydrate Stability Conditions

Methane hydrates exist under a limited range of temperature and pressure conditions such that the depth and thickness of the zone of potential methane hydrate stability can be calculated given information on temperature and pressure gradients with depth, and gas and formation water chemistry. Phase-boundary information (Figure 3.1) coupled with subsurface temperature conditions (Figure 3.2) indicate that the upper depth limit for methane hydrates is about 150 m in continental polar regions, where surface temperatures are below 0°C. In oceanic sediment, methane hydrates occur where the bottom-water temperature approaches 0°C and water depths exceed about 300 m. The lower limit of methane hydrate occurrence is determined by the geothermal gradient, where the maximum lower limit is about 2,000 m below the solid surface (i.e., seafloor in marine environments and the land surface in continental polar regions), although the lower limit is typically much less depending on local conditions (Figure 3.2).

It is important to note that most studies of methane hydrate stability conditions assume hydrostatic pore-pressure gradients (reviewed by Collett, 2002). Pore-pressure gradients greater than hydrostatic correspond to higher pore-pressures with depth and a thicker methane-hydrate stability zone, whereas a pore-pressure gradient less than hydrostatic (which can only occur on land) would correspond to a thinner methane hydrate stability zone. Most methane hydrate studies also assume that methane is the only gas occupying the clathrate structure; however, it is well established that the addition of other hydrocarbon gases such as ethane or propane to the pure methane gas system shifts the stability curve to the right in Figure 3.1, thus deepening the zone of potential methane-hydrate stability. Salt, such as NaCl, when present in a methane-hydrate system also lowers the temperature at which methane hydrates form. In many field studies the potential impact of variable gas chemistry and pore-water salinities are not fully evaluated when considering the range of methane hydrate stability conditions.

3.2. Gas Source

It has been shown that the availability of large quantities of hydrocarbon gas from both microbial and thermogenic sources are an important factor controlling the formation and distribution of methane hydrates (Kvenvolden, 1993; Collett, 2002; Collett et al., 2008a). Geochemical analysis of gases obtained from recovered methane hydrate samples indicate that the methane in many oceanic hydrates is derived from microbial sources; however, thermal sources have been observed within several hydrate occurrences in the Gulf of Mexico, Caspian Sea, Black Sea and onshore in the Mackenzie Delta and northern Alaska (reviewed by Collett, 2002).

Some of the more sophisticated methane hydrate assessment studies have attempted to quantify the potential source of the gas (Collett, 1995; Klauda and Sandler, 2005; Frye, 2008; Wood and Jung, 2008; Bureau of Ocean Energy Management, 2012) when estimating the volume of gas within a given hydrate accumulation. These estimates generally include the assessment of a set of minimum source-rock criteria such as organic richness (total organic carbon), sediment thickness, and thermal maturity as they apply to both microbial and thermogenic gas sources.

Microbial Gas Source

Microbial gas is produced by the decomposition of organic matter by microorganisms. Two primary pathways have been identified for the generation of microbial gas: carbon dioxide (CO_2) reduction and fermentation. Although fermentation is the pathway for gas generation in some modern environments, CO_2 reduction is the more important process leading to the development of ancient microbial gas accumulations. CO_2 needed for reduction to generate methane is mostly derived from the oxidation and thermal decarboxylation of in-situ organic matter. Thus, abundant organic matter is needed for the formation of microbial methane. Finley and Krason (1989) have shown that, for geologic conditions observed on the Blake Ridge, a marine sediment with an average organic carbon content of 1% could yield enough gas to form hydrates within approximately 28% of the available pore space of a sediment with 50% porosity, if all the organic matter were converted to methane. However, organic carbon to methane conversion efficiency of 100% is unreasonable (Kvenvolden and Claypool, 1988). Accordingly, a lower microbial conversion efficiency of 50% was assumed in the 1995 USGS assessment of gas hydrate resources in the United States (Collett, 1995), a value was then used to set a minimum organic carbon content required for hydrate formation of 0.5%. Due to the relatively low organic carbon content of most sediments, production of microbial methane internally within the methane hydrate stability zone alone is a limiting factor for the development of significant methane hydrate accumulations. Paull et al., (1994) have shown that gas recycling and upward migration of methane from deeper sources in a marine sedimentary sequence is essential for the formation of significant methane-hydrate accumulations. Once a methane hydrate stability zone is established, microbial gas may accumulate as a result of recycling natural gas from below the base of the stability zone and from continued microbial gas production at depth.

Our understanding of the role that microbially generated gas may play in the formation of methane hydrate in nature has continued to grow in recent years. In 2008, Minerals Management Service (now known as the Bureau of Ocean Energy Management, BOEM) released the results of a comprehensive probabilistic methane hydrate resource assessment for the Gulf of Mexico (Frye, 2008). The BOEM assessment dealt primarily with methane generated by microbial processes and their assessment model was developed around three modules: (1) charge, (2) container or reservoir, and (3) concentration or methane hydrate saturation. Much like previous assessments models, in the BOEM “charge module”, gas is generated by converting organic carbon into methane through biogenic processes. The rate of microbial conversion of organic carbon to methane was assumed to be a function of the ambient temperature of the sedimentary section and the rate of water flux through the sediment, with the rate of water flux being controlled by the permeability of the sediments. The BOEM “charge module” thus provides a method to systematically estimate the amount of microbial gas that could be generated from sedimentary section with a given concentration of organic carbon, which yields an estimate of the potential methane hydrate content within an each assessment cell area. Wood and Jung (2008) also included the analysis of the volume of “historical organic carbon deposition” in their assessment of methane hydrates Earth’s marine environment.

Thermogenic Gas Source

Thermogenic methane is generated during the thermochemical alteration of organic matter. During early thermal maturation, methane is produced along with other hydrocarbon and non-hydrocarbon gases and is commonly associated with crude oil generation. At the highest thermal maturities, methane alone is formed by the cracking of carbon-carbon bonds in kerogen, bitumen, and oils. As temperature increases during thermal maturation, each of the hydrocarbon species is formed during optimal thermal windows. For methane, optimum generation occurs at 150°C (Tissot and Welte, 1978; Wiese and Kvenvolden, 1993). As discussed above, most of the gas within the sampled methane hydrate occurrences in the world has been shown to be derived from microbial sources. Thus, most of the published methane hydrate assessments have focused on assessing only microbial gas sources. However, recent studies in northern Alaska (Collett et al., 2008a) and Canada (Dallimore and Collett, 2005) have again documented the importance of thermogenic gas sources to the formation of highly concentrated methane hydrate accumulations. For the most part, the role of thermogenic-derived gas in most methane hydrate field studies has likely been underappreciated.

3.3. Gas Migration

As discussed above, highly concentrated methane hydrate accumulations contain a substantial volume of gas, which is potentially derived from microbial and/or thermogenic sources. Typically, not enough microbial methane is generated internally within the methane-hydrate stability zone alone to account for the gas content of most methane hydrate accumulations (Kvenvolden, 1993). In addition, most methane hydrate accumulations are in sediments that have not been deeply buried or subjected to temperatures high enough to form thermogenic gas. Thus, the gas within most hydrate accumulations is likely concentrated in the hydrate stability zone by a potential combination of processes — one of which, gas migration, would appear to be a critical component within most methane hydrate petroleum systems.

Methane, along with other hydrate forming gases, migrates within a sedimentary section by one of three processes: (1) diffusion, (2) gas dissolved within migrating water, or (3) as a bubble or a separate continuous gas phase. The terms “bubble” and “continuous gas phase” have been used here to further describe the range of the physical nature of a gas phase within the void space of sedimentary section. Migration of gas by diffusion is a slow process and would not likely result in the movement of enough gas to form a concentrated methane hydrate accumulation (Xu and Ruppel, 1999). However, Malinverno (2010) has proposed a mass balance model for the formation of methane hydrate in which the methane required for hydrate formation is generated in fine-grained sediments with relatively low organic carbon concentrations (<0.5% dry weight faction), which is allowed to migrate by diffusion into nearby coarse-grained (sand) layers where it forms concentrated methane hydrate deposits. This mechanism may account for the presence of methane hydrate in closely associated stacked layers of alternating coarse- and fine-grained sediment layers. But it is difficult to use this same model to explain the occurrence of massively bedded thick (>50 m) hydrate-bearing sand sections as observed in the Gulf of Mexico (Boswell et al., 2012a, 2012b) and the Nankai Trough (Fuji et al., 2008).

It is well established, however, that the migration of gas by advection as either a dissolved component in water or as a separate gas phase can be a highly efficient process. Two basic models have been proposed to describe the interrelation between advective gas migration and the formation of methane hydrate. In a model originally proposed by Hyndman and Davis (1992), water (with a dissolved aqueous phase of methane and other potential hydrate formers) moving upward into the hydrate zone encounters decreasing methane solubility, which results in the exsolution of methane and the formation of methane hydrate. Numerous field and laboratory studies show that methane hydrate forms only where the concentration of methane in the pore waters exceeds solubility. In most marine settings (outside of areas of active methane venting), no methane hydrate is present in sediments near the seafloor because the concentration of dissolved methane is low (Claypool and Kaplan, 1974). The other basic model for the formation of methane hydrate in sediments involves the upward migration of methane as a bubble phase (separate gas phase) into the hydrate stability zone, with hydrate nucleation taking place at the bubble and pore-water interface. Both models require permeable pathways to allow for the migration of water and/or a gas phase, but the gas-phase migration model requires relatively enhanced fluid flow pathways in comparison to the aqueous migration model. It is generally concluded that both pore-water flow and gas phase migration in sediments are focused along permeable pathways such as fault systems or porous-permeable sediment layers. Therefore, if effective migration pathways are not available, it is unlikely that a significant volume of methane hydrate would accumulate.

Building on the regional scale gas migration and hydrate formation model of Hyndman and Davis (1992), Jain and Juanes (2009) presented a physical model that couples multiphase fluid flow with sediment mechanics to permit the investigation of the upward migration of gas through a water-filled sediment column. Jain and Juanes (2009) report that grain size is the main factor controlling the mode of gas transport in the sediment, and they show that coarse-grain sediments favor capillary invasion, whereas fracturing dominates in fine-grain media. Their results predict that in fine sediments, hydrate will likely form in veins following a fracture network pattern, and the hydrate concentration will likely be quite low. In coarse sediments, the buoyant methane gas likely invades the pore space more uniformly, in a process akin to invasion percolation, and the overall pore occupancy is likely to be much higher than in a fracture-dominated regime. These results are consistent with laboratory experiments and field observations of methane hydrate in natural systems.

3.4. Availability of Water

Upon closer analysis it is obvious that methane hydrate is mostly water. The ideal gas/water molecular ratio of structure I [sI] hydrate is 8/46, whereas the ideal gas/water ratio of structure II [sII] hydrate is 24/136. These gas/water ratios confirm the observation that methane hydrates contain a substantial amount of water. For the most part, water is ubiquitous in marine and terrestrial sediments, but we have seen in several situations that the apparent lack of “available” water has precluded the formation of methane hydrate. The observation of gas bubbles at vent sites and other similar features in numerous deep water environments document the fact that gas is somehow allowed to migrate through thick methane hydrate stability zones (reviewed by Tréhu et al., 2004; 2006). One of the models used to explain the processes allowing for gas migration through a hydrate stability zone involves bubble-phase gas migration along fracture pathways, in this system, the walls of the fracture become coated with methane hydrate, and the migrating bubble-phase gas travels along internal conduits within the hydrate-filled fractures without coming into contact with the formation free-water, which prevents the formation of methane hydrate.

Several researchers have also proposed an “equilibrium model” for the migration of hydrate forming gases through hydrate stability zones (Liu and Flemings, 2006). As gas migrates into the hydrate stability zone from below in this model, hydrate forms, depletes the pore water, and elevates salinity until the pore water salinity prevents the further formation of methane hydrate. This process generates pore-scale localized three phase equilibrium and allows free gas to migrate to the seafloor. In this model, elevated pore water salinities provide a mechanism for vertical migration of free gas through a methane hydrate stability zone. Torres et al., (2011), however, indicated that the analysis of pore fluids from sites with massive hydrate deposits on the Cascadia accretionary margin (IODP Sites 1249 and U1328), Krishna-Godavari Basin (India) and the Ulleung Basin (Korea) showed no evidence for the formation of a salinity front that can shift the thermodynamic equilibrium and sustain gas transport through the methane hydrate stability zone, as postulated by Liu and Flemings (2006). Torres et al., (2011), concluded that "hydrofracturing" and critical gas pressures below the methane hydrate stability zone more likely support the gas transport similar to the model proposed by Jain and Juanes (2009).

We have also seen, in one case from northern Alaska, a free-gas-bearing sand reservoir within the predicted methane hydrate stability zone. In this situation, it appears likely that an isolated sand body in a thick shale section was originally charged with free gas to irreducible water saturations of only several percent (Collett, 2004). At some time in the past, the hydrate stability zone advanced, due to climate cooling and corresponding depression of the geothermal gradient, to a depth well below the free-gas-saturated sand body. Methane hydrate, however, did not appear to form in this isolated sand reservoir due to the lack of available pore water.

3.5. Reservoir Rocks

The study of methane-hydrate samples indicates that the physical nature of in-situ methane hydrates is highly variable (reviewed by Sloan and Koh, 2008). Methane hydrates are observed (1) occupying pores of coarse-grained sediment; (2) nodules disseminated within fine-grained sediment; (3) a solid substance, filling fractures; or (4) a massive unit composed mainly of solid methane hydrate with minor amounts of sediment. Most methane hydrate field expeditions, however, have shown that the occurrence of concentrated methane hydrate is mostly controlled by the presence of fractures and/or coarser grained sediments in which methane hydrate fills fractures or is disseminated in the pores of sand-rich reservoirs (Collett, 1993; Dallimore and Collett, 2005; Riedel et al., 2006; Collett et al., 2008a, 2008b; Fuji et al., 2009; Park et al., 2008; Yang et al., 2008; Lee et al., 2011b; Yamamoto et al., 2012a, 2012b). Torres et al., (2008) concluded that hydrate grows preferentially in coarse-grained sediments because lower capillary pressures in these sediments permit the migration of gas and nucleation of hydrate. The growth of methane hydrate in clay-rich sediments, however, is less understood. But Torres et al., (2008) further concluded that in smaller pores, capillary forces will preclude the exsolution of methane from pore fluids, thus limiting the amount of gas available for the formation of methane hydrate. Cook and Goldberg (2008) also proposed that in cases where the concentration of gas in water exceeds solubility within a clay-rich sedimentary section, hydrate forms in pore-segregated fracture planes that propagate in the direction of the maximum principal stress — in most cases, near vertical fractures. This proposed model appears to account for the occurrences of fracture-filling methane hydrates that are not associated with larger, through-going fault systems.

In review articles by Boswell and Collett (2006) and Boswell et al., (2007), four different methane hydrate play types were identified and compared within a "methane hydrate resource pyramid" (Figure 3.3). Resource pyramids are commonly used to display the relative size and producibility of different types of energy resources. Within a resource pyramid the most promising and accessible resources are depicted at the top and the most technically challenging are shown at the base. The pyramid shape results from the natural tendency for the most abundant elements of a resource group to also be the most difficult to extract. At present, four different methane hydrate play types or occurrences are known (as depicted in Figure 3.3): (1) sand-dominated reservoirs, (2) clay-dominated fracture reservoirs, (3) massive methane hydrate deposits exposed on the seafloor, and (4) low-concentration disseminated deposits encased in largely impermeable clays. Similar methane hydrate occurrences were described by

Milkov and Sassen (2002). The first two of these play types, have been described as "worthy of further exploration" as both provide the "reservoir" permeability necessary for the formation of highly concentrated hydrate accumulations (Boswell et al., 2007). These two play types are also often closely related and found in combination. These combination reservoirs consist of horizontal to subhorizontal coarse-grained permeable units (sands for the most part) and contain apparent vertical to subvertical fractures that may be conduits for gas migration (Collett et al., 2008c).

Sand-Dominated Reservoirs

The apex of the methane hydrate resource pyramid (those resources that are closest to potential commercialization) is represented by high methane hydrate saturated accumulations in sand-dominated reservoirs in polar regions. Collett (1995) assigned an in-place resource of 16.7 trillion cubic meters (590 trillion cubic feet) for Arctic sand-dominated reservoirs on the North Slope of Alaska. In a more recent assessment of methane hydrate resources on the North Slope of Alaska, Collett et al., (2008a) 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. No similar assessments exist for other Arctic permafrost settings.

The next most prospective methane hydrate resources are those of moderate-to-high concentrations within sandstone reservoirs in marine environments. Due to the relatively distal nature of the deep marine geologic settings, the overall abundance of sand within the shallow geologic section is generally low. Also, the extraction of these resources is subject to the high costs of deep water exploration and development. The most favorable marine hydrate accumulations, however, will likely be in the vicinity of existing production infrastructure such as in the Gulf of Mexico. 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.

Production testing and modeling has shown that concentrated methane hydrate occurrences in sand reservoirs are conducive to existing well-based production technologies. For both arctic and marine hydrate-bearing sand reservoirs, there are no apparent technical roadblocks to resource extraction; the remaining resource issues deal mostly with the economics of hydrate extraction.

Clay-Dominated Fracture Reservoirs

On the methane hydrate resource pyramid below the resources associated with sand-dominated reservoirs, there are massive deposits of methane hydrate generally encased in fine-grained muds and shales (Figure 3.3), the most promising of which occupy fracture systems. However, unlike sand systems where grain-supported reservoirs result in high matrix permeability and for which there are promising production concepts, exploitation of methane in shale-encased fractured accumulations will require improved extraction technologies.

Recent field studies have shown that localized, deeply buried, highly concentrated, and fracture dominated methane hydrate deposits are likely more common than previously considered (Riedel et al., 2006; Collett et al., 2008b, 2008c; Hutchinson et al., 2008b; Park et al., 2008; Collett and Boswell, 2012). In addition, many of these occurrences can be directly linked to surficial seep-related hydrate deposits.

Seafloor Massive Methane Hydrate Deposits

The majority of marine methane hydrate accumulations that have been studied to date are in fine-grained, clay-dominated sediments associated with surficial seep-related massive methane hydrate deposits (reviewed by Milkov and Sassen, 2002). This type of hydrate deposit is commonly associated with mounds that lie exposed on the seafloor. In many cases, these mounds appear to be dynamic and connected to deep fracture-filled methane hydrate systems that also act as 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 also constrained by the probable destruction of sensitive sea-floor ecosystems.

Clay-Dominated Disseminated Methane Hydrate Deposits

At the base of the methane hydrate resource pyramid (Figure 3.3) are finely disseminated accumulations, typified by the Blake Ridge (as cored and logged during ODP Leg 164), in which there are large volumes of methane hydrate at low saturations (~10% or less) over extensive regions. Most of the in-place global methane hydrate "resources" may reside within this resource class. The prospects for economic recovery of natural gas from this highly disseminated resource, however, are extremely limited with current technologies, and major improvements in extraction methods are required to enable commercial exploitation of such deposits.

By all accounts, 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 recent methane hydrate exploration and production studies in northern Alaska and Canada, and offshore in the Gulf of Mexico, off the southeastern coast of Japan, in the Ulleung Basin off the east coast of the Korean Peninsula, and along the eastern margin of India. Production testing and modeling has shown that concentrated methane hydrate occurrences in sand reservoirs are conducive to existing well-based production technologies (Anderson et al., 2008, Dallimore et al., 2008a, 2008b; Moridis et al., 2008; Yamamoto and Dallimore, 2008). For both arctic and marine hydrate-bearing sand reservoirs, there are no apparent technical roadblocks to resource extraction; the remaining resource issues deal mostly with the economics of hydrate extraction. 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.

It is acknowledged that most of the previous discussion in this report dealing with use of the methane hydrate petroleum system concept (as defined in Collett et al., 2009) focuses on the formation of concentrated methane hydrate accumulations as targets for energy exploitation. But in a recent personal communication from Professor Gerry Dickens (Rice University, Houston, Texas; February, 2013), Professor Dickens noted that the occurrence of methane hydrate at any scale should be viewed as a "dynamic component of broader carbon cycling………the amount and distribution of methane hydrate at any location must link to the inputs and outputs of methane over time, which ultimately are related to inputs and outputs of carbon. Much of the research today continues to focus on describing methane hydrates as static deposits rather than understanding them as gas dynamic systems." There is an obvious growing need for the development of integrated time dependent models to understand the geologic controls on the formation, occurrence, and stability of methane hydrates in nature.

4. ODP-IODP and Industry Sponsored Historical Methane Hydrate Research Drilling Expeditions

As discussed previously in this report, methane hydrates occur in two environments: deep marine and onshore arctic. The presence of methane hydrates in offshore continental margins is inferred mainly from anomalous seismic reflectors that coincide with the base of the methane-hydrate stability zone (BGHSZ) (reviewed by Kvenvolden, 1993). This reflector is commonly called a bottom-simulating reflector (BSR). The BSR is commonly interpreted to mark the boundary between methane hydrate-bearing sediments above and free-gas-bearing sediments below. This boundary creates a strong acoustic impedance contrast on recorded seismic lines, but BSRs are also associated with non-hydrate related features, most notably Opal-CT transitions. Because the BSR follows the BGHSZ, generally at a constant depth below the seafloor, the bright reflector with a polarity opposite to the seafloor typically cuts across bedding planes and mimics the seafloor topography (hence the name 'bottom-simulating' reflector). In less deformed areas, however, the BSR can be conformable to bedding and can be difficult to identify. BSRs have been mapped to depths as great as 1,100 m below the sea floor.

Methane hydrates have been recovered from shallow sediments cores within the upper 30 m of the sea floor in almost every marine basin, including the Gulf of Mexico, the Cascadia continental margin of North America, the Black Sea, the Caspian Sea, the Sea of Okhotsk, the East Sea / Sea of Japan, and the North and South Atlantic Ocean (Collett, 2002; Collett et al., 2009). They have also been recovered at greater depths along the southeastern coast of the United States on the Blake Ridge, in the Gulf of Mexico, along the Cascadia margin of the United States and Canada, the Middle America Trench, offshore Peru, India, China, South Korea, and on both the eastern and western margins of Japan (Collett et al., 2009).

In recent years, a growing number of deep sea drilling expeditions have been dedicated to locating marine methane hydrates and to obtain a greater understanding of the geologic controls on their occurrence (Figure 4.1). The most notable projects have been those of the Ocean Drilling Program (ODP) and the Integrated Ocean Drilling Program (IODP), including ODP Legs 164 (Paull et al., 1996) and 204 (Tréhu et al., 2004) and IODP Expedition 311 (Riedel et al., 2006). Industry focused methane hydrate drilling projects have also contributed valuable data, such as the two legs of the DOE-sponsored Joint-Industry Project in the Gulf of Mexico: Gulf of Mexico JIP Leg I (Ruppel et al., 2008) and Gulf of Mexico JIP Leg II (Collett and Boswell, 2012). National led methane hydrate drilling projects have also contributed to our understanding of methane hydrates in nature. These national efforts are typically led by a central government agency, which is responsible for funding and managing these efforts. One of the more important series of national led projects has been conducted in the offshore of Japan, including the METI Nankai Trough Project in 1999-2000, the METI Tokai-oki to Kumano-nada Project in 2004, and the MH-21 Nankai Trough Pre-Production Expedition in 2012 (Tsuji et al., 2004, 2009; Yamamoto et al., 2012a, 2012b). Additional national led projects, including those India, the NGHP Expedition 01 (Collett et al., 2008b, 2008c, 2008d), as well as those in the offshore of China (GMGS-1: Zhang et al., 2007a, 2007b; Yang et al., 2008; Wu et al., 2008) and the Republic of Korea (UBGH1: Park et al., 2008; Park, 2008) (UBGH2: Lee et al., 2011a, 2011b) have provided a wealth of information on the occurrence of methane hydrate in nature.

Methane hydrate in onshore arctic environments is typically closely associated with permafrost. It is generally believed that thermal conditions conducive to the formation of permafrost and methane hydrate have persisted in the Arctic since the end of the Pliocene (about 1.88 Ma). Maps of present day permafrost reveal that about 20% of the land area of the northern hemisphere is underlain by permafrost (Figure 4.2). Geologic studies (Molochushkin, 1978) and thermal modeling of subsea conditions (Osterkamp and Fei, 1993) also indicate that permafrost and methane hydrate may exist within the continental shelf of the Arctic Ocean. Subaerial emergence of portions of the Arctic continental shelf to current water depths of 120 m (Bard and Fairbanks, 1990) during repeated Pleistocene glaciations, subjected the exposed shelf to temperature conditions favorable to the formation of permafrost and methane hydrate. Thus, it is speculated that "relic" permafrost and methane hydrate may exist on the continental shelf of the Arctic Ocean to present water depths of 120 m. In practical terms, onshore and nearshore methane hydrate can only exist in close association with permafrost, therefore, the map in Figure 4.2 that depicts the distribution of onshore continuous permafrost and the potential extent of "relic" subsea permafrost also depicts the potential limit of onshore and nearshore methane hydrate. It also appears that most permafrost-associated methane hydrate accumulations probably developed from preexisting free-gas fields that originally formed in conventional hydrocarbon traps, then were converted to methane hydrate upon the onset of glaciation and cold arctic conditions.

Methane hydrate accumulated in Arctic regions of permafrost and in deep lakes such as Lake Baikal in Russia (reviewed by Kvenvolden, 1993; Collett et al., 2009), are associated with permafrost in Canada, Alaska, and northern Russia. Methane hydrate has also been recently discovered associated with alpine permafrost on the Qinghai-Tibet Plateau in southern China. Onshore methane hydrates (Figure 4.2) are present in the West Siberian Basin and are believed to be in other permafrost areas of northern Russia. Permafrost-associated methane hydrates are also present in the North American Arctic. Direct evidence for methane hydrates on the North Slope of Alaska comes from studies of cores from two methane hydrate research wells, and there is indirect evidence from drilling and open-hole industry well log for the probable presence of numerous methane hydrate layers in the area of the Prudhoe Bay, Kuparuk River, and Milne Point oil fields. Well-log responses attributed to the presence of methane hydrates have been obtained in about one-fifth of the wells drilled in the Mackenzie Delta. More than half of the wells in the Arctic Islands of Canada are inferred to contain methane hydrates (Judge et al., 1994; Osadetz and Chen, 2005). The combined information from Arctic methane-hydrate studies shows that, in permafrost regions, methane hydrates may exist at subsurface depths ranging from about 130 to 2,000 m.

Two of the most studied permafrost-associated methane hydrate accumulations are those at the Mallik site in the Mackenzie River Delta of Canada and the Eileen methane hydrate accumulation on the North Slope of Alaska (Figure 4.3 A-B). The Mallik methane hydrate production research site has been the focus of three geologic and engineering field programs (1999/2002/2007-2008 Mallik Gas Hydrate Testing Projects) and yielded the first fully integrated production test of an onshore methane hydrate accumulation. The science program in support of the DOE and BP-sponsored Mount Elbert methane hydrate test well project in northern Alaska generated one of the most comprehensive data sets on an Arctic methane hydrate accumulation along with critical methane hydrate reservoir engineering data. In 2011/2012, DOE partnered with ConocoPhillips and the Japan Oil, Gas and Metals National Corporation (JOGMEC) to investigate a new production method in which carbon dioxide injected into a methane hydrate-bearing rock unit can release methane while sequestering carbon dioxide in hydrate form. The field testing phase of the Iġnik Sikumi methane hydrate production test well project was completed in 2012. The results of the Mallik, Mount Elbert, and Iġnik Sikumi methane hydrate geologic and production studies will be discussed later in this report.

As shown in Figure 4.1 and as discussed above, methane hydrate has been recovered and/or inferred to exist in numerous marine and onshore polar basins. However, only a limited number of accumulations have been examined and delineated with data collected by deep scientific drilling operations. Included in the following section of this report and summarized in Table 4.1 is a systematic review of the goals and accomplishments of 16 of the more significant methane hydrate research drilling expeditions and projects to date. Note that the following expedition summaries are variable in length, which in some cases reflect the complexity of a particular expedition. But the amount of information available to the public from each of these expeditions is also highly variable, which in turn is reflected in the content of each of the expedition summaries as presented in this report.

4.1. ODP Leg 164 (1995)

As the first marine drilling expedition dedicated to the study of methane hydrates, ODP Leg 164 (Shipboard Scientific Party, 1996) was designed to investigate the occurrence of methane hydrate in the sedimentary section beneath the Blake Ridge off the east coast of the United States (Figure 4.4).

Scientific Objectives of ODP Leg 164.

1. *Assess the amount of gas trapped in hydrate-bearing sediments.*
2. *Understanding lateral variability in methane hydrate abundance.*
3. *Understanding the relationship between BSRs and methane hydrate development.*
4. *Investigating the distribution and in-situ fabric of methane hydrate within sediments.*
5. *Establishing changes in physical properties (porosity, permeability, P-wave velocity, thermal conductivity, etc.) associated with methane hydrate formation and decomposition in continental margin sediments.*
6. *Determining whether gas contained in methane hydrate is produced locally or migrated from elsewhere.*
7. *Investigating the role of methane hydrate in formation of authigenic carbonates.*
8. *Determining the chemical and isotopic compositions, hydration number, and crystal structure of natural methane hydrate.*
9. *Investigating the potential connection between large-scale sediment failures and methane hydrate decomposition.*
10. *Establishing the origin of the Carolina Rise Diapirs and their influence on associated methane hydrate.*

ODP Leg 164 began with the departure of the scientific drilling ship *JOIDES Resolution* from Halifax, Nova Scotia on 31 October 1995. The first sites drilled during Leg 164 included a series of short holes, drilled at three sites (Sites 991/992/993) on the crest and flanks of the Cape Fear Diapir. The Cape Fear Diapir is one of about 20 large structures that originate from deep within the sediments of the Carolina Trough and penetrate through the Carolina Continental Rise. Next on Leg 164, Sites 994, 995, and 997 were established as a transect of holes on the southern flank of the Blake Ridge that extends from an area where a BSR is not detectable to an area where an extremely well-developed and distinct BSR exists. The transect was situated where variations in the development of the BSR and seismic blanking are especially distinct. However, the geology and topography along this transect are relatively simple, which provided an opportunity to assess basic properties of hydrate-bearing sediments and to understand lateral hydrate variations caused by local lithologic, chemical, and hydrologic factors. Site 994 is situated at the end of the transect where the BSR is not detectable and, thus, served as a background or reference site. ODP Leg 164, Site 996 was established on the crest of the Blake Ridge Diapir. The objectives at this site were to investigate (1) methane migration and methane hydrate formation in a pockmarked fault zone where methane is leaking out of the continental rise, (2) the source of fluids and gases in a seafloor seep, and (3) the influence of these fluids on the host sediments. ODP Leg 164 ended in Miami, Florida on 19 December 1995. The technical specifications of the *JOIDES Resolution* and the science labs on the ship are reviewed in "Section 5. Methane Hydrate Research Drilling Platforms" of this report.

ODP Leg 164 Sites 994, 995, and 997 comprise a transect of holes that penetrate below the base of methane hydrate stability within the same stratigraphic interval over a relatively short distance (Figure 4.5). The presence of methane hydrates at Sites 994 and 997 was documented by direct sampling; no methane hydrates were conclusively identified at Site 995 (Shipboard Scientific Party, 1996). Based on analysis of pore water chloride concentrations and downhole logging data, it was determined that disseminated methane hydrates occur throughout the stratigraphic interval from about 190 to 450 mbsf in all three holes drilled along the transect (Figure 4.6). The depth to the lower boundary of the log inferred methane-hydrate-bearing interval on the Blake Ridge, roughly corresponds to the predicted base of the methane hydrate stability zone and it is near the lowest depth of the observed interstitial-water chloride anomaly (Figure 4.6). The observed chloride concentrations also enable the amount of methane hydrate that occurs on the Blake Ridge to be determined by calculating the amount of interstitial water freshening that can be attributed to methane hydrate dissociation. The estimated methane-hydrate saturations (percent of pore space occupied by methane hydrate) in the recovered cores had a skewed distribution, ranging from a maximum of about 7% and 8.4% at Sites 994 and 995 to a maximum of about 13.6% at Site 997 (Shipboard Scientific Party, 1996).

A significant portion of the Blake Ridge appears to be underlain by methane hydrates, but as discussed above in the review of the "methane hydrate resource pyramid", the concentration of hydrates on Blake Ridge appears to be low and the host sediments are mostly clay, which collectively raises a concern over the production technology required to produce gas from widely disseminated methane hydrate accumulations in clay-rich sediments.

During ODP Leg 164, an unprecedented level of success was achieved using the pressure core sampler (PCS), a device that returns a short core to the surface at formation pressures so that gasses are not lost. Gas volumes captured by the PCS were used to indicate the presence of methane hydrate and free-gas beneath the BSR on Blake Ridge during the drilling leg (Dickens et al., 1997). This drilling leg also represented the first extensive use of downhole wireline logs to characterize the distribution and concentration of methane hydrates and associated free-gas accumulations (Collett and Ladd, 2000). The evolution of pressure coring and the use of downhole logs to characterize the in-situ nature of methane hydrates are further reviewed in "Section 6. Pressure Core Tools and Lab Developments" and "Section 7. Downhole Well Log Analysis of Methane Hydrate" of this report.

Scientific Conclusions and Contributions of ODP Leg 164.

1. *Amount of gas trapped in hydrate-bearing sediments: Analysis from Leg 164 drill sites on the Blake Ridge indicates that methane hydrate occupies 1% to 2% of the sediment volume in a zone that is 200-250 m thick. If the rest of the ~26,000-km^2 region around the Blake Ridge where BSRs are present contains as much methane hydrate, rough estimates indicate that about 10 Gt of methane carbon is stored in this region. Given the number of localities worldwide in which methane hydrate occurs, the results of ODP Leg 164 provide further evidence that methane stored as methane hydrate in marine sediments represents a significant component of the global fossil carbon reservoir.*
2. *Lateral variability in methane hydrate abundances: Interstitial water chloride profiles were used as a proxy indicator for the amount of in situ methane hydrate. A zone with anomalously low chloride values occurs at approximately the same depths (~200 to 440*

mbsf) over the 10-km transect. The similarity of the chloride profiles at the ridge sites strongly suggests that methane hydrate is correlative over the expanse of the Blake Ridge.

3. *Relationship between bottom-simulating reflectors and methane hydrate development: Downhole sonic log and vertical seismic profile data indicate decreasing interval velocities near the depth of the BSR. The change in sediment velocity may be related to either changes in the amount of hydrate above the BSR or the presence of gas bubbles below.*
4. *Distribution and in situ fabric of methane hydrate within sediments: Methane hydrate recovered at Site 996 occurred as massive pieces, as veins filling vertical fractures, and as rod-shaped nodules. Fine-grained hydrate was not directly observed in sediments from any of the sites, but proxy measurements, such as the chloride concentration of interstitial pore waters, indicated that fine-grained hydrates had been present prior to core recovery. Calculations indicate that sediments in the zone from 200 to 450 mbsf had a minimum average methane hydrate content of 1% and that some individual samples contained more than 8% methane hydrate.*
5. *Changes in sediment physical properties: Well-log measurements show the methane hydrate-bearing and free gas-bearing zones are associated with distinct characteristics, whereas shipboard lithologic and physical properties measurements did not indicate any differences in these sediments.*
6. *Source of gas contained in methane hydrate (local production or migration): The interstitial-water chemical data at Site 996 suggest that methane is transported upward along faults from underlying methane hydrate-bearing sediments. This is consistent with the occurrence of hydrate as vein fillings. At Sites 994, 995, and 997, shore-based isotopic and organic geochemical studies showed that the gas contained within the hydrates on the Blake Ridge are from a microbial source.*
7. *Role of methane hydrate in formation of authigenic carbonate: Fine-grained, disseminated authigenic carbonate was present in sediments at all sites. Indurated diagenetic carbonate was recovered primarily at Site 996 and but also from one horizon at Site 993. At Site 996, interstitial-water chemistry data suggests that carbonate precipitation is caused by intense microbial oxidation of methane, which results in high alkalinity and high bicarbonate concentrations. The methane arriving at the seafloor at this site is largely microbial and has a composition similar to that of the gases from Sites 994, 995, and 997. Fluids and gases venting at Site 996 have probably been transported upward from the underlying methane hydrate-bearing sediment section that slopes up around the diapir.*
8. *Chemical composition, hydration number, and crystal structure of natural methane hydrate: Methane hydrate decomposition experiments indicate volumetric ratios of gas: water range from 130 to 160 and show that gas in the hydrate is ~99% methane.*
9. *Connection between large-scale sediment failures and methane hydrate decomposition: Drilling along the top of the Cape Fear Diapir, which breeches the seafloor within the scar of the giant Cape Fear Slide, revealed soft-sediment deformation features and several biostratigraphic gaps. Both are the result of mass-transport processes associated with sediment failure and were caused by the Cape Fear Slide or emplacement of the diapir. The results of drilling did not provide any direct evidence as to whether large-scale sediment failures are related to methane hydrate decomposition.*
10. *Origin of the Carolina Rise Diapirs and their influence on associated methane hydrate: The chloride concentration of interstitial waters from sediments overlying the Cape Fear Diapir (Sites 991, 992, 993) and the Blake Ridge Diapir (Site 996) are high; the ratio of chloride to other ions suggests nearby sources of evaporitic salts. Thus, it seems likely that both diapirs are salt cored.*

4.2. Japan Nankai Trough Project (1999-2000)

In 1994 the Petroleum Council of Japan recommended that the energy resource potential of methane hydrates in the offshore of Japan should be further assessed. In response, the Ministry of International Trade and Industry (presently the Ministry of Economy, Trade and Industry; METI) developed plans for a methane hydrate exploratory drilling project named "Nankai Trough" as part of the 8th Five-Year Plan for Domestic Petroleum and Natural-Gas Resource Development by the Japanese Government. The project was led by the Japan National Oil Corporation (presently the Japan Oil, Gas and Metals National Corporation: JOGMEC) on behalf of MITI. The focus of this project was to assess the resource potential of methane hydrates inferred previously from the identification of BSRs on seismic lines from the area off the Tenryu River in Shizuoka Prefecture (Tsuji et al., 2004, 2009). This project was designed explore for both hydrates and conventional oil and gas resources in the Nankai Trough.

Scientific Objectives of the Japan Nankai Trough Project (1999-2000)

1. *Assess the energy resource potential of methane hydrates associated with known BSRs and conventional oil and gas resources in the Tertiary sediments of the Nankai Trough.*
2. *Contribute to the improvement of Japan's petroleum research and development capabilities by developing and testing new technologies and verifying applications through field testing.*
3. *Conduct advance marine research drilling, coring, and downhole logging operations to characterize the occurrence and distribution of methane hydrates in the Nankai Trough.*

The first five years of the Japan National Gas Hydrate Program culminated in 1999/2000, with the drilling of a series of closely spaced core and downhole logging holes in the Nankai Trough (Figure 4.7). Drilling of the "MITI Nankai Trough wells" began on 10 November 1999 and was completed on 5 February 2000. Drilling operations were conducted from the semi-submersible drilling rig *M. G. Hulme Jr*. The use of industry and geotechnical drilling rigs in methane hydrate research drilling programs is further reviewed "Section 5. Methane hydrate Research Drilling Platforms" of this report. The 1999/2000 Nankai Trough drilling and coring program targeted an area of a prominent BSR located about 50 km from the mouth of the Tenryu River at a water depth of 945 m. This drilling project, consisting of two site survey or "pilot" holes, the "main" research hole, and three "post-survey" wells, confirmed the existence of methane hydrate in the intergranular pores of turbiditic sands based on the analysis of downhole logging data, and observations from both conventional and pressure cores (reviewed by Tsuji et al., 2004, 2009; Figure 4.8). Downhole operations during the MITI Nankai Trough drilling program included LWD logging of the second pilot hole, wireline logging in two of the post-survey wells, and pressure coring in both the main hole and the second post-survey well. The main hole was also cored, with conventional wireline core tools, over the interval from 1,110 to 1,272 mbsf. The main hole was also wireline logged and VSP surveys (zero-offset and walk-away) were conducted in the main hole to a depth of 1,555 mbsf.

A newly developed pressure and temperature controlled coring system (PTCS) was deployed a total of 39 times (in the main hole and the second post-survey well) during the MITI Nankai Trough program, with an estimated core recovery ranging from 37 to 47 percent. The development and use of pressure core systems to study methane hydrates is further reviewed in "Section 6. Pressure Core Tools and Lab Developments" of this report.

At the site of the 1999/2000 MITI Nankai Trough wells (Figure 4.8), four hydrate-bearing sand-rich intervals (interpreted as turbidite fan deposits) were recognized. Methane hydrate was determined to fill the pore spaces in these deposits, reaching saturations as high as 80% in some layers. Individual hydrate-bearing sand layers were less than 1-m-thick, with the cumulative thickness of the hydrate-bearing sands totaling about 12 to 14 m.

Scientific Conclusions and Contributions of the Japan Nankai Trough Project (1999-2000)

1. The presence of extensive BSRs in this area of the Nankai Trough was confirmed as identified from seismic surveys carried out as a part of MITI's domestic geophysical surveys, and the site survey for the MITI Nankai Trough well drilling program.
2. Drilling, coring, and downhole logging operations under the 1999/2000 MITI Nankai Trough drilling program confirmed the presence of methane hydrate in the Nankai Trough.
3. Confirmed the existence of methane hydrates in the intergranular pores of turbiditic sands as a pore-space hydrate based on LWD, wire-line logging, and coring by both conventional methods and using the pressure core system (PTCS) developed by JNOC.
4. A new advanced pressure-temperature core system (PTCS) was developed and deployed for the first time under this project.
5. The technical and operational success of the 1999/2000 MITI Nankai Trough drilling program led to the proposal and inauguration of a 16 year, three-phase hydrate research program that has become known as MH21 and is further discussed later in this report.

4.3. ODP Leg 204 (2004)

ODP Leg 204 to Hydrate Ridge, located on the Cascadia continental margin offshore Oregon, was the first deep-sea drilling expedition dedicated to understanding methane hydrate processes in accretionary complexes (Tréhu et al., 2004). ODP Leg 204 was the first time that (1) digital infrared scans of core temperature were systematically used for the identification of methane hydrate samples for further study, (2) hydrate-bearing cores were recovered and logged at in-situ pressure conditions, and (3) ODP Leg 204 featured for the first time the acquisition of LWD data prior to coring at a given site, providing an initial comprehensive estimate of methane hydrate distribution that was used to design the subsequent coring program. The development of new pressure coring capabilities are further reviewed in "Section 6. Pressure Core Tools and Lab Developments" of this report. The technical specifications of the *JOIDES Resolution* and the science labs on the ship are reviewed in "Section 5. Methane Hydrate Research Drilling Platforms" of this report.

Scientific Objectives of ODP Leg 204 (2004).

1. Assess the stratigraphic and structural controls on hydrate development. Test the hypothesis that the distribution, texture, and chemistry of hydrate and related pore fluids beneath Hydrate Ridge are different compared to the slope basin.
2. Understand the formation of massive hydrate deposits near the seafloor and obtain constraints on the rate of hydrate formation, the depth extent of the massive hydrate, and mechanisms for transporting methane-rich fluids to the seafloor.
3. Obtain a high-resolution set of pore water samples, with the goal of using the dissolved chloride and the isotopic composition of these waters to constrain models of formation and dissociation of methane hydrates on this margin.
4. Determine the geochemical impact of methane hydrate formation and dissociation on the geological record by characterizing the isotopic composition of the pore fluids and carbonates associated with methane hydrates to provide the framework needed to unravel the history of methane hydrate formation and dissociation recorded in benthic foraminifers and authigenic carbonate phases.

5. Obtain better estimates of methane hydrate and free gas volumes, based on geophysical mapping and modeling techniques, which is needed to better estimate the global abundance of hydrate and to evaluate its role in climate change and its potential for economic exploitation.
6. Determine the mechanical, hydrological, and dynamic properties of hydrate-bearing sediment to better constrain models of slope instability induced by earthquakes, changes in sea level, or changes in ocean temperature.
7. Characterize the biological communities associated with the occurrence of methane hydrate and underlying free-gas zones on Hydrate Ridge.

A total of nine drill sites were established during ODP Leg 204 (Figure 4.9). The sites are located in water depths of 780–1,210 m near the southern part of Hydrate Ridge. A three-dimensional (3-D) seismic data volume provided the tectonic and stratigraphic information needed for the reconstruction of the geologic history Hydrate Ridge (Chevallier et al., 2006). LWD data acquired at the beginning of the leg provided initial estimates of the hydrate distribution as inferred from electrical resistivity anomalies. These estimates were used to plan the subsequent coring program. The use of LWD log data on Leg 204 to characterize the in-situ nature of methane hydrates and to guide the coring portion of the leg are further reviewed in "Section 7. Downhole Well Log Analysis of Methane Hydrate" of this report

The presence of methane hydrate was confirmed at most of the sites drilled during ODP Leg 204 (Figure 4.10). The amount of methane hydrate present, when averaged over the entire methane hydrate stability zone (Figure 4.10), is generally estimated to be ~2% of the sediment pore space (Tréhu et al., 2004). Methane hydrate concentrations increases to ~10% near methane vents at the southern summit of the ridge, where massive methane hydrate forms in the upper 20–30 mbsf and occupies 20%–30% of the total volume (i.e., bulk volume).

As discussed in the methane hydrate petroleum system review presented earlier in this report, during ODP Leg 204, two distinct modes of methane hydrate formation were recognized. In the first, highly concentrated methane hydrate occurrences near vent sites form where gas is transported from greater depth within the accretionary prism along discrete conduits (Torres et al., 2004a, 2004b). At South Hydrate Ridge it appears that gas is migrating from the deeper parts of the accretionary prism along a coarse-grained stratigraphic conduit (Tréhu et al., 2004), labeled Horizon A in Figure 4.10. This mechanism focuses gas from a large region in the subsurface to seafloor vents. Geochemical data indicate that most of the gas that forms the summit hydrate deposit has migrated from greater depth and has either a thermogenic or altered biogenic character. In the other mode of methane hydrate formation, 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 by advective fluid flow.

Scientific Conclusions and Contributions of ODP Leg 204 (2004).

1. Multiple proxies for the presence of methane hydrate and the determination of hydrate concentrations were determined to be consistent and complementary during ODP Leg 204. They indicated the presence of methane hydrate at all of the sites established during the drilling leg. Useful proxies included electrical resistivity anomalies measured downhole with LWD and wireline logging, low-temperature anomalies measured with IR camera scans immediately after cores came on deck, *low chloride concentration measured in interstitial waters, anomalously low C_1/C_2 ratios measured in vacutainer samples, and gas volumes measured from pressure core samples.*

2. *The strong seismic reflector, Horizon A, was determined to be an ash-rich layer that serves as a fluid pathway transporting methane and other hydrocarbons from the accretionary complex to the summit of Hydrate Ridge.*
3. *Near the southern summit of Hydrate Ridge, very high concentrations of methane hydrate are present from the seafloor to about 30 meters below seafloor (mbsf), and they contain significant amounts of C_{2+} hydrocarbon gases in addition to methane.*
4. *High chloride concentrations near the summit of Hydrate Ridge indicate that hydrate formation is recent and rapid; and necessitates gas transport in the gas phase.*
5. *Detailed analysis of physical properties and IR thermal anomalies combined with lithologic description demonstrates that methane hydrates are concentrated in the coarse-grained layers in ash-rich turbidite sections such as Horizon B at Sites 1244 and 1246.*
6. *In a slope basin east of Hydrate Ridge, at Site 1251, methane hydrate concentration is quite low, with the probable exception of a 12-m-thick zone of relatively high concentration near the base of the GHSZ.*
7. *All of the sites established during ODP Leg 204 show an abrupt decrease in C_1/C_2 gas geochemistry ratio at the BSR except for Site 1252 (where there is no BSR). Several different mechanisms have been proposed to explain this observation. It is most likely related in part to the preferential incorporation of ethane into the hydrate structure.*
8. *Analysis of pressure core data and seismic modeling revealed only limited evidence of significant free-gas volumes below the BSR on north Hydrate Ridge.*
9. *Several different geochemical mixing and fractionation signals provide constraints on fluid flow and methane hydrate dynamics, which have shown the accretionary complex is permeable and is a source of fresh water that has originated from dehydration of subducted oceanic crust and sediment. ODP Leg 204 provided a systematic transect across the margin that can be integrated with structural information to constrain depth and volume of dewatering and the mechanism of fluid expulsion.*
10. *ODP Leg 204 demonstrated the need for a multidisciplinary "hydrocarbon systems" approach toward modeling, integrating, and interpreting a wide range of geological, biogeochemical, and geophysical data in order to understand the formation and evolution of marine methane hydrate deposits and to predict methane hydrate distribution elsewhere.*

4.4. Japan Tokai-oki to Kumano-nada Project (2004)

After the success of the 1999-2000 Nankai Trough Project, in 2001 METI launched new project entitled "Japan's Methane Hydrate R&D Program," operated by the Research Consortium for Methane Hydrate Resources in Japan (also known as MH21), to evaluate the resource potential of deepwater methane hydrates in the Nankai Trough area much like the goals of the previous Nankai Trough project. But, this project is intended to go much further and promote the technical development and recovery of methane hydrate, and to provide a long term stable energy supply to Japan. On behalf of METI, the Japan Oil Gas and Metals National Corporation (JOGMEC) and the Agency of Industrial Science and Technology (AIST) has developed a highly integrated methane hydrate research and development program including both basic research and field studies. This program is now built around an 18-year plan to be completed in 2018 (initially planned as a 16-year program but the goals of this effort were revised in 2008).

Scientific Objectives of the Japan Tokai-oki to Kumano-nada Project (2004) and the MH21 program.

1. Understanding the conditions and features of methane hydrate occurrence around Japan.
2. Estimating the amount of gas stored in hydrates.
3. Assess the economic viability of methane hydrate fields offshore Japan.
4. Conduct methane hydrate production tests in selected fields.
5. Developing technologies for commercial production.
6. Exploit methane hydrate resources without adversely affecting the environment.
7. The specific objectives of the 2004 Tokai-oki to Kumano-nada drilling project, included (a) verify the seismic indicators for the presence of methane hydrate, (b) conduct LWD logging to identify potential hydrate occurrences and to guide coring and other project activities, (c) conduct wirelne logging to acquire data (such as NMR and acoustic log data) that cannot be easily collected with LWD logs, (d) conduct coring to visually observe the growth habit and in-situ nature of methane hydrates, (e) collect core samples from the surface through the entire methane hydrate stability zone in order to understand the sedimentologic controls on the origin of methane hydrates, and (f) to obtain high quality methane hydrate samples for laboratory analysis.

Since the first research Nankai Trough drilling efforts in 1999/2000, a series of seismic surveys were conducted in the Nankai Trough area in 2001 and 2002, and a multiwell drilling program was successfully carried out in early 2004. In the 2004 drilling program, also known as the Tokai-oki to Kumano-nada Project, sixteen sites were drilled and significant methane hydrate-bearing sands were cored and analyzed with various downhole geophysical logging tools. Efforts to assess the amount of methane hydrate stored in the Nankai Trough continue, with field production testing in 2012/2013 (as reviewed later in this report) and development of the technologies needed for commercial production of hydrates by 2018. The Japan National Gas Hydrate Program is also notable for its direct participation and leadership of all three phases of the Canadian Mallik methane hydrate research program and the Iġnik Sikumi project on the North Slope of Alaska (as reviewed later in this report).

The multi-well "METI Tokai-oki to Kumano-nada" drilling project was successfully carried out in early 2004 (Fujii et al., 2009; Tsuji et al., 2009). A total of sixteen sites (32 wells) were drilled in water depths ranging from 720 to 2,030 m (Figure 4.7). Drilling operations commenced on 22 January 2004 and were completed 122 days later on 18 May 2004. The ship made six port calls during this project. A total of 16 wells were drilled as LWD holes, two wells were instrumented to acquire highly accurate temperature data (Takahashi and Tsuji, 2005; Fukuhara et al., 2009), two wells were wireline logged, and 12 wells were cored (including conventional wireline and PTCS pressure cores), and two wells (including one horizontal well) were cased to test various completion technologies. All of the drilling operations for this project were conducted from the scientific drilling ship *JOIDES Resolution.*

The LWD leg was the single largest element of the program, taking a total of 35.1 days to drill 16 dedicated LWD holes. As described, LWD logging not only provided general data and information on hydrates, but it also provided a guide for selecting locations, core targets, and survey intervals for the subsequent parts of the project. In the two wells that were wireline logged, the tools were conveyed to the bottom of the hole through the drill pipe much like standard ODP and IODP operations (see "Section 7. Downhole Well Log Analysis of Methane Hydrate" of this report for more information on methane hydrate related well logging operations). The conventional wireline coring tools used from this expedition included the APC and XCB systems, which were loaned to the project by IODP. The PTCS pressure core system is deployed during both 1999/2000 and 2004 Nankai Trough expeditions is further described in “Section 6. Pressure Core Tools and Lab Developments” of this report.

One of the primary goals of the 2004 drilling program was to test the relation between BSRs and methane hydrate occurrences and to obtain data needed to calibrate seismic responses to the methane hydrate deposits. Tsuji et al., (2004, 2009) report that there is no clear correlation between the volume and occurrence of methane hydrate and the nature of the underlying BSR and that downhole LWD provided the most useful data for detecting methane hydrate. Based on the analysis of both the available downhole log data and core observations, three different types of methane hydrate occurrences were identified: (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 massive methane hydrate occurrences were also observed at Sites 1 and 2, with pore-filling hydrates at Sites 4 and 13 (Figure 4.11). The recovered hydrate-bearing sand layers were described as very-fine- to fine-grained turbidite sand layers measuring several centimeters to a meter in thickness (Fujii et al., 2009). However, the gross thickness of the hydrate-bearing sand layers at Site 4 is as much as 50 m (282-332 mbsf). In addition, the zone dominated by elevated “spiky” resistivities at Site 4 (Figure 4.11), within the depth interval from about 110 to 265 mbsf, is interpreted to also contain methane hydrate. The gross thickness of the hydrate-bearing sand layers at Site 13 is as much as 100 m (95-197 mbsf). Facies analysis indicated that the hydrate-bearing sands were deposited in distributary channels to distal lobes within a submarine fan system. Analysis of pressure cores and downhole log data show that average methane hydrate saturations in the cored sand layers ranged from 55 to 68%, with the average sediment porosities ranging from 39 to 41% (Fujii et al., 2009). The geochemical analysis of samples collected during both Nankai Trough coring programs indicate that the gas within the recovered methane hydrates was derived from a microbial source with methane carbon isotopic values ranging from –95.5 to –63.9 ‰ (PDB) and the $C_1/(C_2+C_3)$ ratios ranging from 4,392 to 5,365 (Waseda and Uchida, 2004).

Fujii et al. (2008) have also reported on a resource assessment of methane hydrates in which they estimated that the volume of gas within the hydrates of the eastern Nankai Trough at about 1.1 trillion cubic meters (about 40 trillion cubic feet), with about half concentrated in sand reservoirs.

Scientific Conclusions and Contributions of the Japan Tokai-oki to Kumano-nada Project (2004) and the MH21 program.

1. *Sixteen sites were drilled at water depths ranging from 720 m to 2,030 m and the hydrate-bearing sediments were easily identified with resistivity well logs at most of the sites where BSRs were detected.*
2. *The occurrence of pore-filling methane hydrate in turbidite sand sections was confirmed from the analysis of downhole log and cores as collected during the Tokai-okito Kumano-nada drilling project in the Nankai Trough.*
3. *The existence of high velocity zones within the methane hydrate stability zone may be the best indication of thick methane hydrate accumulations which may be good targets for exploration and production testing.*
4. *Although most of the methane hydrate bearing sediments identified in the wells were associated with BSRs, some of the hydrate saturated turbidite sands occurred well above the base of methane hydrate stability zone did not have obvious BSRs below them.*
5. *It was shown that BSRs are not always good indicators of concentrated methane hydrate occurrences and cannot be used to accurately predict in-situ methane hydrate volumes.*

6. Further technical refinements of the PTCS core system allowed for the improved pressure core recovery and the first measurement of core physical properties under "in-situ pressure conditions".
7. Precise in situ temperature measurement system (DTS) was successfully developed and deployed at the beginning of the drilling campaign. The temperature profile and the temperature gradient through the hydrate-bearing zone were estimated in a "quasi steady-state condition".
8. The acquisition and recovery of high quality downhole log data, new seismic data, and both conventional and pressure cores have allowed for the probabilistic estimate of the amount of gas resources associated with methane hydrates in the Nankai Trough. These same data have also been used to develop computer simulations to predict the production characteristics of methane hydrates as inferred to occur in the Nankai Trough.

4.5. Gulf of Mexico JIP Leg I (2005)

The first direct evidence for the presence of methane hydrates in the Gulf of Mexico was obtained in 1970 on Deep Sea Drilling Project (DSDP) Leg 10, when gas-rich sediment cores were recovered from the deep-water Sigsbee Plain and the Gulf of Campeche (Shipboard Scientific Party, 1973). The occurrence of methane hydrates in the Gulf of Mexico was confirmed during DSDP Leg 96, when numerous samples were recovered from sub-bottom depths ranging from 20 to 40 mbsf in the Orca Basin (Sites 618 and 618A), which is located about 300 km south of Louisiana beneath about 2,000 m of water (Shipboard Scientific Party, 1986). Near-surface (0-5 m) marine sediment cores provided evidence of methane hydrate on the Louisiana continental slope (reviewed by Brooks et al., 1986, 1994). These seabed methane hydrate deposits formed as nodules, interspersed layers, and as solid masses in association with apparent vent related fracture systems at water depths ranging from 530 to 2,400 m.

The Chevron-led Gulf of Mexico Gas Hydrate Joint Industry Project (JIP), a consortium of industry participants and government agencies in partnership with the DOE, was formed in 2001 to (1) study hazards associated with drilling hydrate-bearing sediments, (2) develop and test geological and geophysical tools to predict and characterize the occurrence of methane hydrate, and (3) sample hydrate-bearing sediments to obtain physical data needed to analyze marine methane hydrate resource and production issues. In 2005, scientific drilling, coring, and downhole logging was conducted to assess hydrate-related hazards in fine-grained sediments with low concentrations of methane hydrate (Claypool, 2006; Ruppel et al., 2008). This expedition, which was named the Gulf of Mexico Gas Hydrate Joint Industry Project Leg I (JIP Leg I), targeted two deep-water locations in the Atwater Valley and Keathley Canyon areas of the Gulf of Mexico (Figures 4.12, 4.13, and 4.14).

Scientific Objectives of Gulf of Mexico JIP Leg I (2005) and the Gulf of Mexico Gas Hydrate Joint Industry Project

1. The development of borehole stability models for hydrate-bearing sediments.
2. Make laboratory measurements of the physical properties of methane hydrate-bearing sediments.
3. Develop and refine existing techniques for processing industry 3D seismic data to constrain methane hydrate saturations.
4. Construct laboratory equipment that can make physical property measurements on cores that have never been removed from in-situ pressure conditions.
5. The specific objectives of the 2005 Gulf of Mexico JIP Leg I were to conduct downhole,

logging, geophysical surveys, and sediment coring to obtain the geologic geophysical, geochemical, and engineering data needed to develop (1) borehole stability models for hydrate-bearing sediments, (2) to obtain physical property measurements of hydrate-bearing sediment core samples, (3) understand the geologic controls on the occurrence of methane hydrate in the Gulf of Mexico.

The 2005 JIP drill sites are located in two contrasting geologic settings in the northern part of the Gulf of Mexico at a water depth of about 1,300 m. The Keathley Canyon (KC) drill sites were located near the junction of four minibasins in a region of salt tectonics (Figure 4.13). Before drilling, methane hydrate was speculated to exist near the base of the hydrate stability zone, because a BSR was observed on the available seismic profiles. Atwater Valley (AT) Block 13 and 14 drill sites are on the floor of the Mississippi Canyon in an area with several prominent seafloor mounds that appear to be related to the venting of brines and natural gas that may have created deposits of methane hydrate (Figure 4.14).

The drilling expedition was conducted from the semi-submersible drillship *Uncle John* between 17 April and 22 May 2005. Complete operational reviews for JIP Leg I are provide in a project summary by Claypool (2006). The technical specifications of the *Uncle John* and the science labs as established on this industry drillship during JIP Leg I are further reviewed in "Section 5. Methane Hydrate Research Drilling Platforms" of this report. JIP Leg I started with the acquisition of downhole LWD data from two dedicated holes at AT13/14 (AT13#1 and AT14#1) and one hole at KC151 (KC151#2) (Figure 4.15). Holes AT13#2, ATM#1 (Mound F site), ATM#2 (Mound F site), and KC151#3 were established for coring and wireline logging. AT13#1 and AT13#2 were designated as reference holes to provide background information about the sedimentary section away from the mud mounds, while AT14#1 was drilled in the flank of Mound F, where seismic data implied the upward migration of fluid has significantly upwardly warped the BSR-like feature at this site. KC151#2, the dedicated LWD hole at the KC151 site, was located about 10 m from the KC151#3 core hole, which was also used for wireline logging and the acquisition of a VSP survey. Note the KC151#1 hole was sited but never drilled.

The downhole logging report within the JIP Leg I summary (Claypool, 2006) provides an exhaustive review of the LWD and wireline logging programs, including information on the goals, the tools deployed, the problems encountered, and the preliminary scientific findings. A variety of coring devices, as provided by the drilling contractor Fugro, were deployed during JIP Leg I. Cores were acquired using two conventional wireline core systems: Fugro Hydraulic Piston Corer (FHPC) and the Fugro Corer (FC) a hammer drive system for taking cores in more highly indurated lithologies. Two pressure coring systems were also deployed: The HYACE Rotary Corer (HRC) and the Fugro Pressure Corer (FPC). However, only five of the 18 pressure cores attempted during the expedition successfully recovered sediments at pressure. The development of pressure coring and the use of downhole logs to study the occurrence of methane hydrate in nature are further reviewed in "Section 6. Pressure Core Tools and Lab Developments" and "Section 7. Downhole Well Log Analysis of Methane Hydrate" of this report.

Although methane hydrate was not physically recovered from the Keathley Canyon core hole, other indicators of methane hydrate, such as elevated downhole-measured electrical resistivities, indicates the probable presence of methane hydrate in the KC151#2 well within the depth interval of 220-300 mbsf (5,059-5,322 ft below sea surface) (Figures 4.13 and 4.15) (Collett, 2005). Using the downhole measured resistivities and the Archie relation to quantify the amount of methane hydrate, Lee and Collett (2008) estimated that the anomalously high resistivity interval in KC151-2 contained a significant amount of methane hydrate, with hydrate saturations averaging about 10% and surpassing 40% in several thin intervals. Sinusoidal patterns in the downhole resistivity-at-the-bit images from the

KC151#2 hole further indicate that this interval from 220-300 mbsf contains numerous, near-vertical structures interpreted as fractures (Collett, 2005; Hutchinson et al., 2008a). Hydrate-filled fractures are the most likely explanation for the localized elevated concentrations of methane hydrate. A slight downhole-measured resistivity anomaly was detected at the depth of the expected BSR (392 mbsf) in the KC151#2 well. Lee and Collett (2008) interpreted a small reduction in the Archie-derived water saturations at the projected depth of the BSR, as indicating low saturations of methane hydrate and free gas, which is consistent with the BSR appearing as a weak reflection in the Keathley Canyon area (Hutchinson et al., 2008a).

Analysis of downhole well log data from the two JIP Atwater Valley wells shows (1) little evidence of significant methane hydrate, other than several thin, possibly stratigraphically-controlled methane hydrate-bearing intervals (Figure 4.14); and (2) downhole logs and core data from these wells further suggest the presence of a complex pore water fluid regime, with variable well log inferred pore water salinities (Collett, 2005). Geochemical analyses of pore fluids from both pressurized and nonpressurized cores in the Atwater Valley wells also indicate the presence of limited low concentrations of methane hydrates (Ruppel et al., 2008). However, pore fluid salinity/chlorinity data indicate higher methane hydrate saturations as much as 7-9% in a series of short sediment cores (<50 mbsf) taken from the crest of one of the apparent vent site mounds in Atwater Valley.

Scientific Conclusions and Contributions of Gulf of Mexico JIP Leg I (2005).

1. *JIP Leg I drilling, coring, and downhole logging operations were safely conducted in the presence of several BSRs and other methane hydrate related features without disrupting the seafloor, drilling operations, or drill systems.*
2. *JIP Leg I coring and logging data imply that local sediment permeability plays the dominant role in controlling the distribution and concentration of methane hydrate in fine-grained sediments.*
3. *At KC151, the enhanced local permeability within the inferred hydrate-bearing interval is in the form of both sand-rich sediments layers and fractures.*
4. *Analysis of logging data from Hole KC151#2 yield methane hydrate saturations as high as 20% within a fractured inferred methane-hydrate-bearing stratigraphic section.*
5. *Comparison of data from holes drilled at Mound F (ATM#1 and ATM#2) shows the area of influence by enhanced fluid flow beneath the mound to be relatively limited.*
6. *Analysis of pore fluids collected from cores recovered during JIP Leg I infer the occurrence of methane hydrate at all of sites established during the expedition. At the AT sites, methane hydrates were mostly concentrated in near-surface sediments of mounds; whereas at the KC sites methane hydrate was concentrated at greater depths in highly fractured silty-clayey sediments.*
7. *Analysis of gas from sediments cores reveal that methane is the predominant gas present at both the AT and KC sites as evidenced by isotopically light methane and very low concentrations of $C_2 – C_5$ hydrocarbons.*
8. *Post-expedition modeling proved that some hazards associated with operations in areas characterized by shallow methane hydrates and/or free gas can be anticipated and avoided by using such models to guide drilling operations.*
9. *JIP Leg I acquired data that validated the approach of inferring methane hydrate distribution and concentrations through the analysis of industry 3D seismic data.*

10. JIP Leg I marked the first time that seismic, electrical, and strength properties were recorded on sediment cores that had been retrieved and maintained at in-situ pressure conditions.

The next phase of the Gulf of Mexico JIP was extended to coarser grained sediments with much higher expected methane hydrate concentrations. In the spring of 2009, the Gulf of Mexico JIP conducted exploratory drilling and LWD operations in the Gulf of Mexico, which are reviewed in "Section 4.11. Gulf of Mexico JIP Leg II (2009)" of this report.

4.6. IODP Expedition 311 (2005)

The existence of methane hydrate on Canada's west coast was first suggested by the occurrence of widespread BSRs observed on reconnaissance multichannel seismic reflection surveys (Hyndman and Spence, 1992). Research drilling and coring during ODP Leg 146 (Figure 4.9) (Shipboard Scientific Party, 1994) and IODP Expedition 311 (Figures 4.16 and 4.17) (Riedel et al., 2006) have yielded the data needed to further characterize methane hydrate accumulations along the Cascadia continental margin (reviewed by Riedel et al., 2009).

ODP Leg 146 (Shipboard Scientific Party, 1994) was not dedicated to the study of methane hydrates. It was designed to examine fluid movement in the Cascadia continental margin and to provide well-constrained estimates of the volume of fluid associated with accretionary sedimentary wedges (Figure 4.9). In addition, the presence of distinct BSRs on the Cascadia margin also provided an opportunity to examine the potential interrelation between the occurrence of natural methane hydrates and BSRs. Similar to the observations from the Blake Ridge on ODP Leg 164, the presence of methane hydrates at ODP Leg 146 (Site 889) was inferred on the basis of gas-rich cores, low interstitial water chloride concentrations, and low temperature measurements in the recovered cores (Shipboard Scientific Party, 1994). Observed chloride anomalies were used to estimate the amount of methane hydrate that occurs at Site 889 by calculating the amount of interstitial water freshening that can be attributed to methane hydrate dissociation. The estimated volume of sediment porosity occupied by methane hydrate in the recovered cores ranged from a minimum of about 5% immediately below the sea floor to a maximum of about 39% near the bottom of well log inferred methane hydrate occurrence at Site 889 (Spence et al., 1995).

To further constrain our understanding of the formation of methane hydrates in accretionary complexes, IODP Expedition 311 established a transect of four sites (U1325, U1326, U1327, and U1329) across the northern Cascadia margin (Figure 4.18). The four drill sites along the transect represent different stages in the evolution of methane hydrate across the margin from the earliest occurrence on the westernmost first accreted ridge (Site U1326) to its final stage at the eastward limit of methane hydrate occurrence on the margin in shallower water (Site U1329). In addition to the transect sites, a fifth site (U1328) was established at a cold vent with active fluid and gas flow. The specific objectives of this expedition were to test methane hydrate formation models and constrain model parameters, especially those that account for the formation of concentrated methane hydrate occurrences through upward transport of methane-bearing fluids.

Scientific Objectives of IODP Expedition 311 (2005).

1. *Obtain high-quality data on the concentration, vertical distribution, and regional variation of methane hydrate and free gas in an accretionary prism.*
2. *Determine the vertical fluid advection and methane fluxes through the sediment section as a function of landward distance from the deformation front.*

Expedition 311 had an ambitious drilling program including extensive pressure coring to recover methane hydrate at in-situ conditions. Also because of the unstable nature of methane hydrate at surface conditions, and of the strong response of some logging tools such as resistivity and acoustic logs to the presence of methane hydrate, logging was a critical component of the expedition. The first part of the expedition was dedicated to LWD logging, in order to identify intervals likely to contain methane hydrate during the coring phase of the project, with a specific goal to identify where pressure coring tools should be deployed. The coring phase also included the acquisition of wireline log and VSP data in order to further characterize the physical properties of the sites established during Expedition 311. The evolution of pressure coring capabilities and along with the development of specialized laboratory equipment for analysis of pressure cores recovered during Expedition 311 are further reviewed in "Section 6. Pressure Core Tools and Lab Developments" of this report.

IODP Expedition 311 at sea operations began on 20 September 2005 with the spudding of the first LWD hole at Site U1325. The LWD operations were completed on 26 September 2005 with the drilling and logging at Site U1329. The next four weeks of the Expedition 311 dealt with coring and wireline logging operations at all of the sites (U1325, U1326, U1327, U1328 and U1329) established during the LWD phase of the project. Expedition 311 officially concluded on 28 October 2005.

As described above, Site U1326 is the westernmost site of the IODP Expedition 311 transect (Figure 4.17), located on the first uplifted ridge of the accretionary wedge. The presence of methane hydrate at Site U1326 was suggested by the occurrence of a wide-spread BSR. Downhole measured resistivity and acoustic logs also indicate the presence of methane hydrate. The interstitial water chlorinity profile from Site U1326 shows abundant low chlorinity anomalies associated with methane hydrate extending to 270 mbsf. Site U1325 is located within a major slope basin that developed eastward of the deformation front behind the first ridge of accreted sediments. Downhole log data suggest that methane hydrate is concentrated in thin reservoir-quality sand layers within an interval between 173 and 240 mbsf close to the base of the methane hydrate stability field. The logs also show that the methane hydrate is heterogeneous, composed of alternating layers of methane hydrate–saturated sands and clay-rich layers with little to no methane hydrate. This is in general agreement with the marked freshening of the interstitial waters observed in the sampled sand layers. Site U1327 is located near ODP Leg 146 Sites 889/890, approximately at the mid-slope of the accretionary prism (Figure 4.17). Pre-coring LWD data showed a thick section with consistently high resistivities from 120–138 mbsf. The data indicate that methane hydrate fills as much as 50% of the pore volume in this interval. However, the same interval was penetrated in the adjacent core holes, Hole U1327C and Hole U1327D, at much greater depths and with lower estimated methane hydrate saturations. This demonstrates large intra-site variability in methane hydrate content that is probably controlled by lithostratigraphic changes or structural complexities. Site U1329 represents the eastern limit of methane hydrate deposits on the northern Cascadia margin. A faint BSR was identified in seismic data at an approximate depth of only 126 mbsf. Neither the downhole log or core data show any evidence of significant methane hydrate concentrations at this site.

Site U1328 is located within a cold vent field consisting of at least four vents. The most prominent vent, referred to as Bullseye vent, was the target for this site. Site U1328 is different from all of the other sites visited during IODP Expedition 311 in that it represents an area of focused fluid flow. The most striking feature in the downhole logs from Site U1328 is the occurrence of high resistivity (>25 ohm-m) layers in the upper ~40 mbsf. Borehole resistivity image logs from the near-surface high-resistivity interval reveal steeply dipping fractures exhibiting high resistivity values, probably the result of methane hydrate. These steeply dipping fractures may act as gas migration conduits that feed the surface vent at this site and are the reservoir (void-space) for the observed fractured dominated methane hydrate occurrence. Massive methane hydrate and methane hydrate-bearing fractures were also observed in the cores from near the seafloor. Observations from Site U1328 suggest a complex, high-variable network of fractures channel fluid and gas to the seafloor where it forms a massive in-situ hydrate cap in the uppermost ~40 mbsf, consistent with previous geophysical observations at Bullseye vent.

In previously published models of methane hydrate formation in an accretionary margin, the highest concentrations of methane hydrate were expected to occur near the base of the methane hydrate stability zone above the BSR, with concentrations gradually decreasing upward as a result of pervasive fluid advection from overall tectonically driven fluid expulsion. The results of Expedition 311, however, show that this model is too simple and that there are additional controlling factors. One of the most significant findings of the Expedition 311 coring and logging programs included the observation that methane hydrate is formed mainly within the sand-rich reservoir-quality formations and is virtually absent in the fine-grained and clay-rich sediments. Thus, the presence of methane hydrate is mainly controlled by lithology, which was reviewed in the methane hydrate petroleum system discussion presented earlier in this report. It was also determined that the existence and physical nature of BSRs are generally unrelated to the concentration of methane hydrate within the pressure-temperature stability zone and provides only a first-order indicator for the potential presence of methane hydrate. All sites drilled during IODP Expedition 311 showed a high degree of heterogeneity in methane hydrate occurrence.

In comparison, the results of IODP Expedition 311 are complemented by ODP Leg 204, which targeted a segment of the Cascadia margin (Hydrate Ridge) that is characterized by fine-grained sediments and low methane hydrate saturations, in contrast to the coarse-grained sediments encountered during IODP Expedition 311, which contained higher concentrations of methane hydrates.

Scientific Conclusions and Contributions of IODP Expedition 311 (2005).

1. *Indirect evidence of the presence of methane hydrate acquired during Expedition 311 included increased electrical resistivities and P-wave velocities on downhole logs, low chlorinity and low salinity pore-water anomalies, numerous infrared cold spots, and decreases in void gas C_1/C_2 ratios, as well as moussey and soupy sedimentary textures in recovered cores. Methane hydrate was also observed directly in recovered cores.*
2. *Methane hydrate typically occupy <5% of the pore space throughout the GHSZ along the transect; however, hydrates preferentially forms in coarser-grained turbidites, resulting in very high local hydrate concentrations. In contrast, though low concentrations of methane hydrate are observed in the fine-grained sediments near the BSR at the cold vent Site U1328, high hydrate concentrations occur within fracture-controlled fluid and gas migration conduits and near the seafloor.*
3. *The combined observations along the Expedition 311 transect of sites show that*

methane hydrate occurs within coarser-grained turbidite sands and silts. The occurrence of methane hydrate appears to be controlled by several factors, including (1) local methane solubility linked with pore-water salinity, (2) fluid and gas advection rates, and (3) the availability of suitable host material such as coarse-grained sediments.

4. *Fluid expulsion occurs at non-uniform rates and produces variable pore fluid geochemistry along the transect. At sites near the deformation front, the pore fluids are slightly more saline than seawater; primarily influenced by in situ ash alteration to hydrous silicates (mostly clay minerals). In contrast, the landward portion of the margin shows freshening of pore fluids with depth, from advection/diffusion of fresher fluids generated at greater depth primarily by dehydration of silicates, such as the smectite-to-illite transition.*
5. *Although seismic data from the Expedition 311 transect dominated by a widespread BSR, by far the largest concentrations of methane hydrate are observed well above the base of the methane hydrate stability zone, at a point where the amount of methane in the pore fluid exceeded the local methane solubility threshold. This condition was most evident at Sites U1326 and U1327, where methane hydrate was observed in sections several tens of meters thick at shallow depths of ~100 m and at concentrations exceeding 80% of the pore volume.*
6. *Coring and downhole logging at the cold vent Site U1328, yielding evidence of methane-hydrate and high concentrations, where beds containing massive forms of methane hydrate occurred within the top ~40 m of the seafloor. Methane hydrates along with the cold vent itself at Site U1328 is the result of focused fluid and gas migrating upward along the underlying fault systems.*

4.7. Malaysia Gumusut-Kakap Project (2006)

The Gumusut-Kakap deepwater oil and gas field, located off Malaysia, has been the focus of development activity since 2004/2005 (Figure 4.19). A key element of the field development plan has been the assessment of numerous geohazards, including issues raised by the widespread occurrence of methane hydrates in the near surface sediments. Prior to exploration drilling, methane hydrates were expected to occur overlying the deeper Gumusut-Kakap prospects due to the appearance of a laterally continuous BSR on regional seismic data (Hadley et al., 2008). The depth of the BSR suggested the base of methane hydrate stability at approximately 150 to 180 mbsf. LWD data from early delineation wells indicated that the sediments within the methane hydrate stability zone are dominantly hemi-pelagic muds with numerous resistivity anomalies of up to 20 ohm-m that occurred in all wells, and at various depths. In two wells, initial estimates of methane hydrate saturations using the Archie's relationship suggested the presence of intervals, roughly 150 m thick, with methane hydrate saturations ranging from 20% to 50% and greater (Hadley et al., 2008). In several wells, these anomalies extended to depths as great as 245 mbsf, well below the depth of the BSR and therefore the presumed depth of the base of methane hydrate stability.

Various authors (reviewed by Collett and Dallimore, 2002) have reported drilling hazards attributed to the presence of methane hydrate. However, a longer-term, and perhaps more difficult to constrain risk was the potential for hydrate dissociation and sediment-wellbore instability caused by the heating of sediment around production wells due to the sustained production of deeper, warmer fluids. With these concerns, a combined geohazard and geotechnical investigation was executed by Fugro

Geosciences Malaysia from the *SRV Bavenit* in 2006 to provide data for the evaluation of geohazards and the design of the development infrastructure at Gumusut-Kakap.

Scientific Objectives of the Malaysia Gumusut-Kakap Project (2006).

1. *Identify and characterize the geohazards, including the presence of methane hydrate, associated Gumusut-Kakap oil and gas fields using exploratory 3D seismic data, deep-tow seismic surveys, high resolution 3D seismic data, logs from delineation wells, and geotechnical well data.*
2. *Use geotechnical core and well log data to characterize methane hydrate occurrence and saturations.*
3. *Undertake numerical modeling to evaluate potential hazards attributed to dissociating methane hydrate.*
4. *Evaluate field development plans and modify as needed.*

The Gumusut-Kakap field program occurred in three phases. In phase one, five shallow boreholes were drilled to depths of 227 to 321 mbsf to acquire additional LWD and wireline log data. Based on these data, during second phase of the field program, three locations (Figure 4.20) were selected for comprehensive data acquisition, including acquisition of conventional and pressure-cores at depths from 117 to 280 mbsf. In the final phase of the program, a series of shallow holes (76 mbsf) were established and a variety of cores acquired ranging from 20-m jumbo piston cores to 0.5-m box cores. Extensive geochemical, geomechanical, and sedimentologic analyses were conducted on the samples collected throughout the program.

The data acquired confirmed the widespread occurrence of methane hydrates throughout the region. Methane hydrates were commonly found in disseminated form with some locations showing additional occurrence of thin, sub-vertical methane hydrate veins. Methane hydrate saturations were calculated from measurements of gas released from depressurized pressure cores and from pore-water chlorinity analyses. Full vertical profiles of interpreted methane hydrate saturation were then computed using Archie's analysis of log data, in which the empirical constants within the Archie's equation were set such that log-based hydrate saturation matched that derived from the pressure core data.

In areas where no methane hydrate veins were observed, methane hydrate occurred fairly ubiquitously from roughly 28 to 223 mbsf with average methane hydrate saturation of 3 to 4% of pore volume. However, where minor thin sand sediments did occur, methane hydrate saturation was much higher, reaching estimated values "approaching 100%". The gas was dominantly methane, resulting in formation of structure I hydrate. However, in the one well where methane hydrate veins were observed in the imaged pressure cores, computed saturations averaged ~15% (significantly less than the pre-drill, uncalibrated analyses using Archie's equation), with maximum values up to 40%. Multi-azimuthal resistivity log data revealed resistivity anisotropies (ratio of horizontal to vertical resistivity) of up to ten to one. This project was among the first to provide the data necessary to yield a better estimate of the true bulk sediment concentration of methane hydrate in fine-grained fracture systems than could be obtained from typical resistivity data alone. In addition, in this particular well, levels of ethane, butane and other higher hydrocarbons increased with depth, resulting in a change from structure I to structure II hydrates, which appears to explain the presence of localized fault related methane hydrate occurrences extending below the regional expression of the BSR.

Ultimately, it was determined that the field development plan calling for the drilling of a number of deviated wells to the desired deeper targets from a centralized facility was not feasible due to the long-term risks of lost sediment integrity related to hydrate dissociation. The field was developed from three separate sub-sea drill centers located in areas with reduced methane hydrate occurrence in the shallow section.

Scientific Conclusions and Contributions of the Malaysia Gumusut-Kakap Project (2006).

1. *Early identification of geohazards using exploration 3D and high resolution deep-tow seismic surveys along with well data allowed timely input to development planning.*
2. *A comprehensive geohazard and geotechnical investigation was performed, which employed downhole logging, pressure coring and other geotechnical methods to characterize subsurface methane hydrates. Integration of logging and core data allowed for the full characterization of the nature of methane hydrate occurrence at the potential drill centers in the field.*
3. *The impact of the mode of occurrence of hydrates (in near vertical veins) can cause significant resistivity anisotropy, which must be accounted for in the determination of methane hydrate saturations.*
4. *Methane hydrate was found to be present at all locations investigated within the field. The methane hydrate was found to vary from structure I to structure II with depth, increasing the depth of methane hydrate stability relative to initial predictions.*
5. *Tension leg platforms (TLP) and Spar development concepts with deviated wells were rejected in part due to the presence of methane hydrate. Key production risks associated with methane hydrates are that dissociation induced fractures could compromise the integrity of TLP foundations and that post hydrate dissociation sediment subsidence could lead to casing and production tubing problems. A subsea development with a semi-submersible floating production system host was ultimately selected.*

4.8. India NGHP Expedition 01 (2006)

Studies of geologic and geophysical data from the offshore of India have revealed two geologically distinct areas with inferred methane hydrate occurrences: the passive continental margins of the Indian Peninsula and along the Andaman convergent margin (Figure 4.21). One of the primary goals of the Indian National Gas Hydrate Program (NGHP) is to conduct scientific ocean drilling/coring, logging, and analytical activities to assess the geologic occurrence, regional context, and characteristics of methane hydrate deposits along the continental margins of India in order to meet the long term goal of exploiting methane hydrates as a potential energy resource in a cost effective and safe manner. The NGHP is coordinated by the Directorate General of Hydrocarbons (DGH) and monitored by a Steering Committee chaired by the Ministry of Petroleum & Natural Gas, Government of India (MOP&NG).

NGHP Expedition 01 was designed to study methane hydrates off the Indian Peninsula and along the Andaman convergent margin, with special emphasis on gaining an understanding of the geologic and geochemical controls on the accumulation of methane hydrate in these two diverse settings. NGHP Expedition 01 was planned and managed collaboratively by the DGH under MOP&NG, the United States Geological Survey (USGS), and the Consortium for Scientific Methane Hydrate Investigations (CSMHI) led by Overseas Drilling Limited (ODL) and Fugro McClelland Marine Geosciences (Fugro).

Scientific Objectives of the India NGHP Expedition 01 (2006).

1. Study the formation of natural methane hydrate in marine sediments. *2. Determine the geologic controls on the formation and occurrence of methane hydrate in nature.* *3. Investigate gas transport mechanisms and migration pathways from source to reservoir.* *4. Examine the effect of methane hydrate on the physical properties of the host sediments.* *5. Investigate the microbiology and geochemistry of methane hydrate formation and dissociation.* *6. Calibrate geophysical and other predictive tools to the observed presence and concentration of methane hydrate.* *7. Identify a site suitable for a future methane hydrate production test.*

Pre-expedition geologic studies of available seismic and industry well data yielded a total of 10 proposed drill sites, exhibiting variable geologic conditions and seismic responses indicative of methane-hydrate-bearing sediments: one site in the Kerala-Konkan area on the west coast of India; eight sites on the east coast of India including six sites in the Krishna-Godavari Basin, and two sites in the Mahanadi area; and one drill site proposed for the convergent margin setting of the Andaman Islands.

For organizational purposes this project was divided into a series of three phases):

Phase-I. Project Planning and Mobilization: This project started with the mobilization of the scientific ocean drilling vessel *JOIDES Resolution*, from Galveston, Texas to Mumbai, India; and the staffing of the science team and the development of a project prospectus.

Phase-II. Field Project Management, Operations and Research: The operational phase of NGHP Expedition 01 began with the arrival of the scientific crew in Mumbai, India on 28 April 2006 and ended 113.5 days later with the departure of ship from its final berth in Chennai on 19 August 2006. The expedition consisted of five separate "legs" as follows:

Leg 1 (April 28-May 16): Sailed southwest from Mumbai to a location in the Kerala-Konkan Basin, Arabian Sea; conducted drilling, logging, and coring operations; then sailed around the southern tip of India to port in Chennai.

Leg 2 (May 17-June 6): Conducted personnel and equipment transfers in Chennai, then sailed to ten sites in the Krishna-Godhawari and Mahandi basins; conducted LWD operations; returned to Chennai.

Leg 3A (June 7-June 25): Informed with the LWD results, the crew sailed to a total of four selected sites within Krishna-Godhawari basin for drilling, coring, and logging operations, before returning to Chennai for personnel and equipment transfers.

Leg 3B (June 26-July 17): Conducted additional drilling, coring, and logging operations at five additional sites within the Krishna-Godhawari region.

Leg 4: (July 18-August 19): After personnel transfers via helicopter, the team sailed east and cored and logged a site east of Little Andaman Island, then traveled northwest to two sites within the Mahanadi Basin, then moved southwest to further explore two additional sites within the Krishna-Godhawari Basin, before finally sailing to Chennai. Drilling, coring, and logging operations were conducted at each site occupied during Leg 4.

Phase-III. Demobilization and Collaborative Post-Field Project Analysis of Geologic Data and Samples: The project included a wide range of collaborative post-field analysis of samples collected during the expedition and reporting of the geologic results of this effort. Phase-III also provided for the publication of the NGHP Expedition 01 Initial Results volume (Collett et al., 2008c) and the NGHP Expedition 01 Downhole Log Data Report (Collett et al., 2008d).

The pre-expedition site review and selection process first focused on the occurrence of seismic identified BSRs, which were inferred to indicate the occurrence of methane hydrate. In addition, the sedimentary section above the BSR was further examined for evidence of potential methane hydrate occurrences. Recent studies of 2D and 3D seismic data and drilling results from northern Alaska, Canada, and the Gulf of Mexico have led to the development of viable methods for identifying concentrated methane hydrate occurrences in sand reservoirs. In general, it has been shown that high amplitude seismic events within the expected methane hydrate stability zone can reveal the occurrence of relatively thick, highly saturated methane hydrate reservoirs. Thus, in the NGHP Expedition 01 site review process, special attention was given to identifying high amplitude stratigraphic and/or structurally controlled features within the available 2D seismic database. The site review process also incorporated conventional oil and gas seismic-stratigraphic exploration concepts. One of the primary methane hydrate reservoir targets was considered to be a series of prominent cut-and-fill channel features along the eastern margin of India.

During its 113.5-day voyage (28 April 2006 – 19 August 2006), the research drill ship *JOIDES Resolution* cored and/or drilled 39 holes at 21 sites (1 site in Kerala-Konkan, 15 sites in Krishna-Godawari, four sites in Mahanadi and one site in Andaman deep offshore areas), penetrating more than 9,250 m of sedimentary section and recovering nearly 2,850 m of core (Figures 4.21 and 4.22; Table 4.2). Twelve holes were logged with LWD tools and an additional 13 holes were wireline logged. NGHP Expedition 01 was among the world's most complex and comprehensive methane hydrate field ventures yet conducted. The necessary data for characterizing the occurrence of in-situ methane hydrate such as interstitial water chlorinities, core-derived gas chemistry, core physical properties, IR thermal images of the recovered core, and downhole measured logging data (LWD-MWD and/or conventional wireline log data) were obtained from most of the research sites established during NGHP Expedition 01. Almost all of the sites established during NGHP Expedition 01, except for Site NGHP-01-01, yielded evidence for the occurrence of methane hydrate. However, the inferred in-situ concentration of methane hydrate varied significantly from site-to-site. All of the primary data collected during the expedition are included in either the NGHP Expedition 01 Initial Reports (Collett et al., 2008c) or the NGHP Expedition 01 Downhole Log Data Report (Collett et al., 2008d); which were prepared by the USGS and published by the DGH on behalf the MOP&NG. The results of the NGHP Expedition 01 have also been summarized in Collett et al., (2008b).

As discussed in "Section 3. Geologic Controls on the Occurrence of Methane Hydrate in Nature" of this report, the concept of a "methane hydrate petroleum system" is gaining acceptance. In the following technical summary, the geologic controls on the stability and formation of methane hydrates are reviewed and assessed for the drill sites established during NGHP Expedition 01.
To understand the geologic controls on the distribution of the methane hydrate stability zone in the offshore of India, NGHP Expedition 01 featured 76 temperature tool deployments in an attempt to

characterize the thermal regime of the sites occupied during the expedition (Figures 4.21 and 4.22; Table 4.2). Two standard IODP temperature tools were deployed during the expedition, including the APCT (eight times) and the DVTP (44 times). The new APCT-3 tool was also deployed 24 times. The downhole temperature data collected during the expedition was used to calculate the depth to the base of the GHSZ at most of the sites that were continuously cored. Methane hydrate exists under a limited range of temperature and pressure conditions such that the depth and thickness of the zone of the GHSZ can be calculated. Most methane hydrate stability studies assume that the pore pressure gradient is hydrostatic (9.795 kPa/m). However, the seafloor temperature and geothermal gradient for any given site can be highly variable. The temperature data acquired during this expedition have been used to estimate of the depth to the base of the GHSZ at each site. In this study a pure methane hydrate was assumed and a pore water salinity of 35 ppt were used to estimate the depth to the base of the GHSZ at 11 sites established during NGHP Expedition 01 (Table 4.2). For the most part, the calculated depth to the base of the GHSZ for each site falls near the estimated depth of the BSR as inferred from seismic data.

The availability of large quantities of hydrocarbon gas from either microbial or thermogenic sources or both is an important factor controlling the formation and distribution of methane hydrates in nature. Stable carbon isotope analyses indicate that the methane in most oceanic methane hydrate is derived from microbial sources, which appears to be also true for most of the methane hydrate occurrences discovered on NGHP Expedition 01 based on the analyses of gas molecular and isotopic compositions (Table 4.2). However, shipboard compositional gas analyses may indicate a thermal origin for a portion of the gas in the hydrate occurrences in the Mahanadi Basin (Sites NGHP-01-18 and NGHP-01-19) and in the Andaman deep offshore area (Site NGHP-01-17). As discussed above in this review, geologic controls on fluid migration limit the availability of gas and water for the formation of methane hydrate and is an important factor that needs to be assessed when considering the controls on the occurrence of methane hydrate. At a regional scale, especially in the Krishna-Godavari Basin, the occurrence of methane hydrate appears to be closely associated with large scale structural features. For example, the fracture controlled methane hydrate accumulation at Site NGHP-01-10 (Figure 4.23) is found at the crest of a relatively large, tightly folded, ridge structure and the occurrence of methane hydrate appears to be controlled by gas flux through the local fracture system generated by the regional stress regime.

At a macroscopic to microscopic scale, the analysis of IR images of conventional cores, X-ray images of pressure cores, downhole LWD derived resistivity images and visual observations of cores upon recovery reveal the occurrence of methane hydrate in the offshore of India in a wide range of conditions. In general, most of the recovered methane hydrate was characterized as either pore-filling grains or particles disseminated in coarser grained sediments or as a fracture-filling material in clay dominated sediments. These observations further indicate the apparent need for effective migration conduits, such a fractures and stratigraphically controlled carrier beds, to deliver and concentrate the gas required for the formation of the observed methane hydrate occurrences.

For the most part, the interpretation of downhole logging data and linked IR imaging, interstitial water analyses, and pressure core imaging from the sites drilled during NGHP Expedition 01 indicate that the occurrence of concentrated methane hydrate is mostly controlled by the presence of fractures and/or coarser grained (mostly sand-rich) sediments. As reviewed in Table 4.2, the presence of concentrated methane hydrate accumulations at nine of the sites occupied during NGHP Expedition 01 (Figure 4.21; Sites NGHP-01-3, -5, -7, -14, -15, -16, -17, -19, and -20) are partially controlled by the presence of suitable host (reservoir) sands. In the case of Sites NGHP-01-10, -12, -13, and -21, however, the recovered methane hydrate constitutes fracture-filling material. The majority of marine methane hydrate systems that have been studied to date are fine-grained, clay-dominated, and associated with surficial gas seeps. The discovery of the 130-m-thick fracture-controlled methane hydrate accumulation at Site NGHP-01-10 (Figure 4.23) appears to be within a fractured clay-dominated system in which methane hydrate is concentrated in vertical and subvertical gas conduits that at one time were connected to a seafloor seep. Further analysis of the downhole-acquired borehole resistivity images from other sites (Figure 4.21, Sites NGHP-01-2, -4, -5, -6, -7, -8, -9, and -11) indicate that many of the individual, apparently stratigraphically-controlled disseminated methane hydrate deposits, actually formed in "combination reservoirs" consisting of horizontal or subhorizontal coarse-grained permeable sediments (sands for the most part) associated with vertical to subvertical fractures that provide the conduits for methane migration.

Scientific Conclusions and Contributions of the India NGHP Expedition 01 (2006).

1. *Conducted comprehensive analyses of methane-hydrate-bearing marine sediments in both passive continental margins and marine accretionary wedge settings.*
2. *The calculated depth to the base of the methane hydrate stability zone, as derived from downhole temperature measurements, closely matches the depth of the seismic identified BSRs at most of the sites established during this expedition.*
3. *Discovered methane hydrate in numerous complex geologic settings and collected an unprecedented number of methane hydrate cores.*
4. *Most of the recovered methane hydrate was characterized as either pore-filling grains or particles disseminated in coarser grain sediments or as a fracture-filling material in clay dominated sediments.*
5. *The occurrence of concentrated methane hydrate is mostly controlled by the presence of fractures and/or coarser grained (mostly sand-rich) sediments.*
6. *Methane hydrates were found occurring in "combination reservoirs" consisting of horizontal or subhorizontal coarse grained permeable sediments (sands for the most part) and apparent vertical to subvertical fractures that provide the conduits for gas migration.*
7. *Delineated and sampled one of the richest marine methane hydrate accumulations yet discovered (Site NGHP-01-10 in the Krishna-Godovari Basin).*
8. *Discovered one of the thickest and deepest methane hydrate occurrences yet known (offshore of the Andaman Islands, Site NGHP-01-17) which revealed methane-hydrate-bearing volcanic ash layers as deep as 600 meters below the seafloor.*
9. *Established the existence of a fully developed methane hydrate system in the Mahanadi basin of the Bay of Bengal.*
10. *Most of the methane hydrate occurrences discovered during this expedition appear to contain mostly methane that was generated by microbial processes. However, there is also evidence of a thermal origin for a portion of the gas within the hydrates of the Mahanadi Basin and the Andaman offshore area.*
11. *Methane hydrate in the Krishna-Godavari Basin appears to be closely associated with large scale structural features, in which the flux of gas through local fracture systems, generated by the regional stress regime, controls the occurrence of methane hydrate.*

In review, NGHP Expedition 01 established the presence of methane hydrates in the Krishna-Godavari, Mahanadi, and Andaman Basins. The expedition discovered one of the richest methane hydrate accumulations yet documented (Figures 4.21 and 4.23, Site 10 in the Krishna-Godavari Basin), recorded the thickest and deepest methane hydrate stability zone yet known (Site 17 in the Andaman Sea), and established the existence of a fully-developed methane hydrate system in the Mahanadi Basin (Site 19). For the most part, interpretation of downhole logging data and linked imaging of recovered cores, analyses of interstitial water from cores, and pressure core imaging from the sites drilled during NGHP Expedition 01 indicate that the occurrence of methane hydrate is mostly controlled by the presence of fractures and/or coarser grained (mostly sand-rich) sediments (Collett et al., 2008c).

It is anticipated that future NGHP efforts will likely include drilling, coring, and field production testing. Site 10 is considered to represent a world class shale-dominated fractured methane hydrate reservoir, worthy of further investigation. NGHP Expedition 01 also discovered significant sand- and silt-dominated methane hydrate reservoirs. Recent NGHP research activities have included the addition of a new site review effort, which is intended to identify additional potentially sand-rich drilling targets and methane hydrate prospects. It has been proposed that in 2013 or possibly 2014, NGHP Expedition 02 may be constituted to drill and log several of the more promising sand-dominated methane hydrate prospects.

4.9. China GMGS Expedition 01 (2007)

In 2004, the Guangzhou Center for Gas Hydrate Research (CGHR) was established to expand methane hydrate laboratory studies and conduct offshore field research focused on evaluating the energy resource potential of methane hydrate in the offshore of China.

In June 2007, a deep water methane hydrate drilling and coring program was successfully completed by the Guangzhou Marine Geological Survey (GMGS), China Geological Survey (CGS) and the Ministry of Land and Resources of China (Zhang et al., 2007a, 2007b; Yang et al., 2008; Wu et al., 2008). Drilling expedition GMGS-1 was conducted from April to June 2007 in the Shenhu Area on the north slope of South China Sea (Figure 4.24) from the drill ship *SRV Bavenit*. Fugro and Geotek provided specialized technical services including drilling, wireline logging, in-situ temperature measurement, pore-water sampling, and pressurized and non-pressurized coring. During Expedition GMGS-1, eight sites were drilled in water depths as great as 1,500 m. Each site was wireline logged to depths as much as 300 mbsf with a set of “high-resolution slim wireline tools”, and five sites were cored.

Scientific Objectives of the China GMGS Expedition 01 (2007) and the China Gas Hydrate R&D Program.

1. *Carry out a broad portfolio of basic research on methane hydrate to fully evaluate the occurrence of methane hydrates in nature. These studies include understanding the sources of gas, the types of deposits formed, their mode of occurrence, the controls on the formation and enrichment of deposits, and their dynamic behavior with time.*
2. *Conduct field investigations of methane hydrate in the South China Sea with the goal of more accurately delineating the nature and extent of this potential resource.*
3. *Develop improved technologies for methane hydrate characterization and production, including high-resolution seismic techniques such as OBS, and techniques for methane extraction from methane hydrates based on findings from integrated programs of laboratory experimentation and numerical simulation.*

4. Develop technologies for the long-term observation of the methane hydrate occurrences at the seafloor to better understand the dynamic process of hydrate formation and decomposition.
5. Assess potential environmental and geohazard conditions associated with methane hydrate exploitation.

The operational plan for GMGS-1 called for two holes at each site, with first hole being a "pilot hole" that was wireline logged to identify any shallow gas hazards. At most sites, a second hole (offset 10-15 m from the pilot hole) was established for sampling and testing. The sampling holes were used to obtain sediment cores and formation temperature data in order to determine the occurrence, distribution, and concentration of methane hydrates at each site. The core plan at each site was first developed from the available seismic data and was refined with the analysis of the wireline log data collected from the pilot hole at each site. Cores were acquired with the Fugro Hydraulic Piston Corer (FHPC) and Fugro Corer (FC) conventional wireline core systems. Pressure coring was also conducted with the Fugro Pressure Corer (FPC) and the Fugro Rotary Pressure Corer (FRPC); the FRPC is a renamed version of the HYACE Rotary Corer (HRC). The development of pressure coring to study the occurrence of methane hydrate in nature is further reviewed in "Section 6. Pressure Core Tools and Lab Developments" of this report. The subsurface temperature profile at each site was determined from temperature measurements using either the Wison EP temperature probe or the Fugro Pore Water Sampler (FPWS).

Methane hydrate was detected at three of the five core sites. The methane hydrate host sediments were predominantly clay, with a variable amount of silt-sized particles including foraminifera. The sediment layers rich in methane hydrate are about 10 to 25 m thick and lie just above the base of the predicted methane hydrate stability zone (BGHSZ) at all three sites. Methane was the predominant gas within core voids as well as in the recovered methane hydrate samples. Analysis of pressure cores confirmed that the methane hydrate accumulated within fine-grained foraminifera-rich clay sediments, with methane hydrate saturations ranging from 20 to 40% (Figure 4.25). It was suggested by Yang et al., (2008) that the relatively high foraminifera content and other silt-size grains may provide the void space and enough free-water for hydrate to grow in these sediments. It is also interesting that a homogenous layer of methane hydrate, limited to the strata immediately above the base of methane hydrate stability zone, is the type of accumulation predicted from the more simple models of methane hydrate formation (e.g. see Hyndman and Davis, 1992; Xu and Ruppel, 1999).

Scientific Conclusions and Contributions of the China GMGS Expedition 01 (2007).

1. Eight sites were investigated during GMGS Expedition 01: SH3, SH6, SH1, SH2, SH7, SH5, SH9, and SH4 (in chronological order). At each site, a pilot hole was drilled first that was subsequently wireline logged. A sampling and testing hole was drilled at five of these locations: Sites SH3, SH1, SH2, SH7, and SH5. The remaining sites, SH6, SH9, and SH4, were not sampled as it was considered that there was little or no prospect of finding any methane hydrate after the wireline logs had been examined.
2. The calculated base of methane hydrate stability (from temperature, pressure, and salinity measurements) at all the sites was near the estimated depth of the BSR on the seismic profiles.
3. Gas composition measurements of samples extracted from recovered cores showed that methane was the dominant gas, with low ethane concentrations (0.01-0.1% ethane).

4. The depth of the sulfate-methane interface at the sites cored varied between 17-27 mbsf.

5. Methane-hydrate-bearing sediments layers were found at three of the sites investigated during GMGS Expedition 01 (SH3, SH2, and SH7), evidence from both pressure cores and the non-pressure cores indicated that the methane hydrate exist at all three sites (SH3, SH2, and SH7), in a disseminated form, with no grain-displacement. The remaining cored sites (SH1 and SH5) showed no evidence for methane hydrate.

6. At Site SH3, methane hydrate was found in two cores just above the base of methane hydrate stability (206 mbsf), with a maximum methane hydrate concentration of 25% of pore volume, calculated from pore-water freshening. The resistivity anomaly from the wireline logs indicated that this layer was approximately 10 meters thick.

7. At Site SH2, a 25-meter-thick layer of methane-hydrate-bearing sediment was found at 195-220 mbsf. The methane hydrate concentration in this interval was consistently high (over 25% of pore volume) with maximum calculated concentrations of 47% of pore volume.

8. At Site SH7, a 25-meter-thick layer of methane-hydrate-bearing sediment was found at 155-180 mbsf. The methane hydrate concentration in this interval was more variable than at Site SH2 but had maximum calculated concentrations of 44% of pore volume.

Zhang et al., (2007a) reported on planning for future expeditions to the Shenhu area and other regions of the northern South China Sea, which are now being planned for the spring of 2013.

4.10. Republic of Korea UBGH Expedition 01 (2007)

The Republic of Korea has a strong national methane hydrate program organized under the Korean Gas Hydrate Research and Development Organization (GHDO) and supported by the Ministry of Commerce, Industry and Energy (MOCIE; now known as the Ministry of Knowledge Economy, MKE). The program includes several government research organizations, as well as industry partners (e.g., the Korean Gas Corporation - KOGAS and the Korean National Oil Company - KNOC). The GHD has four basic missions (as reviewed by Park, 2008): (1) confirm and map methane hydrate distribution in the East Sea (Ulleung Basin); (2) acquire a "clean energy source" to replace conventional petroleum sources; (3) develop technology for methane hydrate reserve appraisal and development; and (4) commercially produce methane hydrates by 2015. Additional research components include methane hydrate climate change implications, as well as CO_2-capture and sequestration.

Research under the GHDO started in 2000 with the acquisition of marine seismic data in the East Sea combined with selected shallow coring and heat flow analyses to characterize the Ulleung Basin and its potential for methane hydrate.

In November 2007, GHDO completed its first large-scale methane hydrate exploration and drilling expedition in the East Sea: Ulleung Basin Gas Hydrate Expedition 1 (UBGH1). KNOC and KOGAS contracted Fugro to supply drilling, wireline logging, coring and associated services for Expedition UBGH1, while Schlumberger and Geotek provided LWD and core analysis services, respectively. The technical leads of the project were the GHDO and the Korea Institute of Geoscience and Mineral Resources (KIGAM) (Park et al., 2008). The field investigations were conducted from the *M/S Rem Etive* during the period from 15 September through 15 November 2007.

Scientific Objectives of the Republic of Korea UBGH Expedition 01 (2007).

1. *Acquire continuous downhole LWD logs to determine the distribution of potential methane hydrate zones in the drilled stratigraphic section.*
2. *Recover hydrate-bearing sediment cores to quantify in-situ methane hydrate and to determine hydrate-sediment structure, hydrate chemistry, and thermal conductivity properties.*

Leg 1 of UBGH1 included the drilling of five LWD holes in the Ulleung Basin (Figure 4.26), which were selected as sites representing the range of geologic conditions expected in the basin. The LWD data acquired during Leg 1 were used to select a subset of three sites that were more likely to contain methane hydrate for Leg 2 drilling and coring operations. A suite of non-pressurized wireline coring systems (FHPC – Fugro Hydraulic Piston Corer and FC – Fugro Corer), and pressurized coring systems (FPC – Fugro Pressure Corer and FRPC – Fugro Rotary Pressure Corer) were used to recover cores during UBGH1. The WISON EP in-situ testing equipment was used to obtain downhole equilibrated temperature data and pore water samples.

Coring during Leg 2, at water depths between 1,800 to 2,100 m, confirmed the presence of hydrate-bearing sediments as deep as 150 mbsf (Park et al., 2008). Methane hydrate was recovered at all three core sites, occurring as veins and layers in clay-rich sediments and as pore-filling material within silty/sandy layers (Figure 4.27). At one site, a 130-m-thick hydrate-bearing sedimentary section of interbedded sands and clays was penetrated. At another site, a similar 100-m-thick hydrate-bearing section was discovered. Analysis of pore-water freshening revealed average methane hydrate saturations of about 30% for the hydrate-bearing sand layers. Methane was the predominant gas within core voids as well as in recovered methane hydrate samples at all three core sites.

A thick fracture-dominated methane hydrate accumulation discovered at one of the sites in the Ulleung Basin is similar to the Site 10 fracture-dominated methane hydrate deposit in the Krishna-Godavari Basin in the offshore of India (as described earlier in this report), with many grain-displacing methane hydrate veins in clay-rich sediments. However, there are also similarities to the methane hydrate found in the interbedded sands and clays drilled on IODP Expedition 311 off the west coast of Canada (as described earlier in this report).

Scientific Conclusions and Contributions of the Republic of Korea UBGH Expedition 01 (2007).

1. *A total of five LWD boreholes, which also served as pilot holes, designated as UBGH1-01A, -04A, -09A, -10A, and -14A, were drilled to depths ranging from 214.6 mbsf to 231.7 mbsf.*
2. *A total of three coring and in-situ testing boreholes (located near corresponding LWD pilot holes), designated as UBGH1-04B, -04C, -09B, and -10B, were to drilled and/or cored to depths ranging from 55.7 to 204.9 mbsf.*
3. *At Site UBGH1-04, methane hydrate was interpreted to occur in thin-layers above the base of GHSZ, most likely coincident with layers of coarser-grained sediment. Methane hydrate saturations were as high as 44% of pore volume.*
4. *At Site UBGH1-09, methane hydrate was found between 63 and 151 mbsf in silty and/or sandy layers. Typical methane hydrate saturations in this interval were about 30% of pore volume, with a maximum saturation of 64% of pore volume.*

5. *At Site UBGH1-10, methane hydrate was found occupying fractures from the near the seafloor to a depth of 141 mbsf.*

The results of UBGH1, along with post-expedition studies were used to justify and develop operational/science plans for a Second Ulleung Basin Gas Hydrate Expedition (UBGH2), which was completed in September of 2010 and is reviewed later in this report.

4.11. Gulf of Mexico JIP Leg II (2009)

As reviewed in "Section 4.5. Gulf of Mexico JIP Leg I (2005)" of this report, the 2005 JIP Leg I drilling program provided an initial confirmation of the occurrence of methane hydrates below the Gulf of Mexico seafloor. Building on the results of JIP Leg I, a key objective of JIP Leg II 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. In 2006, scientists from the BOEM, the USGS, the DOE and other organizations (the "JIP Site Selection Team") began this effort in cooperation with the JIP by focusing on those sites in which methane hydrate-bearing sands may be indicated in existing well log data. One highly prospective site was identified through the 2006 public release (Smith et al., 2006) of well log data for the AC818 #001 well (Figure 4.28). In an effort to increase the inventory of prospective drill sites, the JIP Site Selection Team extended the search to locations in which methane hydrate-bearing sands were indicated in geophysical data, but for which direct well confirmation was not available (Hutchinson et al., 2008a). Most notably, team members from AOA Geophysics presented two sites for consideration that had been observed during prior shallow hazard assessment studies. The first, Walker Ridge 313 (WR313), was the site earlier described by McConnell and Kendall (2002). A second site, Green Canyon 955 (GC955), was prospective due to a pattern of seismic inferred gas accumulations within a four-way closed structure in an area of expected high fluid flux (McConnell, 2000; Heggland, 2004). The ensuing detailed evaluation of these two sites included two phases. First, quantitative seismic inversions for methane hydrate saturations were conducted by WesternGeco (Shelander et al., 2010, 2012). In both the WR313 and GC955 locations, these inversions suggested methane hydrate saturations of 50% or more in units of seismically-resolvable thickness. The second phase consisted of simultaneously integrating the inversion results with the geological-geophysical evaluation to assess the presence of gas sources and sand-rich lithofacies linked by migration pathways (Hutchinson et al., 2008a). In 2008, additional potential drill sites in Alaminos Canyon 21 and surrounding blocks as identified by BOEM scientists were added to the list of potential JIP Leg II drill sites. Similarly, a fourth prospective site in GC781 was introduced, which included features very similar to those observed in WR313 although at significantly shallower water depths and drilling depths (Hutchinson et al., 2009). However, shortly before the expedition was launched in April 2009, it was determined that ongoing industry drilling operations in the GC781 area precluded obtaining the permissions required for JIP drilling at the GC781 site. Ultimately, JIP Leg II was launched with a total of 20 drill locations permitted within the WR313, CG955, and AC21/EB992 sites (Collett et al., 2010).

The primary goal of GOM JIP Leg II (Figure 4.28) was the collection of a comprehensive suite of LWD data within methane-hydrate-bearing sand reservoirs (Boswell et al., 2012a). GOM JIP Leg II began on 16 April 2009 with the transfer of authority to Chevron representatives on the *Helix Q4000* located in Green Canyon Block 195. Ultimately three sites were occupied with seven LWD holes being drilled, including the Walker Ridge 313 (WR313; Figures 4.28, 4.29, and 4.30), Green Canyon Block 955 (GC955 Figures 4.28 and 4.31), and Alaminos Canyon 21 (AC21; Figures 4.28 and 4.32) sites. GOM JIP Leg II officially ended on 6 May 2009 with the release of the rig in Alaminos Canyon Block 21. For more information on the LWD tools used on GOM JIP Leg II see "Section 7. Downhole Well Log Analysis of Methane Hydrate" of this report.

For the GOM JIP Leg II, an advanced set of LWD tools were deployed to obtain data on formation lithology, electrical resistivity, acoustic velocity, and sediment porosity; which allowed for the greatly improved evaluation of methane hydrate in both sand and fracture dominated reservoirs. The technical and scientific contributions of GOM JIP Leg II are summarized in Collett and Boswell (2012) and discussed in considerable detail in additional reports by Boswell et al., (2012a, 2012b), Cook et al., (2009, 2012); Frye et al., (2009, 2012); Guerin et al., (2009a, 2009b), McConnell et al., (2009a, 2009b), and Mrozewski et al., (2009).

Scientific Objectives of Gulf of Mexico JIP Leg II (2009) and the Gulf of Mexico Gas Hydrate Joint Industry Project

1. *Confirm the occurrence of methane hydrate at high concentration in reservoir quality sands in the Gulf of Mexico.*
2. *Develop a better understanding of the potential scale of methane hydrate occurrence within the basin; including data from relevant test sites that would assist in the further refinement of the BOEM basin-wide assessment.*
3. *Further develop and calibrate the integrated prospecting approach employed by the JIP to delineate and characterize methane-hydrate-bearing sands prior to drilling.*
4. *Obtain detailed information on the nature and architecture of methane hydrate occurrences in the Gulf of Mexico.*
5. *Obtain the data to further assess the selection of optimal sites and design of field sampling programs for JIP Leg III pressure-core and wireline data acquisition.*

The primary attribute of the Walker Ridge drill site was a series of anomalous seismic responses that aligned with the inferred base of the methane hydrate stability zone (McConnell and Kendall, 2002). Several of these seismic events, when traced downdip to the west, switch seismic "polarity" from a strong positive response to a strong negative response at a common horizon that cross-cuts stratigraphy (Figure 4.29). This configuration of seismic responses was interpreted to indicate free gas accumulations (the negative anomalies) being trapped within porous and permeable sand horizons by up-dip accumulations of methane hydrate within the sediment pore space. WR313-G was the first well drilled during the GOM JIP Leg II (Figures 4.28, 4.29 and 4.30) and is one of two wells drilled within the Terrebonne mini-basin during this expedition. WR313-G was located in a relatively down-dip position into the basin, and targeted a bright amplitude reflector within a unit informally known as the "blue" unit. The WR313-G well encountered the base of the methane hydrate stability zone at a depth of ~900 mbsf (~2,959 fbsf) based on the extrapolation to this well location of the depth of the seismic phase reversal denoting the probable contact between hydrate-bearing and underlying free-gas-bearing sediments.

While drilling the apparent muddy sediments (characterized by relatively high gamma ray log values) above the primary target at the WR313-G well, a zone of elevated resistivity (from 4 to 10 ohm-m) was encountered through a thick interval from 257 to 376 mbsf (843 - 1,235 fbrf). Initial interpretation was that this zone marks a strata-bound occurrence of hydrate-filled fractures within an interval of clay-dominated sediments. The main target in the WR313-G well was encountered at an expected depth of 852 m (2,796 fbsf).

Analysis of the gamma ray and density logs indicate that the sedimentary section from 427 to 930 mbsf (1,400 to 3,050 fbsf) in the WR 313-G well is characterized by numerous thin sand and silt layers within mostly a clay-dominated section. Notable methane hydrate-filled sands, however, were encountered at 601 mbsf (1,973 fbrf) (10-ft thick sand at 6 ohm-m) and at 831 mbsf (2,727 fbsf) (10 ft of net sand at 6-10 ohm-m within a 26-ft interval). The "blue" seismic reflector target, was observed from 852 to 874 mbsf (2,796-2,866 fbsf). A net of ~9 m (~30 ft) of sand containing methane hydrate at high saturations (peak resistivity near 200 ohm-m) was confirmed within this ~22-m-thick (~70 ft) thick gross interval. The resistivity and acoustic derived methane hydrate saturations within sand reservoir sections are similar with average peak values exceeding 80%.

The WR313-H well was the second well drilled within the Terrebonne mini-basin during this expedition (Figures 4.28, 4.29 and 4.30). The WR313-H well was drilled up-dip and ~2 km to the east of the WR313-G well. This location tested the "blue" unit at approximately the up-dip termination of the seismic inferred methane hydrate occurrence, with the primary target for the WR313-H well being the deeper "orange" unit. The pre-drill estimate of methane hydrate saturation for the "orange" target was 53% (Boswell et al., 2012a, 2012b). The WR313-H well was also designed to test a third dipping seismic reflector, the "green" unit, in a position below the base of the expected methane hydrate stability zone where the "green" unit was predicted to be water-bearing. The base of the methane hydrate stability zone in the WR313-H well is at a depth of ~876 mbsf (~2,873 fbsf) based on the extrapolation of the depth of the seismic phase reversal denoting the probable contact between hydrate-bearing and underlying free-gas-bearing sediments at this well location.

The shallow, fracture-filling methane hydrate occurrence was again observed at about 168 to 314 mbsf (~550-1,030 fbsf) in the WR313-H well. In WR313-H, the near-vertical methane hydrate-filled fractures are clearly visible on the resistivity images from ~180 to 305 mbsf (~590-1,000 fbsf) and from ~490 to 690 mbsf (~1,670-2,264 fbsf), which coincides with the separation in the propagation resistivity curves, as expected (Cook et al., 2009, 2012).

As in the WR313-G well, the shallow sedimentary section within the WR313-H well is dominated by muds with thin interbeds of sand, including several possible methane hydrate-bearing sands ranging up to 1-m-thick. Sediments interpreted to be correlated with the "blue" seismic reflector were reached at ~649 mbsf (2,131 fbsf) in WR313-H well and had graded into a more mud-rich interval with reduced porosity and only limited occurrence of methane hydrate, when compared with WR313-G. The top of the main target "orange" unit was penetrated at 806 mbsf (2,646 fbsf). This unit consisted of two lobes of very clean sand, each with sharp basal and upper contacts. Resistivity in the upper (5.0-m-thick) lobe were very high (~30 to 300 ohm-m), while the lower lobe (6.5-m-thick) was less resistive (~3 to 30 ohm-m). The resistivity and acoustic derived methane hydrate saturation range from peak values greater than 90% in the upper lobe with slightly lower peak saturations of about 85% in the lower sand lobe. The drilling continued below the inferred base of the methane hydrate stability zone (~876 mbsf, ~2,873 fbsf), penetrating additional reservoir-quality sands associated the "green" event.

In the pre-drill site review process, the primary evidence for the occurrence of methane hydrate at the GC955 site was the confluence of strong seismic amplitude reflectors indicative of gas sourcing within a closed, complexly faulted structural high coincident within a long-lived sand delivery fairway (Figures 4.28 and 4.31). Seismic amplitudes with polarity in phase with that of the sea-floor (suggesting horizons across which acoustic impedance substantially increased) were observed. These anomalies provided additional support to the interpretation of methane hydrate at elevated saturations in units of appreciable (seismically resolvable) thickness (McConnell et al., 2009b).

Ultimately three wells were drilled in GC955 (Figures 4.28 and 4.31), the first well GC955-I was drilled very close to a late-stage channel axis (to maximize the occurrence of sand reservoirs) in a location with muted geophysical indications of methane hydrate (McConnell et al., 2009b). The GC955-I well encountered the base of the methane hydrate stability zone at a depth of ~444 mbsf (~1,456 fbsf). The targeted sand section in the GC955-I well was encountered within the depth interval from of ~362 to 479 mbsf (1,189-1,572 fbsf) and is characterized by mostly low gamma ray log values, but also by enlarged hole conditions as shown by the irregular caliper logs. In Hole GC955-I, only a few meters of the targeted sand interval display moderate resistivity excursions near ~427 mbsf (~1,400 fbsf), indicating the possible presence of methane hydrate with the log derived peak methane hydrate saturations of <50%.

As described by Boswell et al., (2012a, 2012b), the GC955-H well targeted high amplitude seismic anomalies with features suggestive of methane hydrate at a projected depth of 398 mbsf (1,307 fbsf). The GC955-H well (Figures 4.28 and 4.31), at a LWD measured water depth of 2,032 m (6,667 ft), was the second location drilled in Green Canyon Block 955 during the GOM JIP Leg II. The depth to the base of the methane hydrate stability zone in the GC955-H well is not easily inferred from either the available seismic or well log data. GC955-H penetrated a thick methane-hydrate-filled fracture section within the depth interval of 192-308 mbsf (630-1,011 fbsf) and at a depth of 413 m (1,356 fbsf) the well encountered a thick methane-hydrate-bearing sand section. High-resolution resistivity images showed the methane-hydrate-bearing sand section to consist of interbedded sands and shales, with sands commonly 0.3-0.6 m (1-2 ft) in thickness, with maximum thickness of 1.2 m (4 ft). These sands are inter-layered with finer-grained silts and muds that are typically 0.15-0.30 m (0.5-1.0 ft) thick (Lee and Collett, 2012). The upper ~23 m (75 ft) of this interval has low and downward decreasing resistivity and is therefore interpreted to be water-saturated. At 413 m (1,356 fbsf), resistivity and acoustic velocity increased sharply, indicating the top of a thick methane-hydrate-bearing sand interval. Through a depth of 450 m (1,475 fbsf), three methane-hydrate-bearing zones of ~27 m, ~4 m, and ~1 m (~88 ft, ~13 ft, and ~3 ft) thick were logged; these zones are apparently separated by two hydrate-free water-bearing sand units. One of the most prominent features on the borehole image logs from Hole GC955-H is the high-resistivity methane-hydrate-bearing sand section between 413 and 450 mbsf (1,356-1,475 fbsf).

The average resistivity and acoustic derived methane hydrate saturations within the drilled sand sections in the GC955-H well range from about 50 to 80%, while the methane hydrate was determined to occupy only about 5% of the void space created by the fractures in the upper part of the well based on the acoustic derived methane hydrate saturations (Lee and Collett, 2012).

Based on the highly successful technical and operational results of the GC955-H well, it was decided to drill the GC955-Q well in a separate fault block in a structurally higher position, potentially placing the sand reservoirs encountered in GC955-H higher in the methane hydrate stability zone (Boswell et al., 2012a, 2012b) (Figures 4.28 and 4.31). On seismic data, this location exhibited a thick sequence of high-amplitude seismic responses that had been assessed a “high” risk of free gas in pre-expedition hazards analysis; however, it was determined that this risk had been sufficiently mitigated by the lack of significant free gas observed below the hydrate-bearing section in the GC955-H well and the mud handling capabilities of the *Q4000*.

Hole GC955-Q was spud and drilled without significant problems to a depth of ~378 mbsf (~1,241 fbsf), where the drilling fluid was changed from seawater to a 10.5 lb/gal water-based mud. At 414 mbsf (1,357 fbsf), the well encountered methane-hydrate-bearing sand, which continued to a depth of at least 438 mbsf (1,436 fbsf) (the deepest useful measured data point). The acoustic velocity derived methane hydrate saturations within the interval at the bottom of the hole peaked at about 75%. The Archie analysis indicates the occurrence of interbedded hydrate-bearing sand units with variable methane hydrate saturations ranging between 40 and 75% to as low as ~20% in adjacent beds. At a depth of 442 mbsf (1,450 fbsf), drilling was halted when a gas release from the well was visually observed by the *Q4000's* ROV. The LWD assembly was eventually recovered to the ship, and the well re-entered and cemented. For a more detailed review of the drilling problems encountered in the GC955-Q well see the operational summary prepared by Collett et al., (2010) and "Section 10. Methane Hydrate Drilling Operational Experience" of this report.

The proposed GOM JIP Leg II drilling sites in AC21/AC65 lie within the Diana sub-basin and target anomalous seismic reflections that occur approximately 183 mbsf (600 fbsf) and 244 m (800 ft) above the inferred base of methane hydrate stability (Figures 4.28 and 4.32). Two wells were drilled through the prospective shallow sand facies in AC21. Hole AC21-A was completed to a total depth of 536 mbsf (1,760 fbsf) in only 12 hours. As expected, the well encountered two sands at 165 and 175 mbsf (541 and 574 fbsf) separated by a ~5-m-thick shale. The resistivity in these sands was consistently ~2 ohm-m, which at this site is believed to indicate the occurrence of sand with low methane hydrate saturations (<10-30%) (Lee et al., 2012). The AC21-B well is located ~2.5 km north of AC21-A and was the last well drilled during the GOM JIP Leg II. The AC21-B well is located at a LWD measured water depth of 1,488 m (4,883 ft). This well logged a single 39-m-thick (128-ft-thick) sand body at 158 mbsf (518 fbsf). As with the AC21-A well, the resistivity of the sand was remarkably consistent at 1.8-2.5 ohm-m. The resistivity and acoustic derived methane hydrate saturations within sand reservoir section of AC21-B well are similar to the values calculated for the AC21-A well with methane hydrate saturations ranging from 10 to 30%.

Scientific Conclusions and Contributions of Gulf of Mexico JIP Leg II (2009).

1. *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.*
2. *Drilling at GC955 revealed a thick sequence of thinly interbedded sands and shales in which methane hydrate is clearly limited to the sand lithologies and occurs at high saturation. As in WR313, the GC955 drill results confirmed the linkage between strong peak trough amplitudes and high methane hydrate saturations in sands.*
3. *The drilling at the WR313 site confirmed the geologic model linking aligned seismic identified anomalous amplitudes and associated phase reversals with methane hydrate occurrence in sands in an interbedded sand-shale sequence. The association of these occurrences with trapped, down-dip free gas appears likely; however, the degree of free gas saturation cannot be confidently determined. Available data suggest that the features observed in the WR313 area exist elsewhere within the northern Gulf of Mexico. Similar "segmented BSRs" occur at as many as 146 additional locations, including documented phase reversals at several horizons within GC781.*
4. *The two wells drilled into the blue horizon in WR313 indicated that methane hydrate will not form only at the BGHS, but may occur within a given unit over large distances and persist well above the BGHS provided the persistence of sufficient reservoir quality.*

5. LWD logs from the WR313 sites indicate that reservoir-quality sands up to 3 m thick can obtain high saturations of methane hydrate at locations 300 m or more vertically above the BGHS.
6. The WR313 LWD logs revealed a widespread, 150-m-thick, shallow, and clay-dominant unit that may hold large quantities of methane as low-saturation, fracture-filling methane hydrate. This unit is distinct from fracture-filling methane hydrates seen elsewhere in the world as the fractures appear to be strata-bound, suggesting reservoir lithology/physical properties as the primarily control on both fracture and by extension, methane hydrate occurrence.
7. The lack of methane hydrate within reservoir-quality sands occurring within the GHSZ, such as was encountered at the GC955-I well underscores the need for consideration of all petroleum system elements, and may commonly be a consequence of lack of gas charge, although some contribution from lack of trap is possible.
8. Within Site GC955, regional mapping shows that reservoir compartmentalization may be a major factor in controlling methane hydrate occurrence; however, the specific controls on the limits of the methane hydrate occurrence within apparent reservoir facies remain poorly understood.
9. In WR313 and GC955, it would appear that the gas was primarily derived from migration from deep sources, and would be expected to have a significant thermogenic component; however Leg II did not collect any gas samples to test this conclusion.

In summary, from an operational standpoint, the GOM JIP Leg II was extremely successful; which was completed on time and under budget, with zero injuries. The performance of the LWD tools was outstanding, without any operational time lost due to tool failure. Scientifically, the expedition was a clear success, yielding extremely valuable and advanced datasets on methane hydrate occurrences ranging from low to high saturation in sands as well as thick sections of fracture-filling methane hydrate in muds. GOM JIP Leg II drilled some of the thickest and most concentrated methane hydrate accumulations yet encountered.

In Spring of 2012, the GOM JIP and DOE announced (Fire-In-The Ice, DOE-NETL Methane Hydrate Newsletter, v. 12, no. 1, 2012) that they will focus their future attention on the development and testing of an integrated suite of pressure coring and pressure core analysis devices with research and development experts in the USGS, Georgia Institute of Technology, Aumann and Associates, Geotek and other academic institutions and contractors. No other drilling programs will be conducted. Later in 2012, DOE reported (Fire-In-The Ice, DOE-NETL Methane Hydrate Newsletter, v. 12, no. 2, 2012) that they have "a strong interest" to use the sites discovered during the JIP 2009 Leg II expedition for further research and development of marine methane hydrate appraisal technology. The following new projects began in 2012: (1) Fugro GeoConsulting will develop detailed scientific and operational plans and recommendations for all aspects of a future offshore drilling, logging and pressure coring campaign targeting reservoirs and seals at the JIP Leg II sites; (2) The Consortium for Ocean Leadership will coordinate scientific input and develop scientific plans for a future marine hydrate expedition(s) to conduct scientific drilling, coring, logging, and analytical activities to assess the geologic occurrence, regional context, and characteristics of methane hydrate deposits along the continental margins of the U.S., with potential emphasis on the Gulf of Mexico and the Atlantic margin; (3) the USGS, the BOEM, and NETL will collaborate on a USGS-led effort to acquire high-resolution, multi-component seismic data needed to characterize methane hydrate-bearing sediments at the JIP sites; (4) Ohio State University will conduct research in collaboration with the BOEM to access well date from more than 1,700 deepwater wells to evaluate indications of methane hydrate in the northern Gulf of Mexico; (5) Oklahoma State University will further analyze the structural and stratigraphic controls on hydrate occurrence and distribution at the JIP sites using new techniques to interpret methane hydrate occurrence in existing seismic and well data collected during prior DOE research efforts at those sites; and (6) Fugro GeoConsulting will develop analytical techniques that will enable more robust and reliable identification and delineation of methane hydrate accumulations and their complex potential interfaces with free gas accumulations in seismic data.

4.12. Republic of Korea UBGH Expedition 02 (2010)

As a part of Korean National Gas Hydrate Program, the Second Ulleung Basin Gas Hydrate Drilling Expedition (UBGH2) was successfully performed by using the *D/V Fugro Synergy* to establish 13 research drill sites in the period of time from 7 July 2010 to 30 September 2010 (Bahk et al., 2011; Lee et al., 2011a, 2011b). The first leg of this expedition was dedicated to LWD operations, while the second leg focused on both conventional and pressure coring.

The primary objectives of the UBGH2 expedition were to collect geologic, geochemical, and geophysical data needed to understand the distribution of methane hydrate in the Ulleung Basin and to find a promising candidate site for future offshore production test, especially targeting sand bodies. It is important to highlight that there is currently a broad consensus among the major international R&D efforts that the subset of methane hydrate resources that are housed in sand reservoirs are the most favorable targets for initial evaluation of production potential.

Scientific Objectives of the Republic of Korea UBGH Expedition 02 (2010).

1. *Confirm the occurrence of methane hydrate-bearing sediments in the Ulleung Basin, East Sea.*
2. *Obtain scientific information on the distribution of methane hydrate-bearing structures as needed to conduct methane hydrate resource assessment.*
3. *Identify suitable sites for an initial methane hydrate production test from sand reservoirs containing methane hydrate in the Ulleung Basin.*

A total of 11 proposed drill sites were selected for further investigation under UBGH2 (Figure 4.33) (Lee et al., 2011a, 2011b). The drilling plan called for first conducting LWD operations at all 11 UBGH2 drill sites (a total of 13 proposed drill holes). After the LWD program (Leg 1), coring was to be conducted at a subset of “high-priority” sites based on the analysis of the LWD data acquired during Leg 1. It was also proposed that two of the “high-priority” sites would be selected for wireline logging including vertical seismic profiling (VSP). The Leg 1 LWD operations began on 7 July 2010 with the mobilization of the Fugro drill ship *D/V Fugro Synergy* from the port of Busan, and ended 33 days later on 8 August 2010 with the drilling and logging of 13 holes as proposed in the Ulleung Basin. The Leg 2 coring operations began on 13 August 2010 and ended with final demobilization in the Port of Busan on 30 September 2010. In all a total of 10 sites were cored during Leg 2, with Site UBGH2-6 being visited twice during the coring leg (Figure 4.33). The 10 sites selected for coring appeared to have the greatest probability of encountering methane hydrates as assessed from the Leg 1 downhole LWD data. In several cases, sites were also selected to acquire data in support of developing a regional geologic framework for the occurrence of methane hydrate in the Ulleung Basin.

The coring program during Leg 2 included the deployment of both conventional wireline and pressurized coring systems, including the Fugro Hydraulic Piston Corer (FHPC), Fugro Corer (FC), Fugro Rotary Core

(FRC), Fugro Rotary Pressure Corer (FRPC; formally named the HYACINTH Rotary Corer) and the Fugro Pressure Corer (FPC). The development and use of pressure core systems to study methane hydrates is further reviewed in "Section 6. Pressure Core Tools and Lab Developments" of this report.

Downhole wireline logging and VSP surveys were conducted at two sites during UBGH2: UBGH2-10 and UBGH2-6. The wireline logging services were provided under contract by Fugro Alluvial Offshore Limited. In-situ temperature measurements were also acquired in all of the UBGH2 core holes with a wireline deployed probe that protrudes through an opening in the drill bit into the undisturbed sediments ahead of the bit.

The remotely operated vehicle (ROV) on the *D/V Fugro Synergy* was used during UBGH2 to conduct extensive site surveys, to obtain shallow sediment push cores, and to monitor the well head at the seafloor for any evidence of fluid and/or gas expulsions. At most sites the ROV site survey and shallow push core program consisted of conducting pre-drilling visual, sonar, and methane survey on a square grid measuring about 100 m on a side. After completing the site survey, the ROV would often take up to about four push cores at each site.

Integrated seismic, well log, and core analysis indicate several different types of methane hydrate accumulations in the Ulleung Basin (Bahk et al., 2011; Lee et al., 2011a, 2011b). The shipboard analysis results collectively indicate that recovered methane hydrates mainly occur either as "pore-filling" in discrete turbidite sand and/or ash layers, or as "fracture-filling" veins and nodules in pelagic/hemipelagic mud. Probably the most striking feature in the basin is the existence of numerous seismic identified vertical chimney structures. Downhole logging and coring activities at four of the UBGH2 sites have confirmed the chimney structures in the Ulleung Basin contain fracture-filling methane hydrate. Seismic data from the Ulleung Basin also clearly shows the development of a thick, potential basin wide, sedimentary section characterized by mostly debris flows. The downhole LWD logs and core data from at least one site suggests the presence of methane hydrate at relatively low concentrations in basal silt-sand sections associated with debris flow units. In support of the main goal of this research drilling project, the UBGH2 LWD and coring program have also confirmed the occurrence of numerous volcaniclastic and siliciclastic sand reservoirs that were deposited as part of local to basin-wide turbidite events, which probably hold the greatest promise for substantial methane hydrate occurrence and production in the Ulleung Basin.

It has been reported that plans are underway to conduct a methane hydrate production test in the Ulleung Basin in the spring of 2014.

Scientific Conclusions and Contributions of the Republic of Korea UBGH Expedition 02 (2010).

1. *The downhole log data from the 13 LWD holes drilled during UBGH2 showed evidence for the presence of methane hydrate. In particular, the sites characterized by chimney structure showed high resistivities and velocities relative to normal marine sediments, which is indicative of significant concentrations of methane hydrates.*
2. *Shipboard analysis of recovered UBGH2 core samples indicates that the recovered methane hydrates mainly occur either as "pore-filling" type within discrete turbidite sand or ash layers, or as "fracture-filling" veins and nodules in pelagic/hemipelagic mud, particularly in the chimney structures.*

3. Analysis of core samples further revealed minor but significant variation in the occurrence of methane hydrate in some pelagic mud without considerable changes in sediment sand content.
4. The analysis of core gas samples indicates that the shallow gas of Ulleung Basin is originated from microbial rather than thermogenic sources. In addition, there is no significant difference of molecular and isotopic composition of the sampled gases between chimney related venting and non-venting sites.
5. Authigenic carbonates were found near the chimney structures at two sites (UBGH2-7 and UBGH2-11). However, distinct live chemosynthetic community or active gas seepage were not identified, suggesting that gas venting is recent and has not yet reach the seafloor or venting activity is now dormant.
6. Analysis of pore water chemistry revealed that the highly concentrated methane hydrates in the chimney structures are associated with brines with higher chlorinity than sea water.
7. Analysis of pore water chemistry suggests that the chimney structures in the basin center were caused by high formation temperatures and rapid sedimentation which led to sediment compaction and clay dehydration reactions that result in fluid overpressures and associated fracturing of the formation.
8. The analyzed depth to the base of methane hydrate stability zone (BGHSZ), as derived from in-situ temperature measurements, match the depth of the BSR at most of the sites established during UBGH2.

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

After the 2001 launch of the "Japan's Methane Hydrate Exploitation Program" (also known as MH21), public interest in methane hydrate as a future domestic energy source grew, and an April 2005 cabinet decision included reference to the promotion of methane hydrate-related technological development to be included in the plan for achieving Japan's Kyoto Protocol targets. Furthermore, the Basic Energy Plan established in a March 2007 cabinet decision and the Basic Plan on Ocean Policy established in a March 2008 cabinet decision included reference to efforts toward commercialization of methane hydrate.

Scientific Objectives and Future Challenges of the "Japan Methane Hydrate R&D Program" as redefined in 2008.

1. Methane hydrate, of which there is expected to be substantial amounts offshore Japan, is positioned as a future energy resource, and impelling technological developments into drilling and production of methane hydrate on an economical basis for future utilization will contribute to the acquisition of a long-term steady supply of energy.
2. In order to improve technologies for the commercial production of methane hydrate in the offshore Japan, the following objectives have been identified: (a) Clarify the occurrence and characteristics of methane hydrates in the offshore of Japan, (b) assess the amount of methane trapped in promising hydrate deposits, (c) assess economic potential for methane hydrate development, (d) conduct production testing of selected methane hydrate fields, (e) improve technologies for commercial production, and (f) establish environmental proven methane hydrate production systems.

3. Based on the findings from the assessment of the resource amounts in the eastern Nankai Trough, MH21 needs to expand the target area to regions off the coast of Japan other than the eastern Nankai Trough.
4. Develop and test technologies that will enable the safe and economic production of methane gas from hydrates and develop environmental impact assessment methodologies.
5. Promotion of International Cooperation: Through participation in overseas projects, MH21 will grasp the trends of overseas studies on exploration, development, and basic research on methane hydrate with the goal to utilize the results of these international cooperative opportunities to further promote projects in Japan. MH21 will promote technical exchanges with overseas researchers in view of academic achievements, information, and human resources, while fully supporting mutually beneficial relationships.

In August of 2008, the Research Consortium for Methane Hydrate Resources in Japan (2008) released a report titled "Phase-1 Comprehensive Report of Research Results", which included a relatively complete review of the expected components of the proposed 2012/2013 methane hydrate production test in the Nankai Trough. In 2008, it was anticipated that production tests would focus on sand layers at water depths of approximately 1,000 m and formation depths of approximately 1,200 mbsf. For the offshore production tests targeting the methane hydrate-bearing sand layers it is assumed that conventional oil and natural gas exploitation technologies would be used. However, it is also assumed that the test could differ to some degree from procedures used to test conventional offshore gas resources based on the knowledge gained from the onshore production test experience at Mallik. The offshore methane hydrate production tests as envisioned will be the first marine methane hydrate test in the world. It is assumed that approximately three years of planning will be necessary for research and preparation in order to safely carry out the offshore production tests.

Specific Goals of Phase-2 (2009-2105) of the "Japan Methane Hydrate R&D Program".

1. Research and development concerning field development technology
- *1.1. Implementation of offshore production test*
  - *1.1.1. Implementation of technology development*
  - *1.1.2. Formulation of implementation plan*
  - *1.1.3. Implementation of test*
  - *1.1.4. Analysis of test results*
  - *1.1.5. Evaluation of reservoir at the test target area*
  - *1.1.6. Environmental impact assessment of test site*
- *1.2. Define and characterize offshore methane hydrate field*
  - *1.2.1. Detailed geological modeling and reservoir characterization*
  - *1.2.2. Conduct reservoir evaluation*
- *1.3. Investigate offshore development system*
  - *1.3.1. Conceptual design of offshore development system*
  - *1.3.2 Technical study on drilling, well stabilization, and well completion*
- *1.4. Analysis of onshore methane hydrate production tests*
  - *1.4.1. Analysis of the second onshore methane hydrate production test results*
  - *1.2.2. Implementation of long-term onshore methane hydrate production tests*

2. Research and Development concerning production method development
- *2. 1. Development of advanced production technology*

2.1.1. *Development of technology for enhancing methane productivity*
2.1.2. *Development of technology to counter/control production impediments*
2.1.3. *Verification with large-scale laboratory test equipment*
2.2. *Development of evaluation technology for productivity and production behaviors*
2.2.1. *Functional improvement of production simulator (MH21-HYDRES)*
2.2.2. *Development of three-dimensional reservoir modeling capabilities*
2.2.3. *Estimation and verification of production test*
2.2.4. *Prediction and verification of production test*
2.3. *Development of evaluation technology for sediment characterization*
2.3.1. *Functional improvement of sediment deformation simulator*
2.3.2. *Evaluation of well integrity*
2.3.3. *Evaluation of sediment deformation*

3. *Research and development concerning resources assessment*
3.1. *Evaluation of methane hydrate resources off the coast of Japan*
3.1.1. *Estimation of the distribution of methane hydrate concentrated zones*
3.1.2. *Comprehensive evaluation of methane hydrate distribution*
3.2. *Investigation of the methane hydrate system*
3.2.1. *Construct methane hydrate system model*

4. *Research and Development concerning environmental impact assessment*
4.1. *Analysis on environmental risks and examination of countermeasures*
4.2. *Development of environmental measurement technologies*
4.3. *Assessment of environmental impacts during tests*
4.4. *Optimization of assessment methods in methane hydrate development*

5. *Evaluation of economic feasibility of methane hydrate development*
5.1. *Review evaluation of economic feasibility of the methane hydrate development*

The following discussion relative to the recent results of the MH-21 Nankai Trough 2012-1013 pre-production test drilling and geoscience field program has been extracted from a series of abstracts associated with four presentations from the 2012 Fall Meeting of the American Geophysical Union (Fujii et al., 2012; Suzuki et al., 2012; Tamaki et al., 2012; Yamamoto et al., 2012a). The Japan methane hydrate project summary report as presented in the 2012 summer issue of the US-DOE Fire-in-the-Ice newsletter series was also used in the following review (Yamamoto et al., 2012b).

The deepwater drilling vessel *D/V Chikyu*, which belongs to the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), was used for drilling and coring operations to establish the MH-21 Nankai Trough 2012-1013 test site, named the AT1 site. The location for the test site was determine through the advanced analysis of 3D seismic data and were calibrated with well log and core data collected during the 2004 Tokai-oki to Kumano-nada drilling project. At the AT1 site, one production well (AT1-P), two monitoring wells (AT1-MC and MT1), and one core well (AT1-C) were established in 2012.

An extensive LWD and wireline-logging program was conducted in the AT1-MC well to evaluate physical reservoir properties of the methane hydrate-bearing sediments and to select the stratigraphic section to be tested in 2013. The well logs from the AT1-MC well 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. Well log correlations between the AT1-MC and MT1 wells, which are separated by a distance of 40 m, exhibit good lateral continuity for the targeted test sand section. In order to obtain additional reservoir and seal property data from the AT1 test site, pressure coring using the new Hybrid

Pressure Coring System (Hybrid-PCS) and non-destructive core analysis using the Pressure Core Analysis and Transfer System (PCATS) were conducted in the AT1-C well, which is located about 10 m northeast of AT1-MC. At the time of this report, the MH21 science team was working on integrating the log, core and other data from the 2012 MH21 drilling campaign at AT1.

The long-term plan has been to conduct the methane hydrate production flow test in the spring of 2013. The planned test has been described as "drill stem test", which are often used in exploratory and appraisal drilling of conventional oil and gas wells. In a series of news releases (http://www.jogmec.go.jp/english/information/news_release/docs/2012/newsrelease_130312.pdf; http://www.yomiuri.co.jp/dy/business/T130319003171.htm) from March 2013, JOGMEC and MITI reported that they had completed a production test of methane hydrates off Aichi Prefecture on 19 March 2013, earlier than initially planned, due to bad weather and equipment problems. The production test had begun 12 March 2013 and was scheduled as a 14-day test. The ministry (MITI) indicated it was difficult to continue because of developing adverse weather conditions and problems associated with sand production from the well and performance issues with a downhole pump. However, the ministry said the test was "fairly successful" and the shortened period would not affect future research and development. It will continue to work toward establishing technologies to produce gas from methane hydrates on a commercial basis by 2018. According to current plans, depending on the results of the 2013 test, as second test in 2014 will be designed to acquire more quantitative data for the assessment of offshore methane hydrate production.

4.14. Mallik Gas HydrateTesting Projects (1998/2002/2007-2008)

As previously introduced in this report, the Mallik methane hydrate production research site in northern Canada has been the focus of three important methane hydrate field tests (i.e., Mallik Gas Hydrate Testing Projects 1998, 2002, and 2007-2008).

Scientific Objectives of the Mallik Gas Hydrate Testing Projects (1998/2002/2007-2008).

1. *At the time of the Mallik 1998 drilling program almost no field research had been undertaken to evaluate the in-situ properties of methane hydrates. The primary objective of this project was first to identify a suitable location with "proven" methane hydrate to conduct a drilling program to collect geologic and engineering data on in-situ methane hydrates.*
2. *Within the Mallik 2L-38 research well program, participating organizations from Japan sought to undertake a variety of verification studies in preparation for exploration drilling (in 1999) of methane hydrate deposits in the Nankai Trough, offshore Japan. These included the evaluation of technologies related to methane hydrate drilling, geophysics, casing and production at an onshore site with a known methane hydrate occurrence. In addition, a long-standing interest in methane hydrate occurrences in permafrost settings led the Geological Survey of Canada (GSC) and the U.S. Geological Survey (USGS) to propose a comprehensive science program to quantify the geologic, geophysical, geochemical and engineering properties of an Arctic methane hydrate occurrence.*
3. *The major objectives of the Mallik 2002 Gas Hydrate Production Research Well Program were to advance research pertaining to methane hydrate production and to assess the environmental implications of terrestrial methane hydrates, including*

geohazard and climate change considerations. The primary operational objective was to undertake a suite of well-constrained short term production experiments.

4. *Within the Mallik 2002 program, in-situ geothermal and geomechanical measurements, borehole and surface geophysical surveys, and a wide variety of core laboratory studies were designed to complement the production test program and to carefully quantify the reservoir properties.*
5. *The Mallik 2007-2008 research well program was designed to achieve the following objectives: (1) develop a geologic basis for characterizing the occurrence of methane hydrates at the Mallik site within a petroleum system model; (2) obtain the data and understanding of the physical properties needed to simulate the response and behavior of a producing methane hydrate reservoir; and (3) establish sustained methane production from a hydrate reservoir by applying depressurization and demonstrate the applicability of conventional hydrocarbon-production technologies.*

The JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well (Mallik Gas Hydrate Testing Project 1998), drilled in 1998 near the site of the Mallik L-38 well (Figures 4.34 and 4.35), included extensive scientific studies designed to investigate in-situ natural methane hydrates in the Mallik field area (Dallimore et al., 1999). The research goals of the Mallik Gas Hydrate Testing Project 1998 included the evaluation of engineering technologies used to drill and core methane-hydrate-bearing strata. A conventional arctic exploratory drill rig, owned and operated by Shehtah Drilling was mobilized to the site in early February 1998. A number of planning measures were taken to avoid drilling problems. For example, a plate-type heat exchanger was used to chill the drilling mud in an attempt to minimize permafrost thawing and to depress the mud temperatures lower than the in-situ formation temperatures when drilling the methane hydrate interval. Drilling of the well began 16 February 1998 and reached the target depth of 1,150 m on 22 March 1998. The hole was first drilled and cased to a depth of 677 m, which is below the depth of the permafrost section. An attempt was made to core from 105 to 176 m with only limited success (eight core runs with a 20.6% average core recovery). After setting the permafrost casing, the hole was then drilled to a core point at 790 m above the main hydrate section. A total of 16 core runs were conducted in the hydrate interval below the core point at 790 m with an average core recovery of 42.1%. In all, 24 coring runs were conducted in Mallik 2L-38 well using the Baker Hughes Inteq (BHI) CoreDrill system, a specially designed pressure-temperature coring system (PTCS), and two different sizes of BHI conventional pipe conveyed core-barrel systems. After coring, the hole was drilled to the target depth of 1,150 m and was wireline logged with the following set of Schumberger provided tools: Array Induction Imager Tool (AIT-EMS-GR-SP), Platform Express (HALS), Dipole Shear Sonic Imager (DSI-GR-AMS), and Fullbore Formation MicroImager (FMI-HNGS).

The cored and downhole-logged methane hydrate intervals in the Mallik 2L-38 well exhibit both high electrical resistivities and rapid acoustic velocities. In total, the methane hydrate-bearing strata was approximately 150 m thick within the depth interval 889 to 1,101 m. Core samples revealed pore-space methane hydrate and several forms of visible methane hydrate in a variety of reservoir-quality unconsolidated sands and gravels interbedded with non-hydrate-bearing silts.

In a recent study, industry-acquired 3D seismic reflection data were used to characterize the occurrence and spatial extent of the Mallik methane hydrate accumulation (Bellefleur et al., 2006). The seismic interpretation technique used in this effort was based on inverting the seismic data to derive acoustic impedances from which acoustic velocity and hydrate saturations can be estimated. This inversion indicates that the deepest methane hydrate interval at Mallik covers an area of only 900,000 m^2, and there is about 771,000,000 m^3 (~27 billion cubic feet) of gas (at standard temperature and pressure, STP) within the Mallik methane hydrate accumulation.

Because of the success of the 1998 Mallik 2L-38 methane hydrate research well program (Mallik Gas Hydrate Testing Project 1998), the Mallik site was accorded to be an important methane hydrate production test site, and two additional methane hydrate production research programs were conducted: (1) The Mallik 2002 Gas Hydrate Production Research Well Program, and (2) the 2007-2008 JOGMEC/NRCan Mallik Gas Hydrate Production Research Program.

In June 2005, the partners in the Mallik 2002 Gas Hydrate Production Research Well Program publicly released the results of the first modern, fully integrated field study and production test of a natural methane hydrate accumulation (Dallimore and Collett, 2005). The 2002 Mallik International Consortium was composed of the Japan Oil Gas and Metals National Corporation, Geological Survey of Canada, U.S. Geological Survey, U.S. Department of Energy, GeoForschungZentrum-Potsdam, the Indian Ministry of Petroleum Geology and Natural Gas, Gas Authority India Ltd., and the International Continental Scientific Drilling Program. From 25 December 2001 through 15 March 2002 the Mallik 2002 Gas Hydrate Production Research Well Program drilled three wells (Figure 4.35) — the JAPEX/JNOC/GSC et al. Mallik 3L-38 and 4L-38 observation wells and Mallik 5L-38 gas hydrate production test well in the Mallik Gas Hydrate Field.

The Mallik 5L-38 well cored and recovered methane hydrates and associated sediments from an interval between 880-1150 m depth (Figure 4.36). These cores were the subject of intensive examination by members of the Mallik Partnership, including scientists and engineers enabled by the International Continental Scientific Drilling Program. Detailed information on the geology, geochemistry, geotechnical, and microbiological properties of methane hydrate-bearing sediments was complemented by an extensive research geophysics program, which included both surface seismic surveys and downhole logging studies. This body of scientific data was designed to complement a novel production testing program, providing the world's most detailed scientific and engineering dataset describing the occurrence and production characteristics of methane hydrates.

More than 150 m of high quality cores were collected during the Mallik 2002 program, allowing for a wide variety of studies. New work included investigations of the kinetics of methane hydrate dissociation from the solid to the gaseous form, studies of the petrophysical properties, investigations of the molecular chemistry and geotechnical properties such as compressive strengths and stress regime. A wide range of geophysical studies were also carried out to quantify methane hydrate distribution. A key aspect of this program was to test new geophysical tools as methods to remotely quantify methane hydrates. Fiber optics instrumentation documented the geothermal regime with meter-scale precision. Surface, downhole, and cross-hole seismic studies were carried out as were a number of advanced well log studies. Downhole measurements allowed for direct estimates of in-situ permeability, and methane hydrate content, and investigations of the natural fractures.

One of the major goals of the Mallik 2002 Gas Hydrate Production Research Well Program (Dallimore and Collett, 2005) was to advance research pertaining to methane hydrate production by undertaking a suite of well-constrained short-term production experiments. The scientific objectives of the Mallik 2002 production testing effort were to confirm the feasibility of natural gas production by depressurization and thermal-stimulation techniques. It is important to note that the Mallik 2002 testing program was not designed as a conventional industry-style production test to evaluate commercial recovery. Rather, it was designed as a series of controlled experiments to (1) test the response of in-situ methane hydrate to changes in pressure and/or temperature conditions, and (2) provide critical engineering data needed to develop, constrain, and calibrate methane hydrate production simulators capable of predicting long-term reservoir response. With these goals in mind, the Mallik 2002 production tests produced gas from methane hydrate with a series of well-constrained and controlled production experiments, each designed to investigate the response of *in-situ* methane hydrate deposits to changes in pressure or temperature. The Mallik 2002 production test results, combined with other project data, were also used to calibrate methane hydrate production simulators, which were then used to predict the expected long-term response of the methane hydrate beyond the duration and conditions of the actual tests.

During the Mallik 2002 testing program, the response of methane hydrates to heating and depressurization was evaluated with careful attention to accurately measuring both input conditions and reservoir responses. Pressure drawdown experiments were designed to study the response of methane hydrate to a reduction in formation pressure conditions. The Mallik 2002 pressure-drawdown tests were conducted using Schlumberger's Modular Formation Dynamics Tester (MDT) wireline tool. The MDT tool was used to conduct small-scale pressure-drawdown tests within five perforated intervals in the Mallik 5L-38 well. The rationale for most of the MDT tests was to reduce reservoir pressure below methane hydrate stability conditions and then "shut-in" the tool to observe the pressure build-up attributed to flowing formation fluids and methane hydrate dissociation. The results of three short duration methane hydrate tests demonstrate that gas can be produced from methane hydrates with different concentrations and characteristics, exclusively through pressure stimulation (Figure 4.37). It was shown by Hancock et al., (2005) that the response of the hydrate-bearing sand reservoirs was similar to a conventional porous-media response. Thus, conventional pressure-transient analytical techniques were used to evaluate the Mallik 2002 MDT test data. Horizontal permeabilities range from less than 0.001 mD to as high as 0.1 mD within hydrate-bearing porous media. In contrast, the expected intrinsic permeability (i.e., without methane hydrate) of the same sands with only water filling the pores would be on the order of 100 to 1,000 mD. The existence of measurable permeability in a reservoir with high methane hydrate saturations (up to 85%) was unexpected. Downhole-measured NMR-log data from the Mallik 5L-38 well also indicated the presence of a movable free-water phase within the hydrate-bearing sandstone reservoirs, which likely represents the compressive porous-media fluid phase along which flow was established and measured during the MDT methane hydrate tests. Downhole acoustic log data from Mallik also shows that methane hydrate occurs as matrix-supporting pore-filling material rather than a grain-coating substance. The presence of an interconnected fluid phase at measurable permeabilities indicates that methane hydrate reservoir-depressurization production techniques may be more effective than previously thought.

Thermal stimulation experiments were designed to destabilize methane hydrates by using circulated hot water to increase the in-situ temperature. A five-day experiment was undertaken within a 13-m-thick section of highly concentrated methane hydrate-bearing strata. The test was conducted by circulating hot fluids (50°C) down the hole at a constant pressure slightly above hydrostatic conditions. Gas from dissociated hydrate flowed to the surface, separated from the circulating fluid, measured, sampled and flared. Gas was continuously produced throughout the test at varying rates with maximum flow rate reaching 360 cubic meters per day (Dallimore and Collett, 2005; Figure 4.38). The total volume of gas flowed was small, reflecting that the test was a controlled production experiment rather than a long duration conventional well test. It also demonstrated the difficulty of heating a relatively large rock mass by conductive heat flow alone.

The Mallik 2002 production research well program proved for the first time that gas production from methane hydrates is technically feasible. The resulting thermal and depressurization production data have allowed the calibration of several reservoir models that were used to simulate the thermal and depressurization tests. Part of the calibration process has been the recognition that methane hydrate deposits are much more permeable than previously thought, they contain natural fractures, and that they may be fractured artificially. Calibrated models must therefore include full appraisal of the unique attributes of the specific methane hydrate field. The Mallik data allowed for the rational assessment of the production response of a methane hydrate accumulation if the various tests were extended far into the future. These studies also show that, among the possible techniques for production of natural gas from in situ methane hydrates, depressurization would produce more gas than just heating the formation. However, applying the combination of heating and depressurizing the methane hydrate simultaneously would produce the greatest amount of gas.

The Mallik 2002 project contributed much to the understanding of methane hydrates; however, it fell short of delivering all of the data needed to fully calibrate existing reservoir simulators. Longer duration production tests will be required to assess more definitively the technical viability of long-term production from methane hydrates; the 2007-2008 JOGMEC/NRCan Mallik Gas Hydrate Production Research Program (Mallik Gas Hydrate Testing Project 2007/2008) was designed to address this need.

As described by Dallimore et al., (2008a, 2008b) and Yamamoto and Dallimore (2008), the 2007-2008 JOGMEC/NRCan Mallik Gas Hydrate Production Research Program was conducted by JOGMEC, NRCan, and the Aurora College/Aurora Research Institute to build on the results of the Mallik 2002 project with the main goal of monitoring long-term production behavior of methane hydrates. The primary objective of the winter 2006-2007 field activities was to install equipment and instruments to allow for long-term production methane hydrate testing during the winter of 2007-2008. The Mallik 2L-38 and Mallik 3L-38 wells (Figure 4.35) were re-entered and each well was logged to establish formation properties prior to testing. After completing drilling operations during the 2006-2007 phase of the project, a short pressure drawdown test was conducted to evaluate equipment performance and assess the short term "producibility" of the methane-hydrate-bearing reservoir. A 12-m-thick methane hydrate interval (1,093-1,105 m), near the base of the methane hydrate stability zone, was tested for 60 hours by reducing the bottomhole pressure down to ~7.3 MPa (equal to a drawdown pressure of ~3.7 MPa). Irregular pumping operations, related to excessive sand production, resulted in unstable fluid flow, which greatly complicated the analysis of the test. However, during the most successful 12.5 hours of the test, at least 830 m^3 (~29, 300 ft^3) of gas were produced. The test results verified the effectiveness of the depressurization method even for such a short duration.

The following winter (2007/2008), the team returned to the site to undertake a longer-term production test with the implementation of countermeasures to overcome the problems encountered in the previous year's program. The 2007/2008 field operations consisted of a six-day pressure drawdown test, during which "stable" gas flow was measured at the surface (Figure 4.39). The 2007/2008 testing program at Mallik established a continuous gas flow ranging from 2,000 to 4,000 m^3/day (~70,000 to 140,000 ft^3/day), which was maintained throughout the course of the six-day (139-hour) test (Yamamoto and Dallimore, 2008; Dallimore et al., 2008b). Cumulative gas production volume was approximately 13,000 m^3 (~460,000 ft^3). Total water production during the test was less than 100 m^3 (~850 barrels) (Dallimore et al., 2008b). The 2007/2008 Mallik production tests have shown that "sustained" gas production from hydrates can be achieved by depressurization alone.

As concluded by Dallimore et al., (2012), all of the Mallik gas hydrate research programs have contributed greatly to our understanding of the energy resource potential of methane hydrates. However, more work is needed to understand the longer term production response of methane hydrates and additional production data are required to develop a practical understanding of their energy resource potential.

Scientific Conclusions and Contributions of the Mallik Gas Hydrate Testing Projects (1998/2002/2007-2008).

1. *The Mallik 1998 project was the first investigation of a natural methane hydrate occurrence beneath permafrost that included extensive dedicated coring and associated engineering and scientific studies.*
2. *During the Mallik 1998 drilling program four coring systems were utilized, including a pressure-temperature coring device (PTCS), a conventional wireline core system, and two conventional drill-string-deployed core barrels. Approximately 37 m of high quality core were collected to characterize an interbedded methane hydrate stratigraphic section. Pore-space methane hydrate and several forms of visible methane hydrate were observed in a variety of sediments. An extensive suite of conventional open hole well logs were also recovered and analyzed from the Mallik 2L-38 well.*
3. *Analysis of the core and well log data from the Mallik 2L-38 well revealed that methane hydrate occurred primarily in sandy sediments with a porosity of 32-45% and in gravel with a lower porosity of 23-29%. The non-methane-hydrate bearing or low methane hydrate content silts generally had similar or slightly lower porosities compared to the sands.*
4. *Based on molecular and isotopic composition of the gases recovered from the Mallik 2L-38 well, it was established that the hydrates at the Mallik site are made-up of methane from a mixture of microbial and thermogenic sources.*
5. *Pore-water geochemistry of sediments recovered from the Mallik 2L-38 well and concluded that sands and gravels with significant methane hydrate content had average salinities of 8 ppt, compared with 34 ppt for non-methane hydrate bearing sediments. This difference in salinities suggests that up to 90% of the pore space in some intervals was filled with methane hydrate.*
6. *Downhole electrical resistivity and acoustic transit-time logs from the Mallik 2L-38 well confirm the occurrence of in-situ methane hydrate at the Mallik drill-site within the subsurface depth interval from 888.8 to 1101.1 m, with well log derived methane hydrate saturations as high as 90%. While the log derived sediment porosities in the methane-hydrate-bearing units of the Mallik 2L-38 well averaged about 30%.*
7. *The Mallik 2002 Gas Hydrate Production Research Well Program included open hole well logging and continuous wireline coring from 885 to 1151 m through the main methane hydrate intervals and below the base of the methane hydrate stability zone. A diverse suite of open hole well logs were completed in the lower interval of the production well with an emphasis on advanced methane hydrate well logging tools. Small scale production tests, consisting of pressure drawdown experiments, were completed in isolated methane-hydrate-bearing intervals of varying methane hydrate saturations. A longer duration thermal stimulation production test was carried out by circulating warm fluids past a 13-m-thick perforated zone with high methane hydrate saturation.*
8. *On the basis of the well log interpretations, approximately 110 m of well defined*

methane-hydrate-bearing strata were encountered in Mallik 5L-38 between 892 m 1107 m. In-situ methane hydrate saturations determined by the analysis of well log data typically ranged from a 50% to 90%. The main methane hydrate zones within the Mallik 5L-38 well can be correlated laterally with the methane hydrate occurrences in the Mallik L-38 and 2L-38 wells. A volumetric estimate using data from the three wells yields 5.39 x 107 m^3 of in-place gas within a local 100 m by 100 m block defined by the wells.

9. *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, each designed to investigate the response of hydrate deposits to changes in pressure and temperature conditions.*
10. *Within the Mallik 2002 program, production test results were combined with other project data to calibrate methane hydrate production simulators.*
11. *The Mallik 2007-2008 research well program successfully established proof of concept that sustained gas production can be achieved by depressurization of methane hydrate reservoirs using conventional oil and gas drilling, completion, and productions methods.*
12. *The Mallik 2007-2008 research well program established the following scientific findings: (1) the development if a petroleum-system model for the emplacement of a methane hydrate field by migrating thermogenic methane along near vertical faults into an overlying regionally extensive structural anticline; (2) quantification of the geologic, geophysical, and geomechanical properties of methane hydrate reservoir sands and enclosing sediments; and (3) establish six days of continuous gas production by reservoir depressurization, with sustained gas- and water-flow rates averaging about 2,000 and 10 m^3 per day respectively, and peak gas-flow rates in the range of 3,500-4,000 m^3 per day.*

4.15. Alaska Mount Elbert Stratigrahic Test Well (2007)

Under the Methane Hydrate Research and Development Act of 2000 (renewed in 2005), the DOE has funded laboratory and field research on both Arctic and marine methane hydrates. Among the current Arctic studies, BP Exploration (Alaska), Inc. (BPXA) and the DOE have undertaken a project to characterize, quantify, and determine the commercial viability of methane hydrates resources in the Prudhoe Bay, Kuparuk River, and Milne Point field areas on the Alaska North Slope (Figure 4.40).

The Alaska, Milne Point area, Mount Elbert Gas Hydrate Stratigraphic Test Well was completed in February 2007 and yielded one of the most comprehensive datasets yet compiled on naturally-occurring methane hydrates (Boswell et al., 2008; Collett et al., 2011). This project started in 2002, following BPXA's response to a DOE request for proposals to evaluate the methane hydrate resources on the North Slope. Over the following three years, the project team conducted regional geological, engineering, and production modeling studies through collaborations with the University of Alaska (Fairbanks), the University of Arizona, and the Ryder-Scott Company. In 2005, extensive analysis of BPXA's proprietary 3-D seismic data and integration of that data with existing well log data (enabled by collaborations with the USGS and Interpretation Services, Inc.; Lee et al., 2009; Inks et al., 2009), resulted in identifying more than a dozen discrete and mapable methane hydrate prospects within the Milne Point area. Because the most favorable of those targets (Figure 4.41) was a previously undrilled, fault-bounded accumulation, BPXA and the DOE decided to drill a vertical stratigraphic test well at that location (named the “Mount Elbert” prospect) to acquire critical reservoir data needed to develop a longer term production testing program.

Scientific Objectives of the Alaska Mount Elbert Stratigrahic Test Well (2007).

1. *Acquire geologic and engineering data including whole rock core, wireline logs, and wireline formation pressure tests data from an arctic permafrost methane hydrate accumulation.*
2. *Use acquired geologic data to constrain estimates of methane hydrate resources in northern Alaska and identify candidate sites for a long-term methane hydrate production tests.*
3. *Confirm and calibrate pre-drill seismic predictions for the occurrence of methane hydrate with the drilling results and data from Mount Elbert test well.*
4. *Obtain reservoir engineering data to reduce uncertainty of key methane hydrate-bearing reservoir properties, enable further refinement and validation of the numerical simulation of the production potential of both Arctic and marine methane hydrates.*
5. *Demonstrate that a methane hydrate scientific research program can be safely and efficiently executed within Alaska North Slope infrastructure.*

The Mount Elbert gas hydrate stratigraphic test well was designed as a 22-day program with the planned acquisition of cores, well logs, and downhole production test data. A surface hole was first drilled and cased to a depth of 595 m. The well was then continuously cored to a depth of 760 m with chilled oil-based drilling fluid using the ReedHycalog Corion wireline-retrievable coring system. This core system delivered 85% recovery through 154 m of hydrate- and water-bearing sandstone and shale. The coring team processed these cores on site, and collected subsamples for analyses of pore water geochemistry, microbiology, gas chemistry, petrophysical properties, and thermal and physical properties. Core samples were also stored in liquid nitrogen or transferred to pressure vessels for future study of the preserved methane hydrates. After coring, the well was reamed and deepened to a depth of 915 m, and was surveyed with a research-level wireline-logging program including nuclear magnetic resonance and dipole acoustic logging, resistivity scanning, borehole electrical imaging, and advanced geochemistry logging. Following logging, Schlumberger’s Modular Dynamic Testing (MDT) was conducted at four open-hole stations in two hydrate-bearing sandstone reservoirs. Each test consisted of flow and shut-in periods of varying lengths, with one lasting for more than 13 hours. Gas was produced from the methane hydrates in each of the tests.

Methane hydrates were expected and found in two stratigraphic zones (Figures 4.42 and 4.43), — an upper zone (Unit D) containing ~14 m of methane hydrate-bearing reservoir-quality sandstone, and a lower zone (Unit C) containing ~16 m of methane hydrate-bearing reservoir. Both zones displayed methane hydrate saturations that varied with reservoir quality, with typical values between 60% and 75%. This result conclusively demonstrated the soundness of the methane hydrate prospecting methods developed primarily at the USGS (Lee et al., 2009; Inks et al., 2009).

The Alaska Mount Elbert gas hydrate stratigraphic test well project included the acquisition of pressure transient data from four short-duration open-hole, dual-packer pressure-drawdown tests using Schlumberger’s wireline MDT (Boswell et al., 2008; Anderson et al., 2008). These tests were conducted in open-hole, and were designed to build upon the knowledge gained from cased-hole MDT tests conducted during the Mallik 2002 testing program. A unique aspect of the Mount Elbert program was that these experiments were conducted in the open hole, removing many complexities related to the

nature and effect of casing perforations. In comparison to the Mallik 2002 MDT tests, the individual Mount Elbert tests were of much longer duration, with the test lengths ranging from 6 to nearly 13 hours.
Four one-meter-thick zones were tested in the Mount Elbert well: two in Unit C (tests C1 and C2) and two in Unit D (tests D1 and D2). Each test consisted of multiple stages of varying duration, with each stage consisting of a period of fluid withdrawal (thereby reducing formation pressure) followed by a period where the pump is shutoff and the subsequent pressure build-up is monitored (Figure 4.44). Gas and water samples were collected during selected flow periods and a fluid analyzer on the MDT tool enabled the identification (but not volumetric measurement) of gas and water as it entered the tool. Also a small programmable sensor was attached to the outside of the tool in order to monitor temperature changes during each test.

To investigate the petrophysical properties of the hydrate-bearing reservoirs, each of the four tests within the Mount Elbert MDT program began with a "pre-flow test" in which pressure was reduced enough to mobilize unbound formation water but not enough to induce methane hydrate dissociation. To provide insight into methane hydrate response to small-scale pressure transients, the pre-flow tests were followed by numerous test stages in which the pressure reduction was great enough to induce methane hydrate dissociation. Much like the MDT results and downhole-measured NMR logs from the Mallik 5L-38 well (as discussed above in this report), the MDT and NMR log data from the Mount Elbert well also confirmed the presence of a mobile pore-water phase even in the most highly methane hydrate-saturated intervals. In the Mount Elbert Unit D sand, the mobile water phase was determined to be about 8 to 10 percent of total pore volume, and in the Unit C sand, it appears to range upward to ~15% (Anderson et al., 2008). The presence of a mobile water phase therefore appears to be required for the initiation of depressurization for a methane hydrate reservoir not in contact with underlying free-gas or water reservoirs.

The MDT test data from the early pre-flow stage that targeted fluid withdrawal without methane hydrate dissociation produced pressure responses that are typical of low-permeability porous media much like the Mallik 2002 MDT tests. Analysis of these pre-flow tests in a variety of advanced reservoir simulators (Anderson et al., 2008) has yielded reservoir permeabilities, in the presence of a methane hydrate phase, of 0.12 to 0.17 mD. Methane hydrate dissociation and production was confirmed in the latter stages of each test in which the pressure was drawn down below methane hydrate equilibrium conditions. All of the pressure transient data from each of the shut-in periods after methane hydrate was dissociated exhibited the same but unexpected behavior: (1) in comparison to the pre-flow shut-in pressures (in which methane hydrate was not dissociated) the measured formation pressures exhibited a dampened response with the pressures building relatively slowly, and (2) the slope of the pressure build-up curves steepened slightly (or kinked upward) as the measured pressures increased. Both phenomena were repeated in each MDT tests that produced methane hydrate. It is clear that these are manifestations of some as yet poorly understood process. Analysis of the MDT test data with methane hydrate computer simulations (Anderson et al., 2008), indicate that the most likely scenario for the observed dampened pressure responses is tied to low gas production volumes and the effects of fluid storage in the annular space around the MDT tool.

Scientific Conclusions and Contributions of the Alaska Mount Elbert Stratigrahic Test Well (2007).

1. NMR-density porosity derived saturations and other log analyses as well as pore water studies indicate methane hydrate saturations in units C and D range from 50 to 75% with a clear linkage to reservoir quality, physical properties, and irreducible water saturations.

2. Laboratory cryogenic scanning electron microscopy, nuclear magnetic spectroscopy, powder X-Ray diffraction, and Raman spectroscopy analysis reveals that that hydrates recovered in the Mount Elbert cores had a cage occupancy of over 99% methane and were a Structure I hydrate that occupied pores between the sediment grains at approximately 70-75% saturation and sporadically as thin veins typically several tens of microns in diameter.

3. Methane hydrate saturations estimated from the analysis of dissolved pore water chlorinates agree with estimates based on logging data when the methane hydrate occupies more than 20% of the pore space; the correlation is less robust at lower saturation values.

4. Gas geochemistry studies from core samples confirmed the thermogenic geochemical signature of reservoir gas and sourcing through microbial biodegradation of hydrocarbons associated with deeper conventional oil and gas reservoirs.

5. It was shown that small reductions in porosity (<4%) correspond to an order of magnitude reduction in intrinsic formation permeability. These studies also confirm prevailing views that lithology and lithostratigraphically-influenced intrinsic permeability and exert primary control on the degree of methane hydrate saturation within porous media.

6. The acquisition of extensive wireline log data enabled comparing the performance and resolution of various log-based methods used to determine methane hydrate saturation. The results indicate a high level of confidence in log-based determinations, particularly when methane hydrate saturations are relatively high (greater than 60% in most cases).

7. Data from the Mount Elbert well validated the pre-drill geophysical interpretations by confirming approximately 30 m of combined highly-saturated methane hydrate-bearing sand reservoirs within units C and D reservoir intervals.

8. The acquired geological, geophysical, and geochemical data also help support the theory that the Mount Elbert hydrate-bearing reservoirs likely represent pre-existing gas accumulations that were later converted to methane hydrate by onset of methane hydrate stability conditions associated with permafrost formation.

9. Analysis of initial pre-flow phase MDT tests (without hydrate dissociation) and NMR wireline log data determined the mobile water phase in the unit D sand to be about 8-10% of the total volume, and in the unit C sand, it appears to range upward to approximately 15%.

10. The MDT test data from each of the early pre-flow stages that targeted fluid withdrawal without methane hydrate dissociation produced pressure responses that typically indicate low permeability porous media, similar to observations of the Mallik 2002 MDT tests. Analyses of these pre-flow tests in a variety of advanced reservoir simulators have yielded reservoir permeabilites in the presence of a hydrate phase of 0.12-0.17 mD.

11. The reservoir data acquired in the Mount Elbert well program enabled reservoir International Code Comparison Project helped evaluate and compare multiple *simulation at both field and pore scales. Analyses of MDT data within the methane hydrate numerical modeling codes and confirmed the ability of those codes to estimate methane hydrate production rates through depressurization.*

12. Reservoir simulations based on an idealized Mount Elbert unit D geologic model have better constrained the range of possible production responses across variable methane hydrate occurrences within the Eileen accumulation and indicate these methane hydrate-bearing reservoirs may be capable of gas production through sustained dissociation by depressurization. These reservoir characterization and modeling techniques have also been applied to identify, compare, and select prospective future production test sites.

4.16. Alaska Iġnik Sikumi Gas Hydrate Production Test Well (2011-2012)

Although methane hydrates are present in numerous marine and Arctic settings, until recently little was known about the technology necessary to produce gas from them. Proposed methods of gas recovery from hydrates (reviewed by Collett, 2002) generally deal with dissociating or "melting" in-situ methane hydrates by (1) heating the reservoir above hydrate formation temperatures, (2) injecting a thermodynamic inhibitor such as methanol or glycol into the reservoir to decrease hydrate stability, or (3) decreasing the reservoir pressure below the hydrate equilibrium. Recently, several studies have shown that it may be possible to produce methane from hydrates by displacing methane molecules in the hydrate structure with carbon dioxide (CO_2), thus releasing methane and sequestering the carbon dioxide (Graue et al., 2006).

Building on promising laboratory studies dealing with methane hydrate CO_2 exchange technology, ConocoPhillips and the US-DOE entered into a cooperative research agreement in 2008 with the goal to develop a multi-year field trial to investigate CO_2 injectivity and the exchange potential of CO_2 with methane (CH_4) in a hydrate-bearing reservoir on the Alaska North Slope (Schoderbek et al., 2012). This project was a multidisciplinary effort that incorporated laboratory and computer simulation models to design the CO_2-CH_4 exchange field test. The criteria used to select the location of the test site included the consideration of the proximity to established infrastructure including roads and production gravel pads, and the occurrence of known hydrate deposits with multiple reservoirs at suitable temperature and pressure conditions. A site was chosen near the L-Pad in the Prudhoe Bay Unit, downhole log data from nearby wells indicated that the Eileen methane hydrate accumulation likely extended across the area of the proposed test site and the test well, named Iġnik Sikumi #1, would likely encounter three hydrate-bearing sandstone reservoirs within the depth interval from 115 to 735 m.

Scientific Objectives of the Alaska Iġnik Sikumi Methane Hydrate Production Test Well (2011-2012).

1. Collaborate with the University of Bergen to develop reservoir scale magnetic resonance imaging experiments to characterize the CO_2-CH_4 hydrate exchange process and efficiencies.

2. Conduct laboratory experiments to (1) evaluate the role of free-water on hydrate *reformation and reservoir permeability, (2) to determine the effect of N2 injection on the CO_2-CH_4 exchange process, and (3) collect experimental depressurization data for simulation model development.*

3. *Develop hydrate reservoir modeling capabilities to simulate the in-situ CO_2-CH_4 hydrate exchange process.*
4. *Obtain geologic and geophysical data needed to locate and quantify methane hydrate deposits suitable for the Iġnik Sikumi field trial.*
5. *Gain experience in drilling and completion technologies related specifically to methane hydrate production.*
6. *Completion of a full quality check of the data from the Iġnik Sikumi well and initial analysis of both the injection and production phases of the test.*
7. *Obtain the data and knowledge to design longer-term production tests needed to advance viable production technologies for methane hydrates.*

The Iġnik Sikumi #1 was spudded by Nordic-Calista Rig 3 on 9 April 2011 and reached planned target depth for the well of 792 m (2,597 ft) on 16 April 2011. Mudlog data, LWD, and a complete wireline logging data suite was collected from the well. The open-hole wireline log suite included acoustic and NMR tools for advanced analysis of methane hydrate saturations. A total of three hydrate-bearing sandstone sections were encountered in the well: unit C, unit D, and unit E (Figure 4.45). The NMR-based and multi-mineral models generated the most reliable values for hydrate saturation, indicating methane hydrate saturations as high 75% in the upper part of unit C. The NMR log also clearly indicated that the remaining pore volume in these hydrate-bearing intervals was filled with a combination of clay-bound, capillary-bound, and movable water. After the well was logged, the wellbore was completed according to the design depicted in Figure 4.46.

Surface operations at the Iġnik Sikumi #1 wellsite re-commenced in mid-December 2011, with the building of a new ice pad and establishment of on-site camp facilities. Equipment for storage and handling of gaseous injectants (N_2, CO_2, and tracer gases) and circulating liquids (glycol-water mix for heating, and water for jet pump power fluid) was staged on the new ice pad. The injection phase of the Iġnik Sikumi test started on 20 February 2012, which featured the injection of a mixture of CO_2 and N_2 over a 12-day period and the well was then backflowed in the depressurization phase for 21 additional days. As reported by DOE, CH_4 was produced immediately at the start of the backflow period, increasing in abundance for two days, and then the produced-gas composition stabilized. Both CO_2 and N_2 abundance dropped from injection percentages at initial backflow to relatively low percentages in less than two days. In the later part of the depressurization phase of the project, the well was operated at pressures below the equilibrium conditions for CH_4 hydrate, which represents a critical data set to further calibrate methane hydrate production computer simulations. The Iġnik Sikumi depressurization test results have also provided invaluable insight to the design criteria for an extended methane hydrate depressurization test in Alaska.

One of the most notable scientific accomplishments of the trial was the identification of a specific mixture of N_2/CO_2 gas that would minimize the loss of injectivity due to the growth of additional CO_2 hydrate in the reservoir. After injecting 210 mscf of a mixture of CO_2/N_2 for 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. The final drawdown stage, which featured formation pressures below CH_4 hydrate stability, saw sustained gas production rates ranging from 20,000 scf/day to 45,000 scf/day. Most of the 162 mscf of injected N_2 was collected during the backflow stage of the test, but about half of the 48 mscf of injected CO_2 remained in the formation. The Iġnik Sikumi field test successfully demonstrated that CO_2 could be injected into a hydrate-filled, water-bearing reservoir, followed by CH_4 production, and CO_2/CH_4 exchange technology may technically feasible in the future (Schoderbek et al., 2012).

Scientific Conclusions and Contributions of the Alaska Iġnik Sikumi Methane Hydrate Production Test Well (2011-2012).

1. *Collaborate with the University of Bergen to develop reservoir scale Laboratory experiments conducted by ConocoPhillips and the University of Bergen demonstrated the effectiveness of exchanging CO_2 for CH_4 in the hydrate structure.*
2. *The Iġnik Sikumi well was successfully drilled to a depth of 792 m. As expected three hydrate-bearing sandstone units were encountered, and petrophysicaly evaluated.*
3. *Successfully wireline logged and instrumented the Iġnik Sikumi gas hydrate field trial well from an ice pad in the Prudhoe Bay Unit.*
4. *Four different well-log interpretation methods were used to quantify hydrate saturation in the Iġnik Sikumi well. The NMR-based and multi-mineral models generated the most reliable values for hydrate saturation, indicating approximately 75% hydrate saturations in the homogenous 14-m-thick upper unit C sand interval. The NMR log indicated that the remaining pore volume was filled with water.*
5. *NMR log analysis indicated that the complementary 25% water saturations in the upper unit C sand interval was comprised of clay-bound, capillary-bound, and movable water. It was determined that some fraction of this water would likely form additional hydrate during the injection phase of the test.*
6. *A cell-to-cell model or tank model, based on a concept of sequential flow in a multi-tank system was developed to determine the appropriate injectant composition and test design.*
7. *One of the most notable scientific accomplishments of the trial was the identification of the optimum mixture of N_2/CO_2 (23% CO_2, 77% N_2) gas that would minimize the loss of injectivity due to additional CO2 hydrate formation.*
8. *Collected a large suite of production data from the Iġnik Sikumi well, including continuous temperature and pressure monitoring and real-time data on return gas compositions and constituent volumes.*
9. *Approximately 210,000 scf of a N_2/CO_2 mixed gas was successfully injected into the upper part of the unit C sands over a thirteen day period. Pressure plots during the injection phase indicate normal "matrix injection" process with no fluid breakthrough or hydraulic fracturing of the reservoir.*
10. *Most of the 162,000 scf of injected N_2 was collected during the production stages more than half of the 48,000 scf injected CO_2 remained in the formation.*
11. *The depressurization stage of the test exceeded previous efforts in the field in both duration and cumulative gas collected. The final drawdown stage that was depressurized below hydrate stability saw an increase in produced gas from an initial 20,000 scf/day to 45,000 scf/day.*
12. *The Iġnik Sikumi field test successfully demonstrated that carbon dioxide could be injected into a hydrate-filled, water-bearing reservoir, followed by methane production, and applications of CO_2/CH_4 exchange technology may be commercially viable in the future.*
13. *Data from the Iġnik Sikumi 2011 drilling and logging operations and the 2012 production testing (injection and flowback) operations was compiled and publically released.*

5. Methane Hydrate Research Drilling Platforms

5.1. Science Platforms

The *JOIDES Resolution* has been utilized for numerous global methane hydrate research projects beginning with ODP Leg 164 in 1995. Other projects have included ODP Leg 204, Japan Tokai-oki to Kumano-nada Project, IODP Expedition 311, and the India NGHP Expedition 01. The science drilling vessel, *D/V Chikyu* has also been used to establish the JOGMEC methane hydrate production test site in the Nankai Trough during the MH-21 Nankai Trough Pre-Production expedition. Relative to the *JOIDES Resolution,* the *D/V Chikyu* has the added capability of a marine drilling riser with associated blowout preventer (BOP). The riser and BOP could afford methane hydrate researchers the benefit of a closed loop drilling mud system, enabling mud logging, the use of large diameter downhole logging and testing tools, and industry style borehole pressure management techniques. Both the *JOIDES Resolution* and the *D/V Chikyu* have integrated core laboratories well established to process conventional wireline cores.

The *JOIDES Resolution* is owned by Overseas Drilling Limited, a subsidiary of Siem Offshore AS, and the ship is operated by the IODP United States Implementing Organization (IODP-USIO). From 2007 to early 2009, the *JOIDES Resolution* was completely retrofitted with new laboratories, structural improvements and significant upgrades. For more information on the *JOIDES Resolution* "conversion", please see the following report as prepared by the Consortium for Ocean Leadership (2013).

The *JOIDES Resolution* has been described as a "floating laboratory" built on what was originally an oil exploration vessel. One of the greatest strengths of the *JOIDES Resolution* is the merger of industry drilling capabilities with one of the more advanced integrated earth science laboratories in the world. For additional information on the technical capabilities of the *JOIDES Resolution* and detailed description of the laboratories (Table 5.1) on the ship, please see the following reports as prepared by the Integrated Ocean Drilling Program (2013a, 2013b, 2013c, 2013d).

The *D/V Chikyu* was built by Mitsui Engineering & Shipbuilding and delivered to the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) on July 29, 2005. The *D/V Chikyu* was designed and constructed as a deep water scientific research drilling vessel. As noted above in this report, the *D/V Chikyu* was built around the concept of a riser drilling system, which are regularly used in the oil and gas industry. There are multiple benefits of riser drilling, which allows for drilling to much greater depths and the use of a BOP adds a significant margin of safety when dealing with unexpected high pressure flow of gas, oil or other formation fluids flowing from the well. But it is also important to highlight that many of the scientific boreholes drilled by the *D/V Chikyu* have been drilled under open-hole conditions without the use of the riser system on the ship. Much like the *JOIDES Resolution,* one of the most distinctive features of the *D/V Chikyu* is her onboard laboratory, which again is one of the most sophisticated ocean-going laboratories in the world. For more information on the technical capabilities of the *D/V Chikyu* and detailed description of the laboratories (Table 5.2) on the ship, please see the following reports as prepared by the Japan Agency for Marine-Earth Science and Technology (2013a, 2013b, 2013c)

In general, both *JOIDES Resolution* and the *D/V Chikyu* are ideal drilling vessels for the study of methane hydrates because of their advanced dynamic positioning capabilities and the combination of both riser and riserless drilling systems when considered together. However, the demands of methane hydrate related pressure coring and the requirements of pressure core analysis go well beyond the normal operational and laboratory capabilities of both ships. Since the first use of integrated pressure coring and core analysis systems on ODP Leg 204 and IODP Expedition 311, we have seen a steady evolution in both the pressure core systems and associated core labs. In most cases, the pressure core systems and pressure core analytical labs are now built into self-contained seagoing containers that can be installed on almost any drilling vessel. The evolution of pressure coring systems for the study methane hydrates are further reviewed in "Section 6. Pressure Core Tools and Lab Developments" of this report.

5.2. Industry Platforms of Opportunity

In addition to the use of well-established scientific drilling platforms, such as the *JOIDES Resolution* and the *D/V Chikyu,* most of the industry and national led methane hydrate drilling expeditions have featured the use of a combination of industry "multi-service" vessels and "geotechnical" drillships. The semi-submersible drillship *M. G. Hulme Jr,* as used on the Japan Nankai Trough Project (1999-2000), was to some degree a unique methane hydrate research platform in that it is a standard industry platform, capable of operating in water depths up to about 1,500 m, but station keeping is by moorings – not dynamic positioning. The *Uncle John* and *Q4000* vessels, as used on the first and second legs of the Gulf of Mexico JIP, are owned and operated by the Helix Energy Solutions Group. Both the *Uncle John* and *Q4000* are classified as "multi-service vessels" in that they are designed to perform well interventions, construction, and drilling for less than the cost of engaging a deepwater drillship.

5.3. Geotechnical and Multi-Service Platforms

The other class of ships that have been extensively used for methane hydrate research drilling include "geotechnical drillships", such as the *SRV Bavenit* (as used on the Malaysia Gumusut-Kakap and the China GMGS Expedition 01), *M/S Rem Etive* (as used on the Republic of Korea UBGH Expedition 01) and the *D/V Fugro Synergy* (as used on the Republic of Korea UBGH Expedition 02); all of three of these vessels were provided on contract to these projects by Fugro. In comparison, the *D/V Fugro Synergy* is probably one of the most representative examples of this class of ship. The *D/V Fugro Synergy* was built to provide geotechnical drilling and coring, with the capability to reach depths of more than 2,500 m below the seabed. For more information on the *D/V Fugro Synergy*, please see the following report as prepared by Fugro-TSM (2013).

The most significant limitation relative to the use of "multi-service" vessels and "geotechnical" drillships as scientific research platforms is the lack of labs and related services. In most all cases the laboratory space and equipment needed to analyze recovered cores and related samples need to be constructed onshore and moved onto the vessel before each expedition, adding significant time and cost to the projects. But it is possible to build and deploy the advanced lab systems needed for these "one-off" methane hydrate expeditions as recently demonstrated during the Republic of Korea UBGH Expedition 02 (UBGH2). All laboratories and associated laboratory equipment as deployed on UBGH2 was provided under contract by Geotek (Figure 5.1; Table 5.3).

5.4. Methane Hydrate Related Core Flow and Sample Handling

Cores acquired during most methane hydrate scientific drilling expeditions area usually handled according to standard ODP/IODP procedures. Modifications to these procedures have been made to enable quick identification of methane hydrate intervals, maintain aseptic conditions for microbiological sampling, and identify and safely manage hydrogen sulfide gas. Inspection of the cored sediment usually begins immediately upon recovery with infra-red (IR) imaging of core while still in the liner.

These scans are used primarily to identify anomalously cool sections of liner that are indicative of recent or ongoing methane hydrate dissociation within the enclosed sediments. In many cases the observed thermal anomalies are immediately cut from the core and either (1) sent to the geochemistry lab for visual inspection and extraction of interstitial waters for geochemical analyses, (2) sampled and stored for later shore-based microbiological studies, or (3) bagged and preserved in liquid nitrogen-filled dewars or methane-charged pressure vessels. Visible methane hydrate samples obtained from the core catcher or otherwise extruded from the core liner are often stored in liquid nitrogen. In most cases, a background sample (non-anomalous) is taken from each core for immediate geochemical analyses. In some cases, core holes pre-identified for microbiological sampling are cored using drilling fluids containing microbead tracers to aid in the identification of uncontaminated sections. Gas samples area routinely collected from void spaces within the cores and analyzed in the onboard geochemistry lab. The remainder of the core is usually measured for sectioning, labeled, and transferred to the core laboratory and allowed to equilibrate to room temperature before further processing.

The laboratories as established on the *D/V Fugro Synergy* during the Republic of Korea UBGH Expedition 02 were one of the more advanced integrated core analysis laboratory configurations yet deployed at sea for the examination of conventional wireline cores in support of a methane hydrate research expedition. The map of the *Synergy* "Work Deck" level in Figure 5.1 shows the location of the major laboratory and work areas on the ship. The three most critical lab spaces included the (1) core processing laboratory, (2) the MSCL/X-ray lab for conventional cores, and the (3) Main Laboratory. The core processing laboratory was the receiving lab for all of the conventional wireline cores upon recovery at the rig floor (which are co-located at the same deck level). As listed in Table 5.3 and shown in Figure 5.1, the core processing laboratory is the equivalent work space to the "catwalk" on the *JOIDES Resolution*, where the core liner is laid-out, cleaned, and IR scanned. In some cases "special" methane-hydrate-bearing samples were quickly cut from the liner and transferred to the main lab for further analysis and sub-sampling or for storage in liquid nitrogen. But for the most part the core in the processing laboratory was measured and cut into 1.5 m sections and an extensive list of time critical subsamples were cut from the core (including interstitial water and microbiological samples, headspace and void gas samples). Additional core end temperature probe data were collected from most core section ends. All of the core, core section, IR scans, and core sample information were directly entered into the Geotek maintained project digital database from computers in the core processing laboratory.

From the core processing laboratory each core section was moved by hand to the MSCL/X-ray lab and processed through the Geotek MSCL-XCT, the Geotek MSCl-S multisensory whole-core track, and the KIGAM thermal conductivity device (Figure 5.1, Table 5.3). After completing the core scans in the MSCL/X-ray lab the core sections were again transported by hand (small cart) to the Main Laboratory for additional processing and sampling (Figure 5.1, Table 5.3). The Main lab was divided into two floors and three specialty core labs: (1) Sedimentology, (2) Physical Properties, and (3) Geochemistry/Microbiology. Once in the Main laboratory, the remaining whole round core sections were first split, from bottom to top, creating separate archive and working halves. The working half was then sampled for further physical properties testing (Table 5.3; moisture and density, shear strength, split-core acoustic velocity, and contact resistivity). Next, the working half of the core was transferred to the sampling table where it was further sub-sampled. Sub-sampling included the regular collection of background material for later sedimentological related studies, as well as targeted sampling of notable features such as carbonate nodules, volcanic ash layers, macrofossils, and other features. The archive half sections were scanned on the Geotek MSCL-XZ multisensory split core track and the Geotek MSL-CIS core scanner (Table 5.3). Visual core descriptions (VCDs) of the archive halves were prepared, augmented by microscopic analyses of smear slides. Digital close-up photographs were taken of particular features for illustrations, as requested by scientists. Both halves of the core were then placed in labeled plastic tubes and transferred to cold storage for the remainder of the expedition.

6. Pressure Core Tools and Lab Developments

The only way to directly determine the in-situ concentrations of natural gas in the subseafloor is to retrieve cores that are sealed immediately after the coring process and recovered to the surface without any losses of the constituents. To achieve this objective, the core must be sealed in an autoclave that is able to withstand the hydrostatic pressure at the coring depth when brought to the surface. This was the concept behind the original ODP Pressure Core Sampler (PCS) and the PCS has proven to be an essential tool for estimating in-situ gas concentrations (Dickens et al., 1997, 2000; Milkov et al., 2004).

Although the PCS is very effective at obtaining samples that are suitable for overall gas concentration analysis, it was not designed to be used for other types of analyses that might reveal the physical structure of gas or methane hydrate in the core. It is also not possible to transfer or sample the PCS core without releasing the pressure. To enable a more comprehensive investigation of methane-hydrate-bearing sediments, the HYACINTH program developed the next generation of pressure coring tools and techniques to non-destructively analyze the cores and to take subsamples for microbiological, chemical and physical analysis at in-situ pressures.

6.1. Pressure Core Sampler (PCS)

The Pressure Core Sampler (PCS) is a downhole tool designed to recover a one-meter-long sediment core with a diameter of 4.32 cm at in situ pressure up to a maximum of 69 MPa (Table 6.1) (Pettigrew, 1992; Graber et al., 2002). The pressure autoclave consists of an inner core barrel, which ideally collects a 1,465 cm^3 sediment core, and an outer chamber, which holds 2,964 cm^3 of seawater/drilling fluids (Figure 6.1). The PCS has been successfully used to study in situ gases in gas-rich and methane hydrate-bearing sediments during ODP Leg 164 on the Blake Ridge (Paull et al., 1996; Dickens et al., 1997; 2000), Leg 201 on the Peru margin (Dickens et al., 2003), and Leg 204 on Hydrate Ridge (Tréhu, et al., 2004; Milkov et al., 2004), as well as on IODP Expedition 311 to the Cascadia Margin (Riedel et al., 2006) and the NGHP01 Indian expedition (Collett et al., 2008d). For IODP Expedition 311, the steel outer and inner barrels of the PCS autoclave were replaced with aluminum barrels so it could be used with the Geotek MSCL-P X-ray system.

During most expeditions, when the PCS was retrieved from the drill pipe, it was immediately inserted into the ice shuck to cool. The cooled PCS autoclave was delivered to a refrigerated pressure coring van for non-destructive measurements and depressurization experiments. When depressurization experiments were completed, the core was X-rayed one final time.

6.2. HYACINTH Coring Systems

Two types of wireline pressure coring tools were developed in the European-Union-funded HYACE/HYACINTH programs: a percussion corer and a rotary corer, which were designed to cut and recover core in a wide range of lithologies where hydrate-bearing formations might exist (Schultheiss et al., 2006). Both tools have been designed for use with the same IODP bottom-hole assembly (BHA) as the PCS (i.e., the APC/XCB BHA). The HYACINTH pressure coring systems were first used successfully on ODP Leg 204 and IODP Expedition 311 to recover methane hydrate and surrounding sediments. The HYACINTH pressure coring systems were also deployed on the Gulf of Mexico JIP Leg I, the Malaysia Gumusut-Kakap Project, the India NGHP Expedition 01, the China GMGS Expedition 01, and both of the Republic of Korea UBGH Expeditions 01 and 02.

The design and operation of the HYACINTH tools differs in five significant respects from that of the PCS:

1. The HYACINTH tools penetrate the sediment using downhole driving mechanisms powered by fluid circulation rather than by top-driven rotation with the drill string. This allows the drill string to remain stationary in the hole while core is being cut, which significantly improves core quality. However, in some cases these systems have failed to penetrate more indurated sediments, which may be more easily dealt with a top-drive rotary system.

2. The coring portion of the HYACINTH tools moves relative to the main bit during the coring process, which also improves core quality. However, the extension of the core barrel up to one meter past the drill bit makes these tools far more susceptible to ship heave than other coring tools, and it is essential that the bit remain stationary on the bottom of the hole during coring.

3. Both HYACINTH tools use "flapper valve" sealing mechanisms, rather than a ball valve, to maximize the diameter of the recovered core. As we will see later in this review discussion, ball valve systems have been shown to be slightly more reliable.

4. The HYACINTH pressure autoclaves are attached to a pressure accumulator filled with gas, which can compensate for drops in core pressure due to tool volume expansion during core retrieval.

5. The recovered HYACINTH cores are contained in an inner plastic liner that enables them to be manipulated and transferred into other chambers for analysis, storage and transportation under full pressure.

6.3. Fugro Pressure Corer (FPC)

The HYACINTH percussion corer was developed by Fugro Engineers BV and is known as the Fugro Pressure Corer (FPC; Figure 6.2, Table 6.1). The FPC uses a water hammer, driven by the circulating fluid pumped down the drill pipe, to drive the core barrel into the sediment up to one meter ahead of the drill bit. The core diameter is 57 mm. Once the core barrel is free from the sediment the wireline pulls the core barrel liner containing the core into the autoclave. A specially designed flapper valve is used to seal the bottom end of the autoclave after the core has been retrieved. The FPC is designed to retain a pressure of up to 25 MPa. It is suitable for use with unlithified sediments ranging from soft through stiff clays to sandy or gravelly material.

6.4. HYACE Rotary Corer (HRC)

The HYACINTH rotary corer was developed by the Technical University of Berlin and the Technical University of Clausthal and is known as the HYACE Rotary Corer (HRC; Figure 6.2, Table 6.1). The HRC uses an Inverse Moineau Motor driven by the circulating fluid pumped down the drill pipe to rotate the cutting shoe up to 1 m ahead of the roller cone bit. The original bit used with the HRC was a narrow kerf, dry auger design cutting shoe, with polycrystalline diamond cutting elements. This design allows the core to enter into the inner barrel before any flushing fluid can contaminate the material being cored. The core diameter is 51 mm. On completion of coring, the tool is lifted off bottom with the drill string and then the core is retracted into the autoclave by pulling in on the wireline in a similar manner to the FPC, and the pressure is sealed by a specially designed flapper valve. The HRC is designed to retain a pressure of up to 25 MPa and was primarily designed for use in sampling lithified sediment or rock. By the time of the UBGH Expedition 02 in Korea the HYACINTH rotary corer had come under the direct management of Fugro and had been renamed the Fugro Rotary Pressure Corer (FRPC).

Over their development period, both the FPC and FRPC (formally the HRC) have been modified to improve their success at retaining pressure and the quality of the cut core. Both tools have seen improved recovery, for example during the NGHP Expedition 01, a total of 97 pressure cores were attempted with an overall success rate of 41%. However, at the last site during the expedition (Site NGHP-01-21) this success rate improved to 75% after modifications were made to the tools. In order to quantify success, "success" was defined as a pressure core with >30% core recovery and >50 bar of pressure. It has also been reported that core systems used routinely in geotechnical drilling, in which the drill string is clamped into a seabed frame (which is not the case on the *JOIDES Resolution* but is the case on all of the Fugro operated projects), have shown that both the success rate and core quality improve relative to those taken with unclamped systems. But in 2009, during the UBGH2 expedition in Korea while using a clamped seabed frame system, the FRPC failed to recover any pressurized cores and for 35 deployments of the FPC only 20 cores were recovered at near in-situ pressure conditions.

6.5. HYACINTH Core Transfer and Analysis

Since the emergence of the HYACINTH core systems on ODP Leg 204, Geotek has led an almost continuous effort to modify and advance the systems used to manipulate and analyze pressure cores (Schultheiss et al., 2009). By IODP Expedition 311, the HYACINTH pressure core manipulator/shear transfer chamber (STC) was attached an integrated with the Geotek Pressure Multisensor Core Logger (MSCL-P); this newly integrated core processing and analysis system was named the HYACINTH Pressure Core Analysis and Transfer System or PCATS. The recovered pressure core could now be pushed and pulled through the MSCL-P sensors using the manipulator under computer control – without being depressurized. The MSCL-P is an automated measurement system for the collection of acoustic P-wave velocity, gamma ray attenuation, and X-ray image data on HYACINTH pressure cores at pressures up to 25 MPa. The MSCL-P pressure chamber is constructed of aluminum and contains an internal set of ultrasonic transducers. X-ray and gamma ray sources and detectors are situated outside of the pressure chamber. The system moves pressurized HYACINTH cores incrementally past these sensors under computer control with a positional precision of better than one millimeter, allowing detailed gamma density and acoustic velocity profiles to be obtained rapidly and automatically along the core as well as creating automated full-core X-ray montages. Once the analyses are completed, some cores are depressurized in place or transferred still under pressure into storage chambers for further analysis.

The ability to manipulate cores, take sub-samples, and make measurements—all at in-situ pressures—were major objectives of the HYACINTH project. PCATS has seen significant improvements over the past few years (Schultheiss et al., 2011). The main improvement that has been made to the PCATS system is the core manipulation capabilities, which now includes fully automated translational and rotational control. A combination of precise rotational controls with high-resolution X-ray imaging provides three-dimensional X-ray visualization through the core that enables complex structural features to be examined in detail. Another new feature of the PCATS system during the UBGH2 Korean expedition was the ability to cut the recovered cores into various lengths and to transfer the core samples, while under pressure, into storage chambers or directly into the KIGAM Gas Hydrate Ocean Bottom Simulator (GHOBS) chambers. The significance of this new capability cannot be overstated. In the past each pressure core represented one sample thus limiting what a core could be used for when it came to destructive processing and measurements. But during UBGH2, it became possible to cut the core into a series of samples, with each sample being directed to a particular analysis or laboratory process and also to long-term storage. PCATS has recently been expanded to include a new triaxial analytical system that enables both small and large strain geotechnical tests on samples of pressurized cores, as well as direct flow measurements of permeability (Schultheiss et al., 2011).

6.6. Pressure Core Characterization Tools (PCCT)

With the emergence of the HYACINTH pressure core transfer capabilities, we have also seen the development of new laboratory systems to analyze pressure cores. One of these new systems, the Instrumented Pressure Testing Chamber (IPTC), as developed by the Georgia Institute of Technology, was first deployed on the Gulf of Mexico JIP Leg I. The IPTC is a HYACINTH-compatible pressure chamber that is connected to the HYACINTH transfer system enabling additional core measurements to be made while the core is still under full in-situ pressures. The IPTC allows measurements of P-wave velocity, shear wave velocity, strength, resistivity, and temperature to be made through holes drilled in the plastic core liner (Yun et al., 2006). The IPTC can also be mated to the new core manipulator developed as part of the Georgia Institute of Technology Pressure Core Characterization Tool (PCCT) system.

The PCCT system includes core manipulation tools and characterization chambers (Santamarina et al., 2012). The core characterization tools in this integrated system are based on a modular design concept in order to maximize flexibility. The primary components of the PCCT include: (1) Core Manipulator, (2) Core Cutter, (3) Effective Stress Chamber, (4) Direct Shear Chamber, (5) Biologic Sub-Sampler, (6) Controlled Depressurization Chamber, and (7) the IPTC, which has been incorporated into this system. The multiple sensors and measurement systems built into the PCCT have been developed to characterize the sediment and to determine hydrological, thermal, chemical, biological, and mechanical properties within the chambers, under controlled pressure, temperature, and effective stress conditions. This highly integrated system allows for the comprehensive characterization of hydrate-bearing sediments under in situ pressure, temperature, and/or stress conditions, and permits detailed monitoring of core scale gas production tests.

In addition to the PCCT system, the KIGAM Gas Hydrate Ocean Bottom Simulator (GHOBS) chambers, as deployed on the second Korea UBGH expedition (UBGH2), have also been designed to obtain high quality mechanical/geotechnical data on pressure cores (Lee et al., 2011a, 2011b).

6.7. PTCS and Hybrid-PCS Pressure Core Systems

An early goal of the national methane hydrate research and development program of Japan was the development of the Pressure-Temperature Coring System (PTCS) (Table 6.1) (Takahashi and Tsuji, 2005). The PTCS was designed and developed by Aumann Associates, under a contract with JNOC (presently the Japan Oil, Gas and Metals National Corporation: JOGMEC). The PTCS was designed to maintain both pressure and temperature of the cores, but the temperature control part of the tool was rarely used and was removed before the 2004 METI Tokai-oki to Kumano-nada drilling project. The PTCS cuts a three meter long and 6.67 cm diameter core. The PTCS also makes use of a ball valve to seal the systems autoclave. The system was tested during the 1998 Mallik project and used for the first time in the 1990/2000 Japan Nankai Trough Project, during which a total of 155 m of section was penetrated with the PTCS and 45 m of core were recovered (40% recovery rate). Aumann Associates redesigned the PTCS for the 2004 Nankai Trough Project, during which the PTCS was deployed in a six wells and cut a total of 203.5 m of sediment with 161.3 m of core being recovered at near in-situ pressures (79.3% recovery rate). The PTCS has one significant limitation: The cores captured within the PTCS cannot be analyzed or transferred to other devices without first depressurizing the system and manually extruding the cores.

As part of the planning and development phase for the third JIP Gulf of Mexico methane hydrate expedition (which was subsequently canceled), it was decided to construct a new pressure core system based in part on the design of the PTCS. This new system, the High Pressure Temperature Corer (HPTC), was also designed by Aumann Associates. As built the HPTC cuts a three meter long and 5.2 cm diameter core. It also features a ball valve sealing system. The HPTC requires large diameter drill pipe (5.906" tool joint ID) to allow enough room to pass the core tool through the drill pipe under field conditions. The original plan was to use a standard drilling casing/landing string that is suitable for this application and available for rental in the Gulf of Mexico (specifications for the casing/landing string: 7 5/8" 0.500" WT, (39#), Q-125, HYDRIL 563 T&C CONNS., RANGE 3, INTERNALLY COATED). But further engineering studies of the casing/landing string indicated that the string could fail under the coring conditions predicted for sites to be drilled during GOM JIP Leg III. The development of HPTC core system was suspended. The use of this tool would have required the construction of a special set of tubulars that could withstand deepwater drilling/coring operations.

As a replacement for the PCS and in preparation for proposed pressure coring during IODP Expedition 337 in 2011, JAMSTEC contracted with Aumann Associates to build a new pressure core system – the Hybrid Pressure-Coring System (Hybrid-PCS) (Table 6.1). In the end the Hybrid-PCS was not deployed on IODP Expedition 337 but was adopted by JOGMEC as the replacement pressure core system for the PTCS (Yamamoto et al., 2012a, 2012b). The Hybrid-PCS is compatible with the standard drill pipe and the coring IODP-BHA on the D/V *Chikyu* and the *JOIDES Resolution* with several minor modifications. The maximum length of a Hybrid-PCS core is 3.5 m, and the diameter is 5.1 cm. After cutting a core, a ball valve at the bottom of the autoclave is closed to seal the core during wireline retrieval.

JOGMEC recently used the new Hybrid-PCS to conduct pressure coring operations from the *D/V Chikyu* during the 2012 phase of the MH-21 Nankai Trough Pre-Production Expedition (Table 6.1) (Yamamoto et al., 2012a, 2012b; Suzuki et al., 2012). During this expedition, 21 pressure cores were recovered from a 60 m interval section in one hole. Sampled lithologies range from clay-rich sediments in the overburden formation to sandy layers with high concentrations of methane hydrate in the targeted interval. Geotek's PCATS was used to transfer, analyze, and subsample 35 m of core recovered under pressure. After X-ray CT imaging and non-destructive analysis under in situ pressures, over 60 samples between 10 cm and 120 cm long were cut and stored for further detailed on-shore analysis by scientists (Geotek maintained web site, http://www.geotek.co.uk/news/jogmec2012, viewed February 2012). PCATS Triaxial, a geotechnical testing cell that can accept pressurized samples directly from PCATS, was also used successfully on this expedition, providing triaxial shear strength, permeability and resonant column data from methane hydrate cores that had been maintained at in-situ pressures.

Since the completion of the 2012 Hybrid-PCS pressure core operations in the Nankai Trough, the GOM JIP has been working with JOGMEC (who is also a member of the GOM JIP) and Aumann Associates to build a replacement system for the HPTC. It has been decided that the GOM JIP and Aumann Associates, along with the support of JOGMEC, will work together to modify the existing Hybrid-PCS system with engineering learning's from the 2012 Nankai Trough coring program and potentially conduct an onshore test of the modified Hybrid-PCS in 2013. The GOM JIP plans to build several copies of the modified and tested Hybrid-PCS as a final project deliverable to US-DOE.

7. Downhole Well Log Analysis of Methane Hydrate

Since the first use of downhole log measurements to characterize the in-situ nature of methane hydrates occurrences more than 17 years ago (Collett, 1983; Collett et al., 1984; Mathews, 1986; Collett and Ladd, 2000), there have been significant advancements in the use of downhole-logging tools to acquire detailed information on methane hydrates in nature. Advanced wireline and LWD tools are now routinely used to examine the petrophysical properties of methane-hydrate reservoirs and the distribution and concentration of methane hydrates within various reservoir systems. The most established and well-known use of well logs in methane-hydrate research are those that provide electrical resistivity and acoustic velocity data (both compressional- and shear-wave data) to estimate methane-hydrate content (i.e., methane hydrate pore volume saturation) in various types of reservoirs. Recent integrated sediment coring and well-log studies have confirmed that electrical resistivity and acoustic velocity data can yield accurate methane-hydrate saturations in sediment grain-supported (isotropic) systems such as sand reservoirs, but more advanced log-analysis models are required to characterize methane hydrate in fractured (anisotropic) reservoir systems (Lee and Collett, 2008, 2009; Malinverno et al., 2008, Cook et al., 2010). New well logging tools designed to make directionally oriented acoustic and propagation resistivity log measurements provide the data needed to analyze the acoustic and electrical anisotropic properties of both highly interbedded and fracture-dominated methane-hydrate reservoirs. Advancements in nuclear magnetic resonance (NMR) logging and wireline formation testing also allow for the characterization of methane hydrate at the pore scale (Kleinberg et al., 2005; Anderson et al., 2011), which has provided invaluable insight on the mechanisms controlling the formation and occurrence of methane hydrate in nature along with data on methane hydrate reservoir properties (i.e., porosities and permeabilities).

Methane Hydrate Well Log Response Characterization

Until recently, most of the existing methane-hydrate well-log evaluation techniques were developed by the extrapolation of uncalibrated petroleum-industry log-evaluation procedures (reviewed by Collett et al., 1984; Mathews, 1986; Collett, 1993; Lee et al., 1993, Collett, 1998a, 1998b; Goldberg, 1997; Collett and Ladd, 2000; and Collett, 2000). The relatively recent emergence of numerous science and industry focused methane hydrate field research programs; however, has led to execution of a long list of marine and onshore Arctic methane-hydrate research drilling and well-logging programs (as reviewed previously in this report), including: ODP Leg 164 (Paull et al., 1996), ODP Leg 204 (Tréhu et al., 2004), IODP Expedition 311 (Riedel et al., 2006), Gulf of Mexico Gas Hydrate Joint Industry Project Legs I and II (Ruppel et al., 2008; Boswell et al., 2012a, 2012b), the India NGHP Expedition 01 (Collett et al., 2008b, 2008c, 2008d), the offshore China GMGS-1 expedition (Zhang et al., 2007a, 2007b; Yang et al., 2008; Wu et al., 2008), UBGH1 and UBGH2 expeditions in the offshore of Korea (Park et al., 2008; Park, 2008; Lee et al., 2011a, 2011b), and the Mallik, Mount Elbert, and Iġnik Sikumi projects in northern Canada and Alaska. Within these drilling projects, well logs have provided robust information about complex methane-hydrate reservoir systems containing pore- and fracture-filling methane hydrate, sediment grains of various sizes and compositions, water at various reservoir states, and free gas (Goldberg et al., 2000; Guerin and Goldberg, 2002, 2005; Kleinberg et al., 2005; Lee and Collett, 2005; Sun and Goldberg, 2004; Murray et al., 2006; Lee, 2007; Collett et al., 2008b; Lee, 2008; Lee and Collett, 2008, 2009; Malinverno et al., 2008, Cook et al., 2010; Sun et al., 2011).

The ephemeral nature of methane hydrate under surface pressure and temperature conditions has placed a greater emphasis on downhole measurements, which are needed to determine the in-situ physical properties of methane hydrates. In addition, within research wells with incomplete core coverage, well log data may serve as the only source of physical property and sedimentological data. Well log measurements also complement the discrete measurements obtained from cores, and offer several advantages over core-based analyses in that they are rapidly collected and represent continuous, in-situ measurements of formation properties. Integration of continuous and multivariate log data with core data can potentially provide ground-truth information obtained from detailed core analyses, resulting in continuous and quantitative records of lithological and reservoir variability. Of particular interest, well logs are also used to identify and quantify pore fluids within potential reservoir sections.

Wireline Logging

Wireline logging has had a long history in both ODP and IODP, in fact ODP Leg 164 saw the first attempt to use of downhole log data to characterize the distribution and pore-volume saturations in a marine hydrate accumulation (Collett and Ladd, 2000). In most methane-hydrate well logging projects, the log data are acquired using either wireline logging or LWD tools. For example, both ODP Leg 204 and IODP Expedition 311 featured an initial LWD drilling phase that was followed by coring and wireline logging operations. Downhole logging aboard the *JOIDES Resolution* during ODP Leg 204 and IODP Expedition 311 were provided by the Lamont-Doherty Earth Observatory Borehole Research Group (LDEO-BRG) in conjunction with Leicester University Borehole Research, the Laboratoire de Mesures en Forages Montpellier, University of Aachen, University of Tokyo, Schlumberger Reservoir Evaluation Services, and Schlumberger Drilling and Measurements.

For a majority of the ODP and IODP holes that are wireline logged, the downhole logging program begins with the total depth of the hole to be logged is reached by either coring or drilling. The borehole is conditioned by pumping viscous mud into the hole to flush any reaming cuttings from the hole and the hole is filled with drilling mud to stabilize the hole. The next step in the logging program is determined by the type of BHA used. For all of the methane hydrate research holes drilled to date, the APC/XCB BHA (3-3/4" landing shoulder and 3-4/5" I.D.) has been used, which allows the logging tools to be deployed through 5-1/2" drillpipe and directly through the bit. Restrictions in the BHA require the wireline tools to be narrower than 3-3/4" for routine logging operations. This restriction limits to some degree that range and type of wireline logging tools that can be deployed during IODP operations.

The IODP Expedition 311 wireline logging program was a good example of an IODP and/or industry methane hydrate wireline logging program. During Expedition 311, the following three wireline logging tool strings were deployed (Figure 7.1):

1. The triple combination (triple combo) tool string (resistivity, density, and porosity measurements), which consisted of the Hostile Environment Gamma Ray Sonde (HNGS), the Phasor Dual Induction Spherically Focused Resistivity Tool (DIT), the Hostile Environment Litho-Density Tool (HLDT), and the Accelerator Porosity Sonde (APS). The LDEO high-resolution Temperature/Acceleration/Pressure (TAP) tool was attached at the bottom of this tool string.

2. The FMS-sonic tool string, which consisted of the FMS, General Purpose Inclinometer Tool (GPIT), Scintillation Gamma Ray Tool (SGT), and the Dipole Sonic Imager (DSI).

3. Vertical seismic profile tools: Versatile Seismic Imager (VSI) or Well Seismic Tool (WST).

Tool name acronyms, the parameters measured by each tool, the depth of investigation, and the vertical resolution of each tool measurement are summarized in Table 7.1**.** More detailed descriptions of individual logging tools and their geological applications can be found in Goldberg (1997), Serra (1984), and the LDEO-BRG Wireline Logging Services Guide (2001).

One of the more advanced recent wireline logging programs was executed in 2007, as part of the Mount Elbert Gas Hydrate Stratigraphic Test Well in northern Alaska (Collett et al., 2011) and is an excellent example of a wireline log data set to consider for review purposes. The Mount Elbert well featured the acquisition of cores, well logs, and downhole measured reservoir pressure-test data. The “main hole” was surveyed with a research-level wireline-logging program that included neutron-density sediment porosities, NMR, dipole acoustic and resistivity logging, triaxial resistivity logging, borehole electrical imaging, and advanced geochemical logging. Caliper data indicate that almost the entire borehole was within several centimeters of gauge, and virtually fully in gauge within the methane-hydrate-bearing intervals. This outcome is due largely to the use of oil-based drilling fluid and successful chilling of the drilling fluids with a surface heat exchanger. Following logging, reservoir pressure testing was conducted with the Schlumberger Modular Formation Dynamic Tester (MDT) at four openhole stations in two hydrate-bearing sandstone reservoirs. Schlumberger Well Logging Services was responsible for conducting all of the post-acquisition processing of the well-log data associated with the Mount Elbert project (Figures 4.42 and 4.43). The cored and logged methane-hydrate intervals (unit C and unit D) exhibit deep-resistivity measurements ranging from about 50 to 100 Ω-m, and compressional-wave acoustic velocities (Vp) ranging from about 3.4 to 4.0 km/sec (Figure 4.42). In addition, the measured shear-wave acoustic velocities (Vs) of the methane-hydrate-bearing horizons in the Mount Elbert well ranged from about 1.1 to 1.8 km/sec.

Logging While Drilling

For discussion purposes, the term LWD is used generically to cover both LWD and measurement-while-drilling (MWD) tools, and systems. The MWD tools, also located in the bottomhole assembly (BHA) with the LWD sensors, measures downhole drilling parameters and wellbore direction and also transmits limited LWD data to the surface in real time. LWD tools, which are powered by batteries or a drilling-fluid turbine, use nonvolatile memory chips to store logging data. Complete LWD data are recorded into this downhole memory and retrieved when the tools are brought to the surface. The tools take time-based measurements and are synchronized with an acquisition system on the drilling rig that monitors time and drilling depth. Because LWD measurements are made shortly after the formation is penetrated and generally before significant drilling-fluid invasion and borehole erosion by continued drilling or coring operations, the adverse impact of these effects on LWD measurements are reduced relative to wireline logging because of the shorter time elapsed between drilling and data acquisition. In most of the completed marine methane-hydrate drilling projects (as reviewed above in this report), the LWD operations are conducted in advance of coring, generally during a dedicated LWD leg. These pre-coring logging operations are critical to the development of the detailed, site-specific coring, core sampling and pressure-core deployment plans.

LWD data also provide real-time borehole monitoring data during drilling, which can be used to assess potential drilling problems associated with the presence of methane hydrate as further descried in “Section 9. Methane Hydrate drilling Operational Experience” of this report.

The primary objective of the Gulf of Mexico Gas Hydrate Joint Industry Project Leg II (GOM JIP Leg II) was the collection of a comprehensive suite of LWD data within methane-hydrate-bearing sand reservoirs (Boswell et al., 2012a) and is an excellent example LWD data set to consider for review purposes. For the GOM JIP Leg II, the semisubmersible drilling vessel Helix Q4000 was mobilized at sea in the Gulf Mexico and a full research-level LWD-data set on formation lithology, electrical resistivity, acoustic velocity, and sediment porosity enabled a greatly improved evaluation of methane hydrate in both sand- and fracture-dominated reservoirs. The two holes drilled at Walker Ridge yielded evidence of a laterally continuous, thick, fracture-filling methane hydrate section, but more importantly both wells also encountered sand reservoirs, between 12 and 15 m thick, highly saturated with methane hydrate. Methane-hydrate-bearing sands were also drilled in two of the three Green Canyon wells, with one occurrence roughly 30 m thick. Interpretation of the Alaminos Canyon drilling results matches pre-drill expectations of sands with uniformly low to moderate methane hydrate saturation over a large area.

The well logging program implemented during the GOM JIP Leg II was developed under the guidance of LDEO-BRG. The main goal of this program was to assess the distribution and concentration of methane hydrates below the seafloor in the Gulf of Mexico. Six LWD and MWD tools, provided by Schlumberger Drilling and Measurements, were deployed in each hole (Figure 7.2, Table 7.2): the multipole acoustic (MP3, SonicScope), resistivity imaging (geoVISION), combination propagation resistivity, density and neutron (Ecoscope), MWD (TeleScope), directional propagation resistivity (PeriScope), and monopole acoustic (SonicVision). Because of its slimmer 4¾" collar, the multipole acoustic tool was placed behind the 6¾" bit and below an 8½" hole-opening reamer, above which were the rest of the 6¾ " LWD collars. Some tools had stabilizers to centralize the collars in the borehole. For additional information about the measurements recorded by each tool on the LWD BHA, see the GOM JIP Leg II operations and results reports by Cook et al., (2009), Guerin et al., (2009a, 2009b), and Mrozewski et al., (2009).

For demonstration purposes, some of the log data collected from the GC955-H well are displayed in Figures 7.3 and 7.4. This well, at a water depth of 2,033 m, was the second location drilled in Green Canyon Block 955 during the GOM JIP Leg II. It was drilled without any significant problems and without any special measures other than the standard use of drilling mud. A thick methane-hydrate-filled fracture section was penetrated within the depth interval of 162 to 290 mbsf and, at a depth of 328 mbsf, a methane-hydrate-bearing sand section was encountered. The drilled interval thus represents the complete range of methane-hydrate reservoir conditions encountered during the GOM JIP Leg II. On the resistivity images (Figure 7.4), methane-hydrate-filled fractures in the depth interval of 162 to 290 mbsf appear as resistive sinusoids. Intervals containing high-angle methane-hydrate-filled fractures can be identified from the propagation resistivity measurements at points where the P40H and/or the A40H curves significantly exceed the P16H and A16H curves because of the electrical anisotropy due to the resistive fracture planes (Figures 7.3 and 7.4). As drilling proceeded below a depth of 382 mbsf, the gamma-ray response of the sediments steadily decreased, indicative of increasing sand content. Overall, a sand-rich unit roughly 100-m-thick was encountered. High-resolution resistivity images showed the unit to consist of interbedded sands and shales, with sands commonly 0.2 to 1.0 m thick and ranging to 2 m thick. These sands are interlayered with shales that are typically 0.2 to 0.5 ft thick. The upper 25 m of this interval has low and downward decreasing resistivity and is therefore interpreted to be water-saturated. At 414 mbsf, resistivity and acoustic velocity increased sharply, indicating the top of a thick methane-hydrate-bearing sand interval. Through a depth of 450 mbsf, three methane-hydrate-bearing zones with thicknesses of 27 m, 4 m, and 1 m were logged. Unexpectedly, these zones are separated by two zones of hydrate-free, water-bearing sands units. The average Archie-derived methane-hydrate saturations within the drilled sand sections in the GC955-H well is about 65%, although the methane hydrate was determined to occupy only about 5 to 8% of the void space created by the fractures in the upper part of the well (Lee and Collett, 2012).

As shown in this review, well-log data can be used to obtain highly accurate reservoir porosities and methane-hydrate saturations over a wide range of methane-hydrate reservoir conditions. Resistivity-, acoustic-, and NMR-log data are used to quantify the amount of methane hydrate in numerous geologic settings throughout the world. Various forms of the Archie relationship, with special consideration for the nature of the reservoir (grain-supported versus fracture-dominated), have become a standard method for assessing methane-hydrate saturations. Only with the integration of pressure-core and acoustic-log data has it become possible to fully characterize anisotropic methane-hydrate reservoir systems. The acoustic properties of hydrate-bearing sediments have received a great deal of attention. Numerous acoustic models, including the *Lee* weighted-average equation, the *Kuster-Toksöz* wave-scattering model, the *grain-contact* model, the *effective-medium* theory, and the *Biot-Gassmann* theory, have all been used to model the acoustic properties of various types of methane-hydrate occurrences and in many cases yield highly accurate methane-hydrate saturation data. One of the most important, but probably simplest developments, has been the realization that NMR well logs can be used to obtain methane-hydrate saturation and other important reservoir information. In closing, well-logging data have 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.

8. Well Instrumentation and Monitoring

Borehole instrumentation has become a major part of both industrial oil and gas and scientific based research projects. The ability to monitor downhole reservoir responses and performance has also been extended to the gas hydrate production test wells in the Mallik 2002 and 2007-2008 projects and the 2011-2012 Iġnik Sikumi test well. We have also seen the emergence of scientific borehole instrumentation within the ODP and IODP efforts.

Since the first deployment of the "Circulation Obviation Retrofit Kit" (or CORK) during ODP Leg 139 in 1991, we have seen significant advancements in seafloor observatory systems. The basic configurations of the CORKs developed under ODP and IODP have been described and summarized in Becker and Davis (2005). The term "CORK" is often used generically to represent any long-term sealed-hole experiment. Most of these systems have been designed to obtain hydrologic properties of individually isolated zones within sealed boreholes. By 2003, the basic CORK-II design included inflatable packers and perforated sampling screens that allow formation fluids to be sampled by OsmoSamplers deployed inside the cased borehole. More recently, modified OsmoSamplers have also been used in CORK deployments to collect microbiological samples. Sensor strings deployed in various CORK systems are typically comprised of thermistor cables and pressure gauges, along with data loggers, designed to obtain temperature and pressure profiles within the sealed holes. Borehole instrumentation has also included the deployment of broadband seismometer/strain-meter packages. CORKS have also been attached to cable observatory systems to enable continuous real-time monitoring.

In 2007, a workshop was convened by the Consortium for Ocean Leadership and the Department of Energy to examine the potential development and use of marine methane hydrate observatories that would be largely based on the ODP/IODP CORK design concept (Torres et al., 2007). This workshop concluded that methane hydrate systems are good targets for seafloor observatories because of the non-static nature of these deposits. It was further concluded that methane hydrate observatories could be used to (1) determine the influence of fluid flow on the stabilization/destabilization of methane hydrates, (2) study the effects of microbial activity on methane hydrate systems, (3) gain a better understanding of the role that hydrates may play in the global carbon cycle and as a potential energy resource, and (4) assess the effects of methane hydrate formation and destabilization on marine slope stability.

Three CORKs have been installed in methane hydrate systems to date, all on the Cascadia continental margin: Hole 892B (offshore Oregon), Hole 889C (offshore Vancouver Island), and Hole U1364A (offshore Vancouver Island). The 892B and 899C CORKs were installed during ODP Leg 146 (Westbrook et al., 1994), which was the second leg to deploy the original CORK system. Unfortunately, operational challenges were experienced while deploying both CORKs during ODP Leg 146. In both deployments, which featured perforated casing liners as part of the infrastructure design, sediment intruded through the perforations at the bottom of the liner, which required both thermistor strings to be shortened. After the leg, it was determined that most of the sensors in Hole 889C were damaged, likely during deployment in rough seas. The 892B CORK collected data for about 1.5 years until the recovery cable was broken during a retrieval event, presumably due to being "frozen in the hole by hydrates" (Becker and Davis, 2005). In 2010, an ACORK was installed successfully in Hole U1364A, near ODP Site 889. The new installation monitors pressure at multiple formation levels on the outside of a 10.75-inch casing string (Davis et al., 2012) with sensors located above and below the base of the methane hydrate stability zone. Data collected five months after deployment document that the observatory is functioning. Future plans are to connect the observatory to the NEPTUNE Canada fiber-optic cable network and the deployment of additional instrumentation within the casing.

Several proposals exists within the IODP evaluation system that deal with the deployment of additional marine methane hydrate observatories. In addition, IODP has funded the development of a new type of observatory that does not require extensive hardware infrastructure; the test deployment of this new observatory was recently approved and scheduled as described below in this report.

A "Simple Cabled Instrument for Measuring Parameters In situ" (SCIMPI) system is a new subseafloor observatory instrument designed for installation in sediments below the seafloor, providing high depth and time resolution measurements of sediment physical properties (Kulin et al., 2013). It is intended to be operated for periods of two years or longer on internal batteries that can be replenished via remotely operated vehicle (ROV). It can also be connected to cabled observatory systems for real-time data acquisition. The main advantages of the SCIMPI are the ability to tailor the measurements to the targeted seabed characteristics and its relatively small amount of equipment and installation requirements, making it an economical and versatile system for scientific research.

The first SCIMPI deployment is scheduled for June 2013 in the Bullseye Vent feature, near IODP Site U1328 (IODP Expedition 311; Riedel et al., 2006), off the Pacific coast of Vancouver Island, Canada (Kulin et al., 2013). The SCIMPI being deployed in the Bullseye Vent feature during IODP Expedition 341S provides long-term observations for understanding subseafloor dynamics, such as changes in seafloor and subseafloor methane hydrate systems.

A SCIMPI is designed to allow the borehole walls to collapse around the device once the drill string through which it is emplaced is withdrawn. A SCIMPI string consists of multiple measurement modules and a command module connected by caballing. The SCIMPI to be deployed during IODP Expedition 341S is configured to measure temperature, electrical resistivity, and pressure. Future designs are expected to include other types of sensors that might provide additional measurements needed to further characterize the geologic controls on the formation and evolution of methane hydrate systems.

Scientific borehole instrumentation under IODP provides the marine research community the opportunity to go beyond normal leg-driven expeditionary science, which traditionally infers sub-seafloor processes based on a snapshot of recovered of samples. Borehole instrumentation represents a step towards a new style of science for the ocean drilling community, which strives to monitor and measure processes as they happen on and beneath the seafloor and to collect time-series data to document the changes that take place through time.

The Mallik 2002 gas hydrate production test well project included a number of borehole monitoring studies (Dallimore and Collett, 2005). The Mallik 5L-38 well (as reviewed in "Section 4. ODP-IODP and Industry Sponsored Historical Methane Hydrate Research Drilling Expeditions" of this report), the main production test well drilled in this project, was completed to a depth of 1,110 m and instrumented with a distributed temperature sensing (DTS) system. The DTS in the Mallik 5L-38 well was strapped to the outside of the casing as it was run into the hole. The fiber-optic DTS system facilitated detailed characterization of the in-situ formation temperatures and their response to drilling- and production induced disturbance.

An important part of the Mallik 2007-2008 project was to develop technologies for monitoring formation responses to production testing (Ashford et al., 2012). Five monitoring cables were mounted on the exterior of the production casing in the Mallik 2L-38 well. Two of the cables were related to acoustic sources linked to an interwell-monitoring system. In addition, two DTS cables and two electrical resistance array (ERA) cables were included in the borehole monitoring system. All five cables experienced some damage during or after the production casing was landed at the bottom of the hole, and the acoustic cables failed completely.

The 2011-2012 Iġnik Sikumi gas hydrate test well project also included the deployment of an advanced array of borehole monitoring systems (Schoderbek et al., 2012), including a three downhole pressure and temperature gauges and a DTS system to measure temperatures along the entire wellbore every two minutes during the test (see Figure 4.46). An experimental Distributed Acoustic Sensor (DAS) array was also deployed in the Iġnik Sikumi well. One of the more difficult operational tasks associated with the instrumentation of the well was the requirement to perforate the well casing without damaging the DTS/DAS systems that were strapped to the outside of the casing. A specialized electromagnetic borehole logging system was used to determine the location of the DTS/DAS cables outside the casing and the perforations were gyroscopically oriented away from DTS/DAS cables, which maintained their integrity after perforation. The downhole pressure and temperature gauges and a DTS system allowed for the precise manipulation of surface and subsurface operational conditions during both the injection and backflow (depressurization) phases of the test. The DTS also provided invaluable information on thermal evidence for the formation and dissociation of methane hydrate in the reservoir during the test.

9. Methane Hydrate Drilling Operational Experience

It is obvious that a great number of technical challenges come with drilling, coring and logging in deep marine environments (as reviewed by Myers, 2008). In the early days of scientific ocean drilling, a fundamental compromise was chosen to drill and core with dual-gradient riserless drilling vessels, which provides access to the seafloor in a broad range of water depths, beyond the easy reach of a drilling riser (Figure 9.1). By drilling with a riserless rig, vital scientific data could be recovered much more quickly at a substantially reduced cost. The choice to use a riserless rig also forces secondary drilling decisions to be made including the removal of a blowout preventer from the well plans and the intermittent use of drilling mud. With the decision to drill in a riserless configuration, engineered drilling fluids cannot be regularly circulated to manage the borehole pressures and to remove cuttings.

In riserless drilling, maintaining borehole stability is a constant challenge and avoiding borehole collapse is a risk in many holes. Standard ODP/IODP drilling operations call for the use of Sepiolote mud sweeps to clean the borehole, but the lack of mud returns to the drilling vessel leaves the driller with few real-time feedback parameters from the wellbore. In recent years scientific ocean drilling has become more dependent on LWD and measurement while drilling MWD technologies to monitor drilling conditions.

The offshore drilling community deals with major wellbore stability challenges that are typically mitigated through the circulation of dense drilling mud to prevent hole collapse and to remove drilling debris. In the scientific ocean drilling realm, we have been very successful in drilling relatively shallow holes (<1,500 m) in water depths greater than 3,500 m. Drilling in these extreme water depths requires the use of the riserless drilling technique which is not constrained by the length limitations of a riser system. The riser-capable drilling vessel *D/V Chikyu* has enabled IODP to drill deep holes in water depths up to 2,500 m. Scientific objectives in greater water depths with borehole penetrations deeper than 2,000 m still remain a major challenge.

In 1995, ODP Leg 164 was the first expedition committed exclusively to methane hydrate scientific drilling objectives. For the first time, ODP purposely cored and logged the entire methane hydrate stability zone and the underlying free gas zone, penetrating a prominent BSR, countering critics concerned about safety of such activities. ODP's Pollution Prevention and Safety Panel, which reviews each site drilled in the program, allowed this campaign because the experts on the panel had ascertained that methane hydrates on the Blake Ridge did not represent a risk to drilling. A new pre-drilling interpretation that a BSR could be formed by as little as 1-2% free-gas below sediments that hardly contain any methane hydrate (Hyndman and Davis, 1992) gave the panel the information needed to assess the risk associated with drilling through BSRs.

Results from several methane-hydrate drilling programs, including ODP 164 (Paull et al., 1996), and ODP 204 (Tréhu et al., 2004), and more recently the Chevron lead Gulf of Mexico JIP Leg I (Ruppel et al., 2008), IODP Expedition 311 (Riedel et al., 2006) and NGHP Expedition 01 (Collett et al., 2008b, 2008c), have shown that drilling hazards associated with methane-hydrate-bearing sections can be managed through careful control of drilling parameters (Collett et al., 2010). However, the possibility of gas flow still exists and is the main concern of the LWD monitoring program in most of the more recent methane hydrate drilling projects. LWD data has been used to provide real-time borehole monitoring data during drilling, which can be used to assess potential drilling problems associated with the presence of free gas-, methane-hydrate-, and water-bearing zones that may flow. The primary measurement used for gas monitoring has been the annular-pressure-while-drilling measurement, or APWD. The presence of free gas in the borehole lowers the borehole-fluid density and decreases the pressure as detected by the

LWD tool string. Sudden pressure increases can also be precursors of gas flow from the formation and into the annulus. The monitoring procedure has consisted of observing any abrupt pressure change and then being prepared to control well pressure with drilling fluid if a decrease of 100 psi or more was detected, corresponding to a gas content of 25% in a borehole drilled to about 300 mbsf (Riedel et al., 2006).

The GOM JIP Leg II expedition provided significant new information on the optimal drilling and well control protocols for deep water methane hydrate research projects. Drilling operations within GOM JIP Leg II were marked by the constant challenge of optimizing data quality while maintaining borehole stability, which is difficult to achieve within shallow unconsolidated sediments. In addition, several of the targets were exceptionally deep: the two wells drilled in Walker Ridge 313 (at more than 900 m below the seafloor) exceeded by more than 300 m the previous record for the deepest methane hydrate research wells (NGHP Expedition-01, Site 17, Andaman Islands). The process of drilling the GOM JIP Leg II wells provided new insights into the optimal drilling strategies for marine "open-hole" LWD drilling programs without surface conductors or drilling mud returns.

Ultimately during GOM JIP Leg II three sites were occupied, seven LWD holes with a total of 4,688 m formation were drilled and logged during this research leg. Penetration depths varied from 340 to 1,093 mbsf. To provide the highest-quality data, the JIP had planned to eliminate the use of heavy drilling fluids and exclusively use seawater with periodic gel sweeps as needed. However, the JIP Leg II wells were unique in the GOM for the depth of openhole drilling below the seafloor, as industry drilling routinely sets surface casing at shallow depths. This plan was altered in the field to include the use of regular drilling mud, upon the observation that inefficient cuttings removal during the drilling of the initial well (WR313-G) resulted in necessary back-reaming and other drilling measures that eroded the hole, thereby compromising the quality of some of the LWD data. Throughout the remainder of Leg II, mud circulation was implemented prior to the onset of pipe-sticking issues (commonly at about 600 mbsf), resulting in substantially improved LWD quality. Careful control of drilling-fluid temperatures mitigated risks related to methane-hydrate dissociation during drilling and led to incident-free drilling through many methane-hydrate-rich sections. In fact, the caliper data clearly indicate that the most stable portions of the wells drilled during JIP Leg II were those in which substantial volumes of methane hydrate were present, providing significant additional mechanical strength to the otherwise highly unconsolidated sediments.

In deepwater, despite the drilling of thousands of wells worldwide in areas where methane hydrate could occur there have been only a small number of reported and minor drilling incidents (Smith et al., 2005; Nimblett et al., 2005). Work conducted within the Gulf of Mexico gas hydrate Joint Industry Project has confirmed that careful drilling fluid temperature control is sufficient to mitigate the risk of methane hydrate dissociation while drilling through low-concentrated, shale-hosted methane hydrates accumulations (reviewed in Ruppel et al., 2008). Similarly, sea-floor methane hydrate mounds and thick methane-hydrate bearing subsurface sands can be effectively detected and avoided with existing shallow-hazard assessment methods. Perhaps the least well constrained methane hydrate-related drilling hazard may be those instances where thick, highly-saturated, methane hydrate-bearing sands at the base of the hydrate stability zone hinder the detection of underlying free gas hazards (McConnell et al., 2012). In arctic settings, methane hydrate typically occurs at high concentrations in sand reservoirs both within and below permafrost. Arctic methane hydrate has been associated with a small number of well control incidents (Collett and Dallimore, 2002). Subsequently, drilling protocols have emerged that enable methane hydrates at high concentrations to be safely drilled.

10. Methane Hydrate Research Planning, Reviews, and Assessments

As discussed in the introduction to this report, one of major goals of the DOE-COL "Methane Hydrate Field Research Program" is the development of a "Science Plan" in which the major scientific questions and unknowns relative to our understanding of methane hydrates in nature will be identified and assessed. This "Historical Methane Hydrate Project Review" report is considered to be a foundational report for the "Science Plan" being developed within DOE-COL research program. In the follow section of this historical review, we have focused on the systematic review of planning documents for major methane hydrate research projects, national and international methane hydrate research assessment reports, and program peer review reports. In many cases these project planning documents and program reviews include detailed analysis of critical unknowns relative to our understanding of methane hydrates and provide to some degree an appreciation of how our understanding of methane hydrates has evolved over the last 15 years.

U.S. Department of Energy – A Strategy for Methane Hydrates Research and Development, 1998
http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/pdf/98hydratestrategy.pdf

This report served as the foundation for the new national program effort in the U.S. in 1998. It was intended to set a 10-year science and technology path that would produce the knowledge and products necessary for commercial production of methane from hydrates by 2015 and will address associated environmental and safety issues. This report identified the following program goals: (1) Define a vast, domestic resource in permafrost regions and surrounding waters. (2) Enable the U.S. to meet a substantive natural gas growth in power generation and transportation in the early 21st century, while meeting requirements for cleaner fuels and reduced emissions of CO_2. (3) Ensure our energy security, foster U.S. industry global competitiveness, and enhance the value of Federal lands that provide 37 percent of the nation's gas production. (4) Focus research on methane hydrate related resource characterization, production, global carbon cycle, and safety and seafloor stability issues. (5) Marshall the resources of the petroleum industry, academia, the National Laboratories, and a broad base of government programs with concurrent interests in methane hydrate research. The Department of Energy, Office of Fossil Energy, will develop and manage the program in consultation with a Management Steering Committee: DOE Office of Energy Research, United States Geological Survey, Minerals Management Service, Naval Research Laboratory, National Science Foundation, Ocean Drilling Program, Natural Gas Supply Association, Gas Research Institute, and American Petroleum Institute. (6) Promote cooperation with the international community, including countries, such as Japan, Canada, and the United Kingdom, who have active methane hydrates R&D programs. This program plan was consistent with the authorization under the Methane Hydrate Research and Development Act of 1998 (the MHR&D Act; 30 USC 1902), which was passed by the Senate on July 17, 1998 and referred to the House of Representatives, and authorized DOE/FE in consultation with the USGS, National Science Foundation (NSF), and Naval Research Laboratory (NRL), to conduct methane hydrates research for the identification, assessment, exploration, and development of methane hydrate resources.

The 1998 DOE plan included a "Technology Roadmap" as illustrated in Figure 10.1, this roadmap illustrates in a simplified manner how technology was expected to proceed from the current state-of-the-art at that time to the technological level necessary to achieve the program goals in Resource Characterization, Production, Global Carbon Cycle, and Safety and Seafloor Stability. This roadmap was expected to change as the program proceeded; with the early results determining the research directions and activities later in the program. The 1998 DOE plan went on to describe in some detail the research needs and activities necessary to achieve the program goals.

U.S. Department of Energy – National Methane Hydrate Multi-Year R&D Program Plan, 1999 http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/pdf/99hydrate.pdf

The 1999 *National Methane Hydrate Multi-Year R&D Program Plan* builds on the 1998 *A Strategy for Methane Hydrates Research and Development* planning document. It was intended to illustrate how technology was expected to develop in support of methane hydrate research and development activities. The Federal role was identified as providing the coordination, integration, and synthesis of research efforts needed to: (1) establish an estimate of gas resources from methane hydrate deposits; (2) develop the technology necessary for the commercial production of methane from hydrates; (3) understand and quantify the dual roles of methane hydrates in the global carbon cycle and their relationship to global climate change; and (4) respond to industry concerns regarding the safety and seafloor stability issues and pipeline plugging concerns attributed to methane hydrates which are currently associated with the exploration, production, and transportation of conventional hydrocarbons.

Much like in the 1998 DOE program planning document, the national R&D program is framed within four technology areas: (1) Resource characterization, (2) production, (3) global carbon cycle, and (4) safety and seafloor stability. The 1999 DOE planning document went on to establish the mission of the *National Methane Hydrate Multi-Year R&D Program* is to carry out the research, development, and demonstration projects necessary to identify and enhance options that could revolutionize 21st century energy markets through the commercial production of methane from hydrates in a safe and environmentally responsible manner. The 1999 DOE planning document also included a listing of the key activities "needed to understand and measure natural methane hydrate deposits in the geologic environment and to accurately assess the potential methane resource", which are summarized in Tables 10.1, 10.2, 10.3, and 10.4.

U.S. Department of Energy – An Interagency Roadmap for Methane Hydrate Research and Development, 2006 http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/pdf/InteragencyRoadmap.pdf

In July of 2006, DOE released an *Interagency Roadmap for Methane Hydrate Research and Development*, which was a joint effort of representatives from the DOE, the U.S. Department of the Interior (including the USGS, MMS, and BLM), the Department of Defense (the Office of Naval Research's, Naval Research Laboratory (NRL)), the Department of Commerce (the National Oceanic and Atmospheric Administration (NOAA)), and the National Science Foundation (NSF). This roadmap outlines a plan of action to fully address the goals of the Methane Hydrate Research and Development Act of 2000 (P.L. 106-193), as amended by Section 968 of Public Law 109-58 (The Energy Policy Act of 2005). This roadmap emphasized the realization of the energy supply potential of hydrates, while continuing to address important hydrate research questions such as sea floor stability, drilling safety, and environmental issues associated with naturally-occurring methane hydrate.

The 2006 DOE led roadmap reviewed the progress and findings of the first five years of the interagency DOE led national program, established long-term goals and key intermediate milestones in three primary focus areas, and outlined the overall program structure and management philosophy. The program set forth in this roadmap was designed to develop a comprehensive knowledge base and suite of tools/technologies that will, by 2015: (1) Demonstrate viable technologies to assess and mitigate environmental impacts related to hydrate destabilization resulting from ongoing "conventional" oil and gas exploration and production (E&P) activities; (2) document the risks and demonstrate viable mitigation strategies related to safe drilling in hydrate-bearing areas; and (3) demonstrate the technical and economic viability of methane recovery from arctic hydrate. By 2025, the Program will: (1) demonstrate the technical and economic viability of methane recovery from domestic marine hydrate; (2) document the potential for and impact of natural hydrate degassing on the environment; and (3) assess the potential to further extend marine hydrate recoverability beyond the initial producible areas.

The 2006 DOE led roadmap also provided a description of the types of activities and areas of investigations that will enable the achievement of the interagency Program's long-term goals, which included: (1) Periodic resource assessments in order to inform the public of the in-place and likely technically recoverable resources of methane in hydrate deposits. (2) Collect and manage existing data through the establishment comprehensive public databases. (3) Collect new data from wells and/or geophysical projects of opportunity. (4) Field studies designed to provide samples and data on methane hydrate in nature. (5) Continue to develop and validate numerical simulations of methane hydrate responses to natural and induce phenomena. (6) Support a variety of cooperative R&D efforts with industrial and academic laboratories. (7) Pursue research that enables discriminating among the different rock-physics models of hydrate occurrence, as well as improved data acquisition and interpretation methodologies. (8) Support the development of new and better tools for obtaining, retrieving, and analyzing natural hydrate/sediment samples under uninterrupted in-situ pressure and temperature conditions. (9) Work to complete installation and support the ongoing operation and maintenance of a permanent sea floor observatory in the Gulf of Mexico. (10) Support the development of improved tools for analysis of deep-marine hydrate occurrences and the distribution, rates, and analysis of fluid and gas flux from the sea floor into the water column. (11) The Program expects that all the major program elements will be integrated together, as appropriate, to maximize the benefit to research.

U.S. Department of Energy – An Interagency Five-Year Plan for Methane Hydrate Research and Development FY2007-FY2011, 2007
http://www.fossil.energy.gov/programs/oilgas/hydrates/MHAC-07-ReportToCongress-final.pdf

As described in the introduction to the 2007 *Interagency Five-Year Plan for Methane Hydrate Research and Development* program planning document, this report compliments the 2006 *Interagency Roadmap for Methane Hydrate Research and Development*. The 2007 research and development plan includes many of the same elements and discussions that can be found in the 2006 roadmap (as described above in this report), but the 2007 research and development plan also includes a long list of cross-cutting programmatically activities planned for the next five years that were determined to be necessary to keep the program on track to achieve its long-term goals.

U.S. Department of Energy – Interagency Coordination on Methane Hydrate R&D, 2007
http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/pdf/MethaneHydrate_2007Brochure.pdf

This brochure, released in 2007, described the ongoing activity of the DOE led interagency research and development programs on methane hydrates. This brochure also draws heavily on the 2006 *Interagency Roadmap for Methane Hydrate Research and Development*, and covers many of the same topics. This document also focuses on the accomplishments of some of the more significant methane hydrate related interagency efforts, including (1) the development of Arctic methane hydrate seismic detection technologies, (2) the coring, logging, and testing of the Mount Elbert Prospect in northern Alaska, (3) the development of improved methane hydrate related experimental capabilities in the USGS and DOE, (4) the use of field data to further our understanding of the methane hydrate systems in nature, (5) the development of an improved understanding of the safety implication of methane hydrates in the Gulf of Mexico, and (6) the further development of improved numerical simulation capabilities in support of methane hydrate field research programs.

U.S. Department of Energy – An Assessment of the Methane Hydrate Research Program, 2007
http://www.fossil.energy.gov/programs/oilgas/hydrates/MHAC-07-ReportToCongress-final.pdf

The Methane Hydrate Research and Development Act of 2000 (P.L. 106-193) called for the establishment of *Methane Hydrate Advisory Committee* (MHAC) to assists the U.S. Secretary of Energy in assessing progress toward program goals, evaluating program balance, and providing recommendations to enhance the quality of the program over time. As charged by the Act, the MHAC must submit to Congress every five years an assessment of the DOE methane hydrate research program. The MHAC assessment from 2007 concluded that there were three critical needs that must be met in order to "broaden" the DOE lead hydrate program: (1) Field testing of concepts and technologies for producing hydrates economically. (2) An accurate assessment of the economic viability of marine hydrates, which exceeds the permafrost resource by several orders of magnitude. (3) A quantifiable assessment of the environmental impact of possible leakage of methane from uncontrolled hydrate decomposition. One of the major findings of the MHAC review was their endorsement of the 2007 DOE Interagency Five-Year Plan (as described above in this report). The MHAC, however, also concluded that "current funding levels (were) not sufficient to achieve the program goals".

National Research Council – United States
Charting the Future of Methane Hydrate Research in the United States, 2004
http://www.nap.edu/catalog.php?record_id=11094

As discussed above in this report, the Methane Hydrate Research and Development Act of 2000 (P.L. 106-193) mandated several levels of coordination and oversight of the methane hydrate research and development program as established by DOE. In addition to the mandates already mentioned, the act calls for the National Research Council (NRC) to study progress made under the program initiated by the act and to make recommendations for future methane hydrate research and development needs. The *Committee to Review the Activities Authorized under the Methane Hydrate Research and Development Act of 2000* was convened by the NRC in 2004. The primary goal of this report is not only to review the progress made under the act and to provide advice on future methane hydrate research and development needs, but also to emphasize the importance of scientific oversight and community input to funding that research.

The *2004 NRC Committee* reviewed a number of projects that had been funded and managed under the Methane Hydrate Research and Development Act, they also made a series of specific recommendations in "four major categories": (1) International collaborative projects; (2) targeted research projects; (3) the USGS interagency projects, and (4) smaller-scale projects. But more important for this review, the NRC *Committee* focused most of their report on a relatively short list of high priority program goals as described below in this report. The *2004 NRC Committee* concluded that the overriding focus of the DOE Methane Hydrate R&D Program in the future should be on the potential importance of hydrate as a future energy resource for the nation and the world. To optimize the potential impact of the amount of hydrate research funding available (about $9 million per year at the time of the review), such a focused program should systematically address research in areas that are poorly or partly understood. These focus areas included: (1) Future field experiments, drilling, and production testing with consideration of testing offshore hydrate that might be of sufficiently large quantity for potential commercial extraction, (2) hydrate deposit identification and characterization, (3) reservoir modeling, (4) technology recovery methods and production, (5) understanding the natural system and climate change potential, (6) geological hazards, and (7) transportation and storage. The NRC *Committee* also concluded that collaboration between the DOE Methane Hydrate R&D Program and other agencies, to augment infrastructure, will facilitate the achievement of program goals. For example, collaboration with the National Science Foundation (NSF), especially with the Ocean Observatories Initiative (OOI) and the Ocean Research Interactive Observatory Network (ORION), would be useful to implement studies geared toward understanding the temporal evolution of methane hydrate systems using long-term observatories on and beneath the seafloor.

National Research Council – United States
Realizing the Energy Potential of Methane Hydrate for the United States, 2009/2010
http://www.nap.edu/catalog.php?record_id=12831

Much like the NRC 2004 review of the of the research efforts funded under the Methane Hydrate Research and Development Act of 2000 (P.L. 106-193), in 2009/2010 the NRC was again requested by Congress to evaluate the Program's research projects and management processes since its congressional reauthorization in 2005 and develop recommendations for its future research and development initiatives. Much like the findings of the *2004 NRC Committee* the findings of the *2009/2010 NRC Committee* also focused on the assessment of the energy resource potential of methane hydrates.

The *2009/2010 NRC Committee* report provided "a positive evaluation" of the Program's scientific progress to date and made the following recommendations. To better meet its goals of assessing the potential of long-term production of methane from methane hydrate, DOE should aim to expand future research in several areas: (1) the design and demonstration of production technologies in the field that can sustain the flow of methane gas from methane hydrate deposits over long periods of time; (2) evaluating and predicting the environmental and safety issues related to production of methane from methane hydrate; (3) reducing the uncertainty that remains in locating and identifying the size of methane hydrate deposits, including the potential volume of methane that might be extracted, and the way methane hydrate might behave or change during production. To support the design of production technologies, the report recommends long-term field production tests in different locations, as well as monitoring the behavior of methane hydrate deposits and surrounding sediments before, during, and after production. Advances have been made in employing "remote sensing" techniques, conducting laboratory experiments, and computer modeling of methane hydrate to determine the location and quantity of methane hydrate deposits and how methane hydrate might behave when it is disturbed during production. It was concluded, however, substantial challenges remain to improve the accuracy and reliability of these assessments. Collecting new physical data both in the laboratory and in the field and developing new tools and models to improve data quality and analysis were recommended as areas of future research focus for the Program.

The *2009/2010 NRC Committee* report also made a series of recommendations relative to (1) environmental and geohazard issues related to methane hydrate production, (2) quantification of methane hydrate resources, (3) methane hydrates as a source if global greenhouse gases, (4) and program management.

The Council of Canadian Academies
Energy from Gas Hydrates – Assessing the Opportunities and Challenges for Canada, 2008
http://www.scienceadvice.ca/en/assessments/completed/gas-hydrates.aspx

In order to develop public policy in support of understanding the role methane hydrates may play as a future energy option for Canada, in 2008 the Natural Resources Canada asked the Council of Canadian Academies to assemble a panel of experts to address the question: What are the challenges for an acceptable operational extraction of methane hydrates in Canada? The panel was asked not to make explicit policy recommendations, but rather to assess the current state of knowledge on matters relevant to possible policy choices.

The mandate of the Council of Canadian Academies (the Council) is to perform independent, expert assessments of the science that is relevant to important public issues. The Council's assessments are performed by independent panels of qualified experts from Canada and abroad. This report was prepared for the Government of Canada in response to a request from the Minister of Natural Resources through the Minister of Industry.

The expert panel assembled on behalf of the Council determined that Canada could be well-positioned to be among the world leaders in methane hydrate exploitation if it were to invest sufficiently in exploration, research, development and production. A long-term government commitment would be needed because commercial production of gas from methane hydrate is unlikely in Canada within at least the next two decades.

To address the knowledge gaps associated with "the methane hydrate opportunity", the expert panel on behalf of the Council further indicated that Canada must choose a level of involvement and investment to advance the national interest in the energy resource potential of methane hydrates. The Council report predicted that interest in methane hydrates in Canada might be based on one of the following three broad approaches:

> (1) Research Only: Canada could continue to perform scientific research on methane hydrate while leaving, for the foreseeable future at least, methane hydrate development as a resource to other countries with more pressing needs for alternative sources of energy.

(2) Research and Limited Development: Canada could devote considerably more funding and effort than at present to research and development of methane hydrate in “sweet spots” to better understand the resource and to develop the expertise needed for extraction and processing, while leaving the major development efforts to other countries.

(3) Major Targeted Research and Development: Canada could make a determined effort to be an international leader in methane hydrate development with hydrate exploitation as a national priority. This effort would require a combination of massive investment, focused strategic R&D, infrastructure facilitation and development of training programs.

The Council’s expert panel also concluded that the Canadian federal government would need to support the following activities to lead to commercial development:

(1) Undertake geological, geophysical and geochemical studies to better delineate the extent, location, quality and potential recoverability of Canada’s methane hydrate resources.

(2) Participate more fully in international collaboration in methane hydrate research.

(3) Undertake a wide range of basic and applied research to gain a better understanding of the environmental issues related to exploitation of methane hydrate.

(4) Support R&D in all aspects of methane hydrate extraction technology.

(5) Encourage the private sector to collect and report data about the occurrence and location of methane hydrate in the course of commercial drilling through methane hydrate formations.

(6) Identify opportunities for developing new technologies for methane hydrate related to instrumentation, drilling and onshore processing, thereby creating technology export opportunities.

(7) Support educational and training initiatives for developing personnel with skills and expertise relevant to methane hydrate.

(8) Include methane hydrate on the agenda for ongoing discussions of community development in coastal and northern communities, and with Aboriginal Peoples.

(9) Undertake one or two major demonstration production/testing projects to extend the engineering and scientific expertise already in place.

(10) Collaborate with provinces and territories to establish taxation and other measures to ensure that (a) clear rules govern the exploitation of methane hydrate resources, and (b) affected areas receive a return of benefits that assist local communities and help develop renewable energy technology and greenhouse gas sequestration.

(11) Evaluate the incremental costs, risks and benefits of including methane hydrate extraction, before deciding whether or not to proceed with conventional natural gas extraction projects in the Far North and off the east and west coasts.

The Council report concluded that although there do not appear to be any insurmountable technological issues regarding the production of gas from methane hydrate, major demonstration projects would be needed to establish the longevity and safe operational practices before any major private investment in methane hydrate is likely.

11. Conclusions

In 1982, scientists onboard the Research Vessel *Glomar Challenger* retrieved a meter-long sample of massive methane hydrate off the coast of Guatemala. This sample became the impetus for the first national research and development program dedicated to methane hydrates by the United States. Over the next 10 years, a long list of organizations compiled data demonstrating the potential for vast methane hydrates accumulations around the world. By the mid-1990s, it was widely accepted that methane hydrates represented an enormous storehouse of gas and it is generally assumed that the immense volume of methane hydrates worldwide could become a significant potential energy resource in the future. Today, however, our understanding of these resources is still evolving. Research coring and downhole logging operations carried out by the ODP, IODP, government agencies, and several consortia have significantly improved our understanding of how methane hydrates occur in nature. Government agencies in many countries are interested in the energy resource potential of methane hydrates. Countries including Canada, China, India, Japan, Korea, and the United States have established effective national led programs and implemented ambitious methane hydrate research drilling and testing programs. These, mostly energy focused research efforts, along with a host of other research programs and field studies have also indicated that methane hydrates may be an important part of the global carbon cycle and naturally destabilized methane hydrates may be contributing to the build-up of atmospheric methane. It is also possible that methane hydrates may play an important role relative to seafloor stability and submarine landslides.

The scientific foundation has been built for the realization that methane hydrates are a global phenomenon, occurring in permafrost regions of the arctic and in deep water portions of most continental margins worldwide. However, more work is needed to create a better understanding of the impact of hydrates on safety and seafloor stability as well as to provide data that can be used by scientists in their study of climate change and assessment of the feasibility of methane hydrates as a potential future energy resource.

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