Quadrennial Technology Review 2015

Chapter 7: Advancing Systems and Technologies to Produce Cleaner Fuels

Technology Assessments

Bioenergy Conversion

Biomass Feedstocks and Logistics

Gas Hydrates Research and Development

Hydrogen Production and Delivery

Natural Gas Delivery Infrastructure

Offshore Safety and Spill Prevention

Unconventional Oil and Gas

U.S. DEPARTMENT OF ENERGY

Quadrennial Technology Review 2015

Gas Hydrates Research and Development

Chapter 7: Technology Assessments

Executive Summary

Recent research confirms that gas hydrates are abundant in nature and exist in a wide variety of forms. These occurrences have unique and differing relevance to issues of future energy supply, long-term global carbon cycling, near-term climate change, and both natural and operational geohazards. Formal assessments conducted within the Department of Interior suggest large resources in gas hydrate deposits onshore in Alaska and throughout the U.S. Outer Continental Shelf. Drilling programs in Alaska, the Gulf of Mexico, and Japan have demonstrated viable exploration approaches and provided initial confirmation of the nature and abundance of those deposits that are most amenable to energy development. Short-duration, scientific production trials have occurred onshore in North America, and most recently offshore Japan, and have revealed the potential for eventual commercial production, although longer term tests are required. Scientific field programs to evaluate the occurrence of gas hydrate, and the flux of methane gas in hydrate-bearing environments sensitive to ocean acidification and climate, are ongoing. These continue to provide new insights into the history and causes of methane release, and the potential for future releases in response to ongoing environmental change.

Research findings to date indicate a range of high-priority scientific study areas and technology development pathways that can contribute substantially to understanding the energy and environmental implications of naturally-occurring gas hydrates. The primary long-term R&D challenges include: 1) providing a refined assessment of the nature and occurrence of gas hydrates within the U.S.; 2) demonstrating integrated technological approaches that can achieve production of natural gas from gas hydrates in an economically-viable and environmentally-responsible manner; 3) determining the role of gas hydrate deposits in the generation of a range of natural and operational geohazards; and 4) elucidating and effectively communicating the role gas hydrates can potentially play in the natural sequestration and cycling of carbon over a range of time-scales, including potential short-term responses to ongoing climate change.

Meeting the R&D challenges listed above by the year 2030 would require a series of large-scale scientific field programs (supported by focused laboratory studies and continued refinement of numerical modeling across a range of scales) that include: 1) geophysical data acquisition; 2) well drilling and logging; 3) sampling and physical and chemical analysis; and 4) reservoir characterization and scientific production testing.

This *Technology Assessment for Gas Hydrates Research and Development* is based on extensive collaborative discussions within the Interagency Gas Hydrate Technical Coordination Team (TCT) and extensive review and public discussion via the Methane Hydrate Federal Advisory Committee. This Assessment also draws from the *Marine Gas Hydrate Field Research Plan* that was developed through open discussions convened by the Consortium for Ocean Leadership and DOE. As such, this Assessment is based on the current consensus view of the scientific community regarding the primary science and technology development opportunities resulting from the recognized wide-scale occurrence of gas hydrates. This Assessment recognizes that recent trends in gas

production in the United States have diminished the interest of the private industry to invest resources in long-term gas hydrate research, either proprietary or in collaboration with the government. As a result, it is expected that R&D will only progress through the continuing augmentation of private-public R&D partnerships with sustained collaboration across federal agencies and with international partners.

Introduction

This *Technology Assessment for Gas Hydrates Research and Development* is based on discussions conducted within the Interagency Gas Hydrate Technical Coordination Team (TCT), which includes representatives of those federal agencies whose missions require the study of naturally-occurring gas hydrates: the Department of Energy (DOE), the U.S. Geological Survey (USGS), the Bureau of Ocean Energy Management (BOEM), the Bureau of Land Management (BLM), the National Oceanic and Atmospheric Administration (NOAA), the Naval Research Laboratory (NRL), and the National Science Foundation (NSF). Together, these agencies, in collaboration with numerous research partners in academia, industry, state/local governments, and the DOE National Lab system, constitute the broader U.S. National Gas Hydrates R&D Program. This Assessment also draws heavily on the Marine Gas Hydrate Field Research Plan developed for the DOE in coordination with the gas hydrate scientific community and the Consortium for Ocean Leadership.[1]

Background

Gas hydrate is a natural form of "clathrate"—unique substances in which molecules of one material (in this case, water) form a rigid lattice that encloses appropriately-sized molecules of another material (in this case, predominantly methane). Historically, the vast majority of research in gas hydrates has focused on the inhibition of spontaneous hydrate formation in oil and gas pipelines and other production equipment (a field of study known as "flow assurance"). However, beginning in the late 1960s, observations and interpretations provided primarily by Russian researchers indicated the conditions suitable for gas hydrate occurrence should be very abundant in nature. A series of deepwater scientific drilling expeditions through the 1970s and 1980s corroborated this view, leading to the relatively recent realization that gas hydrate deposits serve as a major global storehouse of organic carbon.

Research over the past three decades has revealed that gas hydrates exist in nature both as a void-filling material within shallow sediments (both onshore in the arctic and within deepwater continental margins) and as massive "mounds" (often in association with unique "chemosynthetic"—i.e., drawing energy not from the sun, but from subsea floor sources of methane gas biota) on deep sea floors. Once thought to be relatively rare in nature, gas hydrates are now known to store immense volumes of organic carbon.[2] In response, national R&D efforts (most notably in the U.S., Japan, China, India, and South Korea) have conducted a series of major scientific drilling programs to assess gas hydrate occurrence. In addition, observation of numerous naturally-occurring gas releases around the globe has led to an increase in field studies to assess the nature and causes of gas venting in order to better constrain the near- to mid-term risks gas hydrate destabilization might pose for ocean ecology and climate change. Further, industry has conducted a limited number of studies, both privately and in concert with the government, to assess the implications of gas hydrates for operational (offshore drilling) safety. These studies have resolved the issue of safe drilling through gas hydrate-bearing sediments, but remain inconclusive regarding issues of long-term well integrity over extended periods of conventional oil and gas production. Therefore, despite the recent increase in scientific investigation, the nature, abundance, and behavior of naturally-occurring gas hydrates, and the potential response of those deposits to external perturbations—either natural or induced—remains poorly understood.

International interest in gas hydrate research continues to grow despite modest U.S. Federal investment and lagging private industry interest. The government of Japan recently conducted the first marine production test, and has announced plans for further, more expansive tests. India continues to plan and conduct gas hydrate evaluation programs in preparation for offshore testing as well. China has conducted field programs for gas hydrate evaluation both onshore (Qilian Mountains) and offshore (South China Sea). South Korea has recently completed two extensive marine gas hydrate exploration expeditions in the East Sea and is currently evaluating opportunities for further field programs. Canada conducted—in collaboration with many international programs—a very successful program of science and technology development in gas hydrates from 1998 to 2012, but ultimately determined to suspend that effort. Various entities in Europe have conducted gas hydrate characterization and environmental studies in the past, and the European Union has recently initiated its first multi-national collaborative effort to assess gas hydrate resource potential. Gas hydrate characterization programs are also underway in other countries, including Vietnam, New Zealand, Brazil, Mexico, Uruguay, Colombia, Iran, and South Africa.

Ongoing R&D Activities

Industry R&D: The amount of industry R&D related to naturally-occurring gas hydrates is uncertain but limited. Industry is primarily interested in the ongoing evaluation of shallow geohazard studies that routinely address gas hydrate issues. As deepwater drilling increased in the early 2000s, these efforts commonly resulted in the avoidance of areas suspected to be gas hydrate-bearing due to lack of information on the true nature of the hazard. In 2000, DOE developed a partnership with Chevron, which convened a Joint Industry Project (JIP) that worked with the Federal R&D effort to investigate the issue of safe deepwater drilling in areas of gas hydrate occurrence, culminating in a drilling program ("JIP Leg I") conducted in the Gulf of Mexico in 2005. By 2007, the drilling safety issue had been sufficiently resolved for most common occurrences of gas hydrates.[3] A small number of proprietary industry projects have included an emphasis on gas hydrate-related operational hazards,[4] with the most significant being the "Gumusut-Kakap" project conducted by Shell and partners offshore Bornean Malaysia in 2006.[5] The Shell program included scientific drilling and specialized coring, as well as numerical simulation, to assess long-term risks from thermal stresses associated with producing oil and gas fluids through overlying gas hydrate-bearing sediments. Ultimately, the effort indicated that these risks could not be effectively constrained given the existing state of knowledge, and the drilling program was modified to drill around the hydrates at substantial expense.[6] DOE is not aware of any subsequent investigations of this issue within industry. In addition, specific gas hydrate-related geohazard issues associated with Arctic drilling, particularly near-shore drilling in areas of "relict" hydrates have been recognized, but DOE is not aware of any significant industry R&D efforts on this topic.

Industry has followed R&D related to gas hydrates as a resource, and the potential timelines and locales of gas production could significantly impact business activities at both local (such as issues of gas supply within specific regions of the Alaska North Slope) and global scales. While certain appraisal attempts have occurred within industry (various data collection activities in Alaska and Canada in the late 1970s[7] and one known dedicated logging program at the Alaminos Canyon 818 accumulation in the Gulf of Mexico by Chevron in 2004[8]), DOE is not aware of any proprietary industry studies on gas hydrate resource development that have been conducted, although various laboratory efforts[9] and desk-top assessment and appraisal activities, such as those reported by Statoil in 2014[10] and Ecopetrol,[11] have been noted.

Industry has enabled and participated in R&D related to gas hydrate resource potential in collaboration with the Federal government. In Alaska, both BP Alaska and Anadarko partnered with DOE to assess gas hydrate resource potential in Alaska in 2001. The Anadarko project drilled an unsuccessful exploratory well in 2004 and was ended shortly thereafter.[12] The BP project conducted a highly-successful scientific data acquisition program at the "Mt. Elbert" site in the Milne Point Unit in 2009,[13] and continued to pursue opportunities for further testing activities. BP developed a plan for a comprehensive long-term, scientific testing program for its partners in June 2010, but that proposal was subsequently withdrawn due to various legal and logistical complications. In 2008, ConocoPhillips Alaska, on the basis of proprietary experimental studies conducted in collaboration with the University of Bergen, partnered with the DOE to test the technical feasibility of methane extraction from gas hydrates via injection, exchange, and sequestration of carbon dioxide. A field trial—in partnership with Japan—conducted in 2011 and 2012, determined that injection and partial exchange and sequestration were accomplished,[14] but that the process was complex and unlikely to result in gas production at rates comparable to what is expected using other gas hydrate production approaches.[15] The project ended in 2013, as did the ConocoPhillips proprietary R&D effort. All partners in the Prudhoe Bay operating units have indicated a lack of ability to accommodate any additional external science programs on currently-leased lands.

With respect to offshore resource appraisals, field-based industry R&D activity has similarly been conducted in collaboration with DOE programs. A second drilling program was conducted by the Chevron-led JIP ("JIP Leg II") in 2009 that was designed to extend the appraisal of drilling hazards to include the characterization of high-saturation gas hydrate occurrences within sand-rich reservoirs (those that are also the prime candidates for energy production). This expedition succeeded in demonstrating: 1) the occurrence of resource-grade accumulations in the US offshore; 2) the ability to drill through them safely; and 3) an effective approach for prospecting for and characterizing such accumulations prior to drilling.[16] In early 2014, the JIP was ended. A DOE solicitation in 2014 seeking to further investigation of resource-relevant gas hydrates in both/either Alaska and the U.S. offshore attracted no industry interest.

The U.S. Federal R&D Program: From 2000 to 2012, the DOE was responsible for developing an external R&D program in collaboration with the private sector. This program was built primarily around a small number of complex field programs conducted in partnership with industry that were supported by targeted R&D efforts with academia, the DOE National Laboratories, and with collaborating federal agencies. DOE's National Laboratories are expected to continue to be a primary source for the fundamental scientific investigation of gas hydrate samples (both natural and synthetic) and the integration of field and laboratory data to advance numerical simulation capabilities (relevant to all gas hydrate R&D issues) at a wide range of scales.[17] Universities serve as key providers of scientific expertise to guide and conduct aspects of the larger industry programs and have conducted a wide range of laboratory, numerical modeling, and field programs on all issues relevant to gas hydrates.

Interagency collaboration has been central to the Federal R&D effort, most notably in the planning and execution of the large field programs in Alaska and the Gulf of Mexico, and in the coordination of the U.S. contributions to international R&D programs. The Methane Hydrate Research and Development (MHR&D) Act specified that an interagency committee, led by DOE, be created to ensure efficient communication and coordination of gas hydrate-related R&D activities across all agencies of the U.S. government. This group, which includes representatives from the National Science Foundation, the U.S. Geological Survey, the Bureau of Ocean Energy Management, The Naval Research Lab, the Bureau of Land Management, and the National Oceanic and Atmospheric Administration, meets periodically to inform their colleagues of new findings and emerging opportunities for synergistic research and collaboration and provides input on draft program plans and other matters. Although final implementation of each agency's programs and budgets are the sole responsibilities of those agencies, each partner to this effort recognizes that continued interagency collaboration is critical to the success of the National R&D effort. As a result, active collaboration within the group has continued to the present, despite the lifting of the legislative requirement with the sunset of the MHR&D Act in 2010. For example, in 2013, the USGS executed a program of advanced seismic data acquisition at two sites in the deepwater Gulf of Mexico that was co-funded and co-planned by USGS, DOE, and BOEM.[18]

Given the requirement for access to leased lands and the need to conduct complex[19] drilling operations, industry support has been essential to the success of the program, and DOE has been able to develop these projects via cost-shared Collaborative Agreements in which DOE funds up to 80% of total project costs. Going forward, the DOE intends to pursue this collaborative model; however, the current decline in industry interest will present significant challenges to the development of successful projects. Academic institutions are also challenged by the requirement for cost-share in DOE-supported research, particularly given the large expense of field programs and the inability for academic institutions to recoup their investments.

These factors encourage collaborative R&D with international partners where feasible. Such cooperation provides information on the varied nature of gas hydrates occurrence and the manifestation of gas hydrate in geophysical data across a wide range of geologic settings. International collaboration also provides a framework for gaining additional experience and testing of field sampling and analysis tools. To date, the primary collaborations have been with major national R&D programs in India, Japan, and S. Korea.

International R&D: The Government of Japan, through the Ministry of Economy, Trade, and Industry (METI), conducts the most highly-funded and active gas hydrate program (named "MH-21") globally. Since 1995, the Japan Oil and Gas Metals Corporation (JOGMEC) has conducted a series of large-scale field programs both in Arctic Canada (1998, 2002, 2007/8) and in the deepwater Nankai Trough off Japan's southeastern coast (2000, 2005, 2012/13). A large and highly-productive complementary laboratory effort is conducted by the National Institute for Advanced Industrial Science and Technology (AIST). The arctic efforts have focused on utilizing known gas hydrates at the "Mallik" site in Canada[19] and within the Prudhoe Bay region (in collaboration with DOE-sponsored programs) to test gas hydrate production technologies; whereas the marine work has included geophysical surveys, multi-well exploratory drilling, and short-duration production testing to confirm the scale of Japan's potential domestic resources.[20] U.S.-Japanese collaboration is enabled by an MOU between METI and the DOE signed in 2008. JOGMEC has also participated as a partner in the Gulf of Mexico JIP and have subsequently continued to support ongoing efforts at the DOE and the USGS to improve the design and performance of specialized gas hydrate coring devices. JOGMEC, the DOE, and the USGS are presently collaborating closely in the review of onshore drilling and testing opportunities on State lands on the Alaska North Slope. To support this effort, an MOU between the National Energy Technology Laboratory (NETL) and JOGMEC was signed in November 2014.

The Government of India has pursued gas hydrate R&D for the past decade. In 2006, the National Gas Hydrate Program (NGHP) concluded a collaborative, multi-month, multi-site drilling and coring program (NGHP Expedition-01) that included wells in the Arabian Sea, the Bay of Bengal, and the Andaman Islands.[21] U.S. Collaborations with India are enabled largely by the USGS, which has played a pivotal role in the planning, execution, and reporting of NGHP field programs. DOE also provided substantial direct support to the 2006 expedition, and in recent years, USGS, DOE, and BOEM scientists have supported India's ongoing geologic and geophysical site reviews. In early 2015, India launched a second, similarly-scaled drilling and coring program (NGHP Expedition-02) focused on exploration of deepwater locations in the northern Bay of Bengal, with the goal of identifying an optimal drill site for gas hydrate production testing in NGHP Expedition-03.

The Government of South Korea has conducted two (in 2007 and in 2010) large-scale marine drilling programs in the Ulleung Basin (East Sea) that has revealed a wide range of gas hydrate occurrences.[22] An announced plan to proceed to a production test in 2015 was recently deferred pending further analysis of potential available drill sites. A Statement of Intent (SOI) between Korea's MOTIE (formerly MKE) and the DOE was signed in 2008 and renewed in 2013. The USGS and the DOE directly participated in Korea's UBGH-01 (2007) and UBGH-02 (2010) expeditions, including enabling direct contributions from scientists in the field, supporting the analyses of required data, and participating in panels advising Korea on field site selection and program plans.

Gas hydrate R&D in China has included two marine expeditions conducted by the Guangzhou Marine Geological Survey (Expeditions GMGS-01 and GMGS-02)[23] as well as onshore drilling programs both in the nation's western[24] and northern[25] permafrost regions. Further activity in China is anticipated.

The Federal Role in Gas Hydrate R&D

Industry has invested greatly in addressing flow assurance issues related to gas hydrates that form spontaneously within production and transmission pipelines; however, private sector spending on gas hydrate energy resource and environmental issues, even in collaboration with the federal government, remains very limited. Although the Federal R&D effort has been characterized by significant industry involvement in the past, the motivations for industry participation have declined significantly since approximately 2010. A 2014 DOE Funding Opportunity Announcement related to field programs on the Alaska North Slope or in the U.S. Outer Continental Shelf (OCS) attracted no proposals from industry. The reasons for this decline include: 1) a determination (enabled by prior DOE investments) that gas hydrates, as they most commonly occur, are a manageable drilling hazard; 2) a declining near-term need to address potential additions to gas resources in many regions of the world; 3) increasing uncertainties related to potential liabilities associated with deepwater scientific drilling using industry drill ships; and 4) continuing constraints within industry to dedicate technical staff and other resources to projects with only long-range implications to corporate profitability, particularly given the development of shale gas and associated gas price declines.

The potential public benefits of gas hydrate R&D are substantial, however, and are consistently recognized in reviews of the subject (for example, see the National Petroleum Council[26]). With respect to gas hydrate resource evaluation, understanding the potential and implications of production of natural gas from gas hydrates could provide an additional option for the supply of clean-burning natural gas to meet rising domestic natural gas demand. While the recent expansion in domestic gas supply has eased near-term supply concerns, this confidence is fueling a rapid acceleration in use of natural gas, both in established markets (such as home heating and manufacturing) and in expanding markets (such as transportation and LNG exports) that may outpace gas supply growth in the mid-term. Given the established multi-decadal timeframes for the evaluation and development of commercial-ready technologies for new resources (as demonstrated previously by the successful entry of both Coal Bed Methane and Shale Gas into the marketplace following earlier federally-funded science and technology programs[27]), R&D into gas hydrates, particularly research that places strong emphasis on identifying and evaluating potential environmental implications of development, is necessary to advance this important resource.

R&D to accelerate gas hydrate science could support global energy security by providing increased means for energy self-sufficiency for many of the world's leading and most rapidly growing economies. Collaborative research could reduce the uncertainties and risks in the production and availability of natural gas. The federal government has a recognized role in addressing key failures of markets to deliver R&D that has the potential to significantly promote the public good.

Gas Hydrate Technology Assessment

Progress in gas hydrate R&D in recent years has been dominated by a series of complex scientific studies conducted in the field. Since 2005, a number of major expeditions (those that have featured deep drilling and sampling) have occurred, providing new opportunities to gain fundamental insights on gas hydrate systems through the comparison of gas hydrate occurrence across a wide range of geologic settings[28] (and the references cited therein). The following describes recent key events and R&D findings and their implications for gas hydrate R&D going forward.

Deep Marine Gas Hydrate Systems

Nankai Trough, Japan: In 1999, the Japanese government drilled the first wells designed to explore for potentially-producible marine gas hydrates in the Nankai Trough off the country's southeastern coast. The expedition succeeded in discovering a thick section of thinly-bedded sand reservoirs in which the sand units were highly-saturated with gas hydrates.[29] A second expedition in 2004 tested various exploration models and confirmed the extensive occurrence of gas hydrate "concentrated zones" throughout the studied region.[30] The drilling led to the development of an integrated characterization process that shifted the reliance from proxy indicators for gas hydrates (including "Bottom Simulating Reflectors") to a fully-integrated approach that included occurrence of host reservoirs, and direct indicators for gas hydrates such as strong geophysical amplitudes and elevated interval velocities within the gas hydrate stability zone.[31] The Nankai Trough program underscored the potential for gas hydrate occurrence at high saturation in a deepwater setting without known conventional oil and gas accumulations, the possibility for extensive sand reservoirs within shallow marine sections, and the close association between reservoir lithology and gas hydrate occurrence.

Northern Gulf of Mexico: The Northern Gulf of Mexico (GOM) was the site of many of the early studies into the nature of deepwater gas hydrates, particularly with regard to the implications of seafloor gas hydrate occurrences for deep sea ecosystems and drilling safety.[32] Initial studies revealed the complexity of the gas hydrate system in the GOM, which was a reflection of the complex geologic structure and highly-variable geochemical and thermal regimes in the GOM that are derived largely from the basin's extensive salt tectonics. The GOM has had two gas hydrate-focused drilling expeditions by the DOE-Chevron Gas Hydrates JIP that confirmed the ability to safely drill hydrates,[33] as well as the occurrence of gas hydrates in reservoir-quality sands in the GOM and the efficacy of petroleum systems-based exploration approaches.[34] The JIP and prior drilling confirms that gas hydrates occur in a variety of forms in the GOM, from massive mounds on the seafloor and dispersed accumulation in fine-grained sediments to high-saturation pore fill in sand-rich sediment. The sources for the gas in the hydrates are similarly complex and likely include both local, shallow biogenic sources as well as long-distance migration of gas from deep thermogenic sources.[35] Ongoing studies in the GOM continue to focus on a wide range of issues, including the role of gas hydrates in mediating the natural flux of methane to the water column and potentially to the atmosphere, as well as the nature of unique chemosynthetic communities associated with gas hydrate seafloor mounds.[36]

The U.S. Atlantic OCS: Blake Ridge, in the southern portion of the U.S. Atlantic Margin, was the subject of extensive gas hydrate investigations initiated by the Integrated Ocean Drilling Program (IODP) Expedition Leg 164 in 1995. These studies confirmed the occurrence of gas hydrates in large volumes over thick sequences, albeit at generally low saturations. The site was once considered to show evidence of large scale, gas venting associated with gas hydrates, but subsequent work suggests that such events are unlikely.[37] Similarly, observation of the close association of the initiation points of seafloor slumps with the up-dip limit of gas hydrate stability prompted speculation as to a causal relationship between the two features; however, detailed study of the largest slide feature (the Cape Fear slide), has shown little evidence of a significant role for gas hydrates in that event.[38] In 2013, the BOEM released its initial assessment of gas hydrate occurrence along the Atlantic Margin[39] and reported that the limited available log and seismic data indicated that the greatest potential for gas hydrate occurrence is likely on the central and northern portions of the margin, where the potential for sand-rich lithologies within the gas hydrate stability zone is highest. In 2014, a review of NOAA seafloor data indicated the presence of more than 500 natural gas seeps all along the margin,[40] suggesting that deepwater marine gas vents may be much more common than previously thought.

Cascadia Margin, Northeast Pacific Ocean: The IODP Expedition 311 was conducted in 2005 to build upon the results of several earlier programs (including IODP Legs 164 [1994] and 204 [2003]) that investigated gas hydrate systems within the accretionary wedge sediments off the coast of the North American Pacific Northwest. IODP X311 consisted of a four-hole transect across the continental slope, as well as a fifth location targeting a known cold vent site. The expedition provided further confirmation of an emerging consensus that the nature and distribution of gas hydrate occurrence within the Gas Hydrate Stability Zone (GHSZ) is highly heterogeneous and is perhaps most strongly controlled by the nature of the host lithology (with gas hydrates present preferentially within the sand units and largely lacking from the intervening muds) and the interaction of geologic structure on dominant fluid migration pathways.[41]

Indian Ocean: In 2006, the Indian government, with technical leadership provided by the USGS and with the support of scientists from dozens of leading research groups worldwide, including the DOE, conducted a 113-day exploratory expedition (NGHP Expedition-01) at more than 20 sites in the Bay of Bengal, Andaman Islands, and Arabian Sea.[42] Pressure coring and pressure-core analysis and imaging technologies made major leaps forward in this expedition, achieving unprecedented recovery rates and never-before-seen images of the detailed structure of gas hydrates in marine sediments. Perhaps most notably, the expedition uncovered a major gas hydrate accumulation at "Site 10" within the Krishna-Godovari basin: a 130-meter-thick concentration of gas hydrates in a variety of modes (disseminated, large nodules, thin veins and fracture fills, all within a fine-grained matrix). The occurrence of such relatively rich accumulations (perhaps 30% gas hydrate saturation)[43] within fine-grained sediments had not been previously observed. Further evaluation of gas hydrate occurrence in the region is being conducted in NGHP Expedition-02.

South China Sea: Two expeditions by the Guangzhou Marine Geological Survey (GMGS) of China drilled, logged, cored, and pressure-cored multiple sites in the South China Sea.[44] Among the primary findings reported was the discovery (at three sites) of unexpectedly-high concentrations of gas hydrates (30% or more) at the base of the GHSZ in un-deformed and fine-grained sediments. Initial interpretations suggest that this level of gas hydrate concentration may have been enabled by the high abundance of silt-size grains and bioclasts such as foraminifera in the sediments,[45] a phenomenon previously seen (albeit to a lesser extent in terms of gas hydrate saturation) at Blake Ridge.

The East Sea/Sea of Japan: The Korean Gas Hydrate Development Organization (GHDO) has conducted two drilling, logging, and coring expeditions in the Ulleung basin of the East Sea (UBGH-01 in 2007 and UBGH-02 in 2010). The expeditions encountered gas hydrates in multiple wells in a variety of forms, including both as pore-fill and (most commonly) as thick sequences dominated by grain-displacing, gas-hydrate-filled fractures.[46] One major accumulation (similar in nature to NGHP-01 Site 10) contained over 130 meters (m) of fracture-filling gas hydrate in fine-grained sediments.[47] The suitability of the sites discovered to date for the purpose of production testing is currently under evaluation. In 2010, Japan conducted initial assessments of hydrates along Japan's western coast, finding significant occurrences of near-seafloor hydrates in fine-grained sediments. The government of Japan has plans to assess these occurrences through its drilling and coring programs in 2015.

Svalbard, Norway: The observation of numerous deepwater gas vents along the western margin of Svalbard, and their close spatial association with the up-dip limit of gas hydrate stability,[48] has resulted in extensive study of the region to determine the potential role of climate-driven gas hydrate destabilization. The site has been fully characterized via geophysical methods as well as seafloor investigations, with evidence that the history and drivers for the venting are likely complex and perhaps related to deeper gas sources and evolving migration pathways over long time periods.[49] The site provides an ideal opportunity to further study the nature of geological processes at the upper limit of deepwater gas hydrate stability.

Gas Hydrates on Shallow Arctic Shelves

The Beaufort Shelf: The shallow arctic shelves, including the Beaufort shelf offshore Alaska, hosts potential "relict" accumulations of gas hydrates. Relict hydrates are those that formed in (onshore) permafrost settings during prior periods of lower sea-level. Ongoing inundation by the sea has warmed average sediment surface temperatures by as much as 15^{o}C, subjecting any gas hydrates that may have originally been associated with these permafrost systems with a major change in thermal regime. The extent to which this system has achieved equilibrium (and therefore dissociated any hydrates present) remains unclear. Conclusive evidence of permafrost on the shelf beyond the very shallow water nearshore is currently not available.[50] In contrast with other regions of the arctic, the area shows very limited evidence of active gas flux.

The East Siberia Arctic Sea: A series of field programs conducted primarily by researchers at the University of Alaska-Fairbanks has indicated the presence of significant gas venting and transmission of vented sea-bed gas through the water column and into the atmosphere in shallow waters of the Eastern Siberia Arctic Sea.[51] It is often suggested that this gas is sourced by permafrost-associated gas hydrates that are actively dissociating in response to a significant change in thermal regime related to post-ice age sea-level rise and coastal inundation. No such relict gas hydrates have yet been documented in the area and other gas sources, including degrading permafrost and deep-sourced thermogenic gas venting, remain potential sources for the observed methane.

Gas Hydrate Onshore Alaska

More than two decades of study by the USGS[52] utilizing hundreds of industry wells have revealed the overall occurrence of permafrost-associated gas hydrates on the Alaska North Slope. Gas hydrates in the region are believed to occur both within and below the permafrost section and are almost exclusively contained within the sand-rich units with no observed gas hydrate occurrence in the intervening shales. The gas source is considered to be migrated, deep-sourced hydrocarbon, with emplacement as free gas within shallow structural-stratigraphic traps occurring at some point prior to the establishment of arctic conditions on the ANS and the subsequent conversion to gas hydrate.[53] In 2006-2008, the USGS surveyed seismic data from the Milne Pt. Unit of the Prudhoe Bay oil and gas production region and utilized thin-bed amplitude analyses[54] to identify more than a dozen discrete gas hydrate prospects.[55] One of these prospects was tested by scientific drilling[56] (BP-DOE-USGS "Mt. Elbert" Well) in 2009, confirming occurrence of gas-hydrate-charged sand reservoirs. In 2011, a gas hydrate occurrence within the westend Prudhoe Bay Unit was further constrained via drilling and logging at the Iġnik Sikumi well.[57] At present, all well-characterized gas hydrates in Alaska exist on Industry-owned leases and are therefore not available for scientific production testing operations. As a result, current work in Alaska is examining the prospectivity of unleased acreage adjacent to the PBU unit for potential field testing.

Gas Hydrate Sampling and Analysis

Pressure Coring Technologies: The effort to understand the nature of gas-hydrate-bearing sediments through drilling programs is central to gas hydrate science and requires the capacity to effectively recover and analyze natural samples. This effort is challenging, as gas hydrates are not stable at surface conditions, and even the most sophisticated sampling technologies can impart significant disturbances to sediments. However, with each field program, substantial improvements are achieved in both well logging/well log analysis and pressure coring technology/pressure core analysis. In 2012, Japan successfully deployed a new pressure-core system specifically designed to core sand reservoirs with high gas hydrate saturations. In early 2013, Georgia Tech and the USGS worked in tandem with Japan to successfully deploy an array of analytical devices[58] during a collaborative program conducted with the National Institute of Advanced Science and Technology (AIST) and Japan Oil, Gas, and Metals National Corporation (JOGMEC). A further generation of the new tool is currently in development by several international R&D programs. Variations are based largely on the diameter of the tool and the related requirements on drill pipe. While larger tools may be more robust, they also require access to drill pipe that has historically been difficult to obtain on scientific drilling platforms. DOE plans to make its pressure coring devices available as feasible for deployment and testing in deepwater drilling programs worldwide; and will deploy the most reliable tools available in its own programs.

Laboratory Study: Critical research needs remain, such as: supplementing the work that can be done with the highly-limited number of natural samples; producing or having the capability to produce representative synthetic samples of gas-hydrate-bearing sediments for laboratory study; and conducting laboratory studies that are more relevant to field problems. Sample creation and characterization is complex, particularly for fine-grained samples, and is also very time-consuming should the preferred method of sample creation utilize gas hydrate formation from natural gas dissolved in water. Significant improvements in these techniques have occurred and are currently being further developed.[59]

Exploration and Remote Sensing

Geophysical Characterization: A critical goal of gas hydrate science is the ability to collect data via various geophysical methods that can be confidently analyzed to determine the abundance and distribution of gas hydrates over large areas in advance of drilling. Such tools would greatly advance the ability to assess local and regional gas hydrate environmental, geohazard, and energy resource implications. The primary tool for gas hydrate evaluation has been—and will likely remain—reflection seismic data.[60] While acquired-for-purpose data (tuned for maximum data quality in the shallow section) will always be preferable, industry standard data has been greatly used to evaluate gas hydrates.[61] In early 2013, a collaborative USGS-DOE-BOEM seismic data acquisition program collected a range of geophysical data, including the first advanced, multi-component, ocean-bottom seismic data at a location with comprehensive well log data through the hydrate-bearing sediments.[62] In certain settings, the joint evaluation of seismic and electromagnetic (EM) data may be of great value, and that technology continues to improve.[63]

Prospecting: Prior to about 2005, gas hydrate exploration relied primarily on the identification of bottom simulating reflectors (BSRs)—anomalous events observed on seismic data that very commonly mark the base of the gas hydrate stability zone—in regions with extensive evidence of gas migration and flux.[64] The initial indication of the unreliability of BSRs as an indicator of gas hydrate occurrence was provided by drilling on the Blake Ridge in 1995.[65] An extensive exploration program conducted in Japan in 2005 tested this approach, and found that BSRs are a poor indicator for the occurrence of gas hydrates at high-concentrations within potentially-producible reservoirs.[66] However, Saeki et al[67] indicated that concentrated zones of gas hydrates in marine settings could be delineated with greater certainty where strong amplitudes of appropriate polarity are found coincident with evidence of increased internal acoustic velocities and geologic evidence of sand-prone lithofacies. A similar integrated approach, which focused on thin-bed analysis of amplitudes, was developed within the USGS and applied successfully to the thin-bed, sub-permafrost situation in Northern Alaska.[68] The concept was first used in a pure exploration mode within the Gulf of Mexico JIP and resulted in the successful selection and drilling of gas hydrate accumulations at two of three sites in 2009.[69]

Much recent attention within the leading international gas hydrate programs has focused on the development of an integrated approach to gas hydrate characterization that applies conventional concepts of petroleum systems prospecting (the search for producible accumulations) to the specific case of gas hydrates.[70] This approach is built on the determination that the most favorable targets for exploration are sand-dominated systems. Therefore, the exploration approach integrates geologic-geophysical evidence for gas sources, gas migration pathways, and suitable reservoir lithologies with direct geophysical evidence for the occurrence of charged reservoirs. Direct evidence includes well-organized, high-amplitude events of appropriate polarity within sand-prone facies within the gas hydrate stability zone (GHSZ). Such events may be associated with seismic phase reversals where stratigraphic units cross the base of the GHSZ.[71]

Assessment of Global Gas Hydrate Volumes

After three decades of contemplation of the issue, no clear consensus of the magnitude of potential in-place volumes of natural gas in hydrate form has emerged. While it appears that a minimum value on the order of 100,000 trillion cubic feet (tcf) is likely, studies continue to appear that are not always easily reconciled with field data, and global in-place resource estimates continue to range over more than two orders of magnitude.[72] Global resources are predominantly (as much as 99%) found in deep marine environments, with an order of magnitude estimate of 1,313 tcf occurring in permafrost-associated settings.[73] Ultimately, total in-place resource volumes are likely not highly relevant to the first-order research issues facing the gas hydrate community. As a result, assessment is evolving to the more practical issues of understanding resource volumes in specific settings that have direct relevance to more focused energy, climate, or geohazard issues—either local or global.

An initial effort to identify potential volumes in areas that are most sensitive to climate change[74] similarly suggests that only a small portion (perhaps 5% of total global resources) is directly relevant to that issue, although little field data has yet been collected in such settings to verify these estimates. Johnson[75] has conducted a global assessment of that portion of the in-place resource residing at high concentrations in sand-rich sediments (the portion most relevant to energy issues) and reported a global value of roughly 43,000 tcf. Regionally, three major efforts, two in the U.S. and one in Japan, have provided the first systematic attempts to quantify gas hydrate resource volumes. Similar gas hydrate resource assessment efforts have been conducted for resources in Arctic Canada (reviewed briefly below), and new efforts are also underway in Korea,[76] China, and India.

Gas Hydrate Resources in the Nankai Trough: In 2008, the Japanese MH-21 program released an estimate of 40 tcf gas in-place within a 5,000-sq. mile area of the Nankai trough off the southeastern coast of Japan. Of that total, 20 tcf was assessed to occur within 10 high-concentration accumulations within fine-grained turbiditic sand reservoirs. Fujii et al[77] reported that this area represents only 10% of the total area around Japan that is prospective for gas hydrates.

Gas Hydrate Resources in the U.S. OCS: As part of its ongoing mission to assess the nation's potential energy resources, the BOEM has conducted an assessment of gas hydrate resources throughout the U.S. OCS. The initial report[78] detailed the methodology of a cell-based, probabilistic assessment of in-place gas hydrate resources in the Gulf of Mexico. This assessment took full advantage of BOEM's extensive well and seismic databases, as well as the latest scientific insights on the controls of gas hydrate occurrence, including particular consideration of issues such as natural gas generation capacity, lateral distribution of shallow salt bodies, and reservoir lithology. The report indicated a mean estimate of 21,444 tcf gas in-place in hydrate form with one-third of that volume (6,711 tcf mean value) assessed as occurring as pore-filling gas hydrate in high-saturations in sand-dominated reservoirs. In 2012, the BOEM[79] released the initial findings for gas hydrate gas-in-place volumes throughout the U.S. Lower-48 OCS, including mean estimates for both the Atlantic OCS (21,702 tcf) and Pacific OCS (8,192 tcfg). When combined with the earlier GOM estimate, the BOEM reports a total U.S. Lower-48 mean estimate of 51,338 tcfg. Data are not sufficient outside the GOM to assess what portion of the total in place resource might be housed in sand-rich sediments. Given the relative lack of data for the Atlantic and Pacific coasts, these assessments utilize a Monte Carlo approach that returns a statistical distribution of results, thus incorporating the relatively high degree of modeling uncertainty into the reported results.

Gas Hydrate Resources on the Alaska North Slope (ANS): In 1995, the USGS assessed 590 tcf gas-in place on the Alaska North Slope,[80] a value that is supported by analyses presented by Ruppel.[81] In late 2008, the USGS,[82] in collaboration with the BLM, delivered the first estimate of technically-recoverable gas hydrate resources anywhere in the world. The geologically-based assessment followed standard USGS approaches developed to assess conventional oil and gas resources, including prediction of the expected size and number of individual gas hydrate accumulations. The existence of such accumulations, and confirmation of the ability to reliably characterize them through geological and geophysical analyses, had been validated in 2007 by the successful drilling of two gas hydrate accumulations predicted by the USGS to be present at the Mount Elbert site in the Milne Point Unit.[83] In total, the USGS reported that roughly 85 tcf of natural gas exists in gas hydrates across the ANS would be recoverable using existing exploration and production (E&P) technologies. The commercial recoverability of this resource will ultimately depend on the development of methods to achieve commercial production rates, as well as the future expansion of transportation and utilization options for ANS gas.

Permafrost-associated Gas Hydrate Resources outside Alaska: Extensive evaluation of gas hydrate occurrences at the Mallik research site and review of existing well data suggest roughly 150 to 360 tcf gas-in-place in the Mackenzie Delta/Beaufort Sea region.[84] A more poorly constrained estimate for the Canadian Arctic Archipelago ranges from 665 to 21,700 tcf.[85] A recent global analysis of permafrost-associated gas hydrate proposed a much more conservative estimate of 13 tcf in-place within three primary Canadian basins[86] and also assigned roughly 780 tcf of in-place gas hydrate resources for a number of basins within Arctic Russia.

Gas Hydrate Production Technologies

Three primary classes of methods historically have been considered with respect to production of methane from subsurface gas hydrates: thermal stimulation, depressurization, and chemical injection. These methods are described with respect to their application in the production of gas hydrates hosted in sand reservoirs using largely existing well-drilling and completion technologies. To date, there has been limited analysis or any field test of gas hydrate production from other gas hydrate occurrence types (such as mounds or fractured-clay systems), and as such, production from those deposits will require development of as-yet unidentified technological approaches.[87]

Thermal Stimulation: Scientific experiments conducted at the Mallik site in arctic Canada (2002) confirmed that thermal stimulation is unlikely to be effective at a commercial scale due to high inefficiencies and complication of flow paths for released gas to reservoirs; however, intermittent thermal stimulation (as needed to address blockages in the well-bore and near-wellbore) will likely be a component of ultimate commercial gas hydrate production systems.[88]

Chemical Injection: The potential to produce methane through injection of destabilizing chemical inhibitors is well known but fraught with numerous cost, safety, and logistical issues that have limited the attention chemical stimulation has received in the scientific community. In contrast, a separate class of injection designed to produce molecular substitution has focused on the injection of CO_2 to achieve the permanent sequestration of the CO_2 in hydrate form in exchange for the simultaneous release of methane.[89] This concept has been recognized in principle for many years but generally considered to be challenged as a viable commercial process by very low exchange rates. However, experimental studies conducted through a collaborative effort between ConocoPhillips and University of Bergen revealed relatively rapid and efficient exchange when evaluated in a porous media context and at relevant pressure-temperature conditions.[90] However, further complications can arise due to the likely presence of free water in natural gas hydrate formations, which would bind injected CO_2 into a CO_2 hydrate prior to interaction with the native methane hydrate. To evaluate this technology's potential, ConocoPhillips partnered with both the DOE and JOGMEC to conduct a field trial of chemical exchange technology (the "Iġnik Sikumi" project) from a single well (a "huff and puff") drilled from a temporary ice pad in the Prudhoe Bay Unit, Alaska.[91] That test used a CO_2-N_2 gas mixture to address the free water issues and confirmed that gas injection is sustainable in water-bearing gas hydrate reservoirs, that some degree of bulk exchange of chemical species does occur, and that it may have certain beneficial effects, (e.g., increasing the mechanical stability of the sediments). However, the chemical and physical reactions in the reservoir are highly complex and difficult to constrain with existing analytical tools. At present, chemical injection—like thermal stimulation—will likely serve a complementary role in ultimate integrated production systems in certain settings, but it is unlikely to achieve the production rates achievable through approaches that are based on reservoir depressurization.[92] Full data sets from the project are available via the NETL web site.[93]

Depressurization: Short-duration pressure response tests conducted during the early Mallik tests provided a somewhat surprising potential for gas production via depressurization.[94] This potential is derived from the determination that gas hydrate reservoirs likely retain sufficient reservoir permeability and mobile water content to enable effective pressure reduction via use of downhole pumps. This finding was confirmed via similar small-scale wireline pressure testing in the 2007 BPXA-DOE-USGS "Mt. Elbert" program.[95] A major milestone was achieved the following year (2008) at a Japanese-Canadian research program at the Mallik site with the demonstration of six days of sustained and stable production through reservoir depressurization.[96] This test was a clear "proof of concept" for the production of gas from naturally-occurring gas hydrates through depressurization. Analyses of the test data suggested that the reservoirs had the potential to exceed the productivity predictions of current numerical models through enhanced permeability related to production-related deformation and natural heterogeneities.[97] A second major milestone occurred in March 2013, when Japan's MH-21 program demonstrated that the concepts tested in the arctic could be successfully deployed in a deepwater setting. JOGMEC achieved depressurization of deepwater turbiditic sands at a total depth of ~1300 meters in ~1000 meters of water depth over a period of six days, with stable production of ~700,000 standard cubic feet per day (scf/d) of gas (roughly 10x the rate that had been observed in the prior Arctic tests).[98] Based on this success, MH-21 has announced plans to proceed with the offshore testing phase of its program, which will feature a longer-duration deepwater flow test.

Despite the promise and simplicity of depressurization, numerous technical challenges exist[99] including potential production hazards associated with the relatively shallow occurrence of producing horizons and the lack of consolidation of both the reservoirs and the overburden, particularly in deepwater settings. Careful sand-control and other existing technologies exist to mitigate these risks, but they will add technical and economic challenges. Consideration of these geohazards are expected to focus initial gas hydrate exploration and production to the most geomechanically-stable settings, which include the more technically-viable, deeply buried, sand-rich accumulations.[100]

Gas Hydrate Reservoir Numerical Simulation

Modeling the response of gas-hydrate-bearing sediments to environmental changes and/or simulated production will be critical to the effective planning of field investigations and the proper interpretation of data collected. Major developments have been made within many of the leading computer codes, and a public source code (HYDRATE RES-SIM) has been made available via the NETL website.[101] The TOUGH+/HYDRATE code (LBNL) has increasing capability to assess geomechanical phenomena related to production-related destabilization via coupling with the FLAC 3D-code.[102] This code has also tackled increasingly complex studies using field data[103] and has been used to model the response of gas hydrate-bearing systems to environmental changes over long-time scales.[104] The STOMP-Hydrate code developed at the Pacific Northwest National Lab (PNNL) produced the initial simulations of gas hydrate production via CO_2 injection and CH_4-CO_2 exchange.[105] These codes, including those used in the Japanese MH-21 program, have benefitted from an international gas hydrate code comparison working group that completed and reported on a set of six shared analyses of fundamental modeling problems,[106] although further fundamental advancement in the models remains greatly challenged by the lack of field data for validation and calibration.

Recent numerical simulations are benefitting significantly from improved understanding of basic reservoir petrophysics (provided by both field and laboratory studies) and improved characterization of the complexity of natural occurrences. Combined, these modeling efforts indicate that previous conceptions of gas hydrate reservoir response as being very slow, with extremely long production lives and long lead times (periods of water production only prior to the onset of natural gas production), are likely incorrect. Recent studies utilizing the well-characterized Gulf of Mexico reservoirs show rapid escalation to peak production rates measured from 10 to more than 40 million standard cubic feet per day (mmscf/d).[107] These rates reveal the combined benefit of modeling the full geologic heterogeneity of gas hydrate systems, including both the beneficial impacts of vertical reservoir variability, which produces a much more rugose dissociation front that provides significantly greater surface area for hydrate dissociation, as well as the complications of acknowledging some permeability to the boundary layers. Codes development continues with current efforts focusing largely on integrating aspects of the progressive geo-mechanical instability and associated production-related hazards, which derive from the dissociation of gas hydrate within intrinsically-unconsolidated sand reservoirs.[108]

Given the relative paucity of field test data and the limited duration of the tests completed to date, very little is conclusively known about the potential commercial viability of production.[109]

Gas Hydrate and Operational Geohazards

Current "operational" gas hydrate-related geohazards relate primarily to oil and gas production activities and can be categorized as: 1) shallow foundational issues related to the installation of infrastructure in areas of shallow sub-seafloor gas hydrates; 2) shallow drilling and well-installation hazards that are encountered by wells targeting deeper horizons ("drilling through"); and 3) long-term hazards associated with producing warm hydrocarbons from deeper zones through shallow gas hydrate-bearing intervals ("producing through").[110] Drilling through hydrates is currently viewed as a relatively short-duration hazard that can be readily managed in hydrate-prone regions through proper application of standard industry drilling protocols[111] that focus on maintenance of appropriate drill fluid temperatures. Producing through hydrates, however, involves long-term thermal stresses from the flow of warm fluids through the shallow portion of production strings. Such stresses can be significant, and in certain areas, are not readily-mitigated with existing technology.[112] Operational geohazards are clearly an issue of industry concern, and one that will continue to be pursued with substantial assistance in fundamental science and numerical modeling capabilities being developed in the public domain. However, studies would clearly advance our collective understanding of the characteristics and behavior of gas hydrates in nature (and under specific gas-hydrate production scenarios) and should be encouraged and enabled where feasible.

Gas Hydrate and Natural Geohazards

A primary naturally-occurring geohazard associated with gas hydrates is seafloor instability related to gas hydrate dissociation, which releases free gas and excess pore water that results in significant pore fluid volume expansion that can substantially reduce the geomechanical stability of the host sediments. Natural phenomena, such as pressure decline due to sea-level drop or temperature rise due to changes in atmospheric or oceanic conditions, can create intervals of potential sediment weakness at the base of gas hydrate stability. The association of large-scale slide events and dissociation of gas hydrates has been investigated over the past decade through field investigations at the Storegga (offshore Norway)[113] and at Cape Fear (U.S. Atlantic Coast).[114] To date, however, these studies have not confirmed a significant role for gas hydrate dissociation. While the case for major past episodes of globally-synchronized gas hydrate-related seafloor failures remain poorly supported with available data, gas hydrates likely do play a role in certain local seafloor failures.

Many chimney-type structures are found to have a central core of gas hydrates,[115] suggesting that gas hydrate formation may have a role in mediating the flow of gas through such features—though the processes are not well understood. In many locales, gas successfully transits the gas-hydrate stability zone and is vented at the seafloor. Ongoing research is revealing that such venting is much more common than previously recognized,[116] with most vents being low volume, low energy features. However, in extreme cases, gas venting may occur in a manner that poses true geohazards. Such events are likely triggered by free gas accumulations that exceed some critical overpressure at a horizon of reduced sediment permeability, possibly at the base of the gas hydrate stability zone. Perhaps the most compelling evidence for such events reported in the literature are the "pingo-like features" observed on the shallow Beaufort Shelf, arctic Canada, which have been interpreted to reflect gas and sediment expulsion associated with ongoing destabilization of permafrost-associated gas hydrates related to post ice-age shelf inundation.[117]

Gas Hydrates, Carbon Cycling, and Global Climate

Gas hydrates play a significant role in mediating the movement of methane within marine sediments and have implications over both long-term and short-term time scales, as discussed below.

Long-Term Carbon Cycling: Gas hydrates are an enormous global storehouse of organic carbon in the form of methane gas. Over long time periods, gas hydrates can be thought of as a global capacitor for organic carbon,[118] taking up methane during certain global environmental conditions and releasing methane during other environmental conditions. While it appears likely that there is net gas uptake into hydrate reservoirs during globally cold conditions (despite lower sea-levels) and net release during warm periods, the issues remain complex. For example, organic matter deposition and the rate of methane generation from organic matter are likely higher in warmer periods.[119] Efforts are currently underway to attempt to decipher data from ocean sediment cores to more firmly record the past history of methane migration and attempt to correlate observed changes with known global processes.

Potential for Near-Term Response to Climate Change: Methane is a highly effective greenhouse gas. Methane has a global warming potential (GWP) of roughly 86 times that of CO_2 averaged over 20 years, declining to a GWP of roughly 28-34 averaged over 100 years[120] as it is gradually oxidized to CO_2. CO_2 is a less effective but much more persistent greenhouse gas. Thus, the release of substantial volumes of methane from gas hydrate accumulations could have significant impacts on global climate.[121] Such releases could be driven by ongoing climate change driven by other factors or other geological phenomena. Despite great attention and speculation on these issues, very little is known regarding the actual potential for such releases. Compelling concepts, such as gas hydrate release in response to sea-level fall and consequent coeval bottom water temperature increases and hydrostatic pressure declines during Late Quaternary glacial periods, have been shown to be unlikely.[122] One numerical modeling study of the response of gas hydrates to changing climate scenarios indicated that release of methane would be gradual over a long time frame rather than catastrophic.[123] Such modeling is, however, highly sensitive to issues such as the nature of the dissociation drivers, the gas migration pathways, the actual inventories of gas hydrates within climate-sensitive settings, and other factors.

At present, the most compelling (but not consensus-based) link between hydrates and climate is derived from studies of the Paleocene-Eocene Thermal Maximum (PETM: 55 million years ago). The PETM does exhibit geochemical signals consistent with rapid large-scale gas hydrate dissociation, and the volumes of such methane injection are difficult to explain without invoking phenomena such as large-scale dissociation of gas hydrates.[124] One recent field study developed a high-resolution carbon isotope record spanning the PETM and found that there were two distinct rapid, large-scale carbon release events.[125] The study found that there was an initial excursion of Carbon-13 (^{13}C) (reflecting release of a large biogenic source of carbon into the atmosphere, such as from methane hydrates) which they called the Pre-Onset Excursion (POE), followed by a second large excursion of ^{13}C, which they called the Carbon Isotope Excursion (CIE). The authors note that the timeframe between the POE and CIE is *"similar to that estimated for the propagation of a thermal pulse to hydrate-bearing depths in seafloor sediments, and suggest that carbon release during the CIE may have been a feedback to warming generated by an initial release during the POE"*. They also note that the *"record suggests that rates of release during the PETM were probably within an order of magnitude of, and may have approached the 9.5 Pgyr-1 associated with modern anthropogenic carbon emissions."* Gas hydrate dissociation has also been linked to even more severe climatic changes in Earth's ancient past,[126] although the data are also inconclusive.[127]

Therefore, findings to date indicate that gas hydrates may have played a significant role in climate events, particularly those that are large, acute, and global in scale. While at present, it is likely that methane (and particularly methane from gas hydrates) is a far less pressing climate concern than CO_2, it remains uncertain whether and how rapidly the nature and dynamics of gas hydrate systems may change in the future. A major scientific question at present is: are we potentially creating the conditions that might lead to a similar acute feedback event?[128] The signals from such feedbacks might be first manifested in the Arctic, where climate change is more pronounced and gas hydrates more closely coupled to the atmosphere/ocean system. Recent studies from the East Siberian Arctic Shelf[129] and from offshore Svalbard[130] suggest release of potentially significant volumes of methane from the Arctic to the ocean. The connection between these releases and gas hydrates remain unclear, and it is not established if these releases are new, or simply newly-discovered.[131] A recent study that modeled potential thermally-driven dissociation of gas hydrates in the Pacific off Washington State found *"that a substantial volume of gas hydrate along the entire Cascadia upper continental slope is* *vulnerable to modern climate change.*"[132] Overall, while the magnitude of methane releases in the arctic appear to be minor in comparison to those from other methane sources, and while methane remains clearly secondary to CO_2 as a climate change concern, the issue warrants further study.[133]

Initial work to incorporate gas hydrate science into forward projections under future climate scenarios has recently been undertaken.[134] Thus far, the cumulative results indicate that methane release will likely be chronic, not catastrophic, and that the vast majority of methane derived from dissociating gas hydrates will not reach the atmosphere due to a variety of natural sinks within sediment and ocean waters. The implications for methane release on ocean geochemistry, including potential acidification, are receiving increased attention,[135] and further study would help clarify the possible roles of hydrates and various possible drivers and feedbacks in our rapidly changing environment.

R&D Needs: 2015-2030

This technology assessment presents the current landscape of gas hydrate science and technology across a wide range of public-interest issues. Overall, the primary research need remains the creation of a knowledge base and suite of tools and technologies that can: 1) increase confidence in the assessment of gas hydrate volumes within the U.S. and an understanding of their distribution/occurrence in specific settings of relevance to resource and climate issues; 2) explain the potential response and implications of those deposits to various environmental changes—either induced or natural; 3) evaluate safe and viable gas hydrate production technologies through field testing; and 4) accurately assess the geohazard and environmental implications of naturally-occurring gas hydrates.

More specifically, evaluation of gas hydrate resource potential requires further research to:

- Determine the necessary conditions for a deposit to be considered a viable production target.
- Reduce the great uncertainty in current assessments of resource volumes within such accumulations.
- Develop new tools for gas hydrate detection and characterization from remote sensing data.
- Determine the physical and chemical response of gas hydrate geological systems to induced environmental changes.
- Improve prediction of the dynamic behavior of gas hydrate reservoirs and bounding sediments, such as through use of numerical simulation with field validation.
- Conduct scientific field experiments and production tests to determine the most effective production technologies and associated environmental implications.

To determine the environmental implications of gas hydrates requires further R&D to:

- Better define the environments where gas hydrates are most sensitive to environmental change.
- Document the occurrence of gas hydrates in those high sensitivity settings.
- Constrain the potential response (both in nature and in rate) of those deposits to potential environmental change over various timeframes.
- Assess the implications of that response for atmospheric and oceanic chemistry.

The Need for Field-based Investigations

The study of naturally-occurring gas hydrates is highly complex. Creation of gas hydrate samples in the lab that sufficiently mimic natural occurrences is highly challenging.[136] In addition, the nature and behavior of gas hydrate deposits have been found to be highly-dependent upon the complex natural heterogeneities that are inherent to geologic systems.[137] As a result, the most reliable and effective route to understanding the occurrence, nature, and behavior of gas hydrates will be through drilling, coring, and reservoir testing programs conducted in the field.

Although the U.S. Federal Program has conducted five safe and successful field programs on time and within budget in both arctic and deepwater settings since 2005, the costs and logistical challenges of both deepwater and arctic field programs continue to escalate. Further, recent developments in natural gas supply in the U.S. (among other factors) have resulted in a significant decline in interest within industry to enable and/or participate in scientific field programs related to gas hydrates. Therefore, it will be necessary to pursue opportunities to conduct field-based science programs (both in Alaska and in the U.S. OCS) through increased collaboration with federal and state government partners, as well as with international gas hydrate R&D organizations.

To ensure the effectiveness of future field programs and the proper interpretation of data collected in the field, it will also remain necessary to support select laboratory and numerical simulation efforts designed to isolate and understand fundamental aspects of gas hydrate system behavior. Similarly, work to improve the effectiveness of specialized equipment to recover, preserve, and analyze natural samples, as well as to collect data through down-hole measurement devices, will remain a high priority.

Gas Hydrate R&D Challenges

Gas hydrate field efforts are complex and often long-term ventures with significant technical and logistical challenges, extended pre-program planning, and post-program data analysis and review. Given suitable levels of industrial and public support, combined with adequate investment and coordinated international collaboration, the following challenges could be successfully addressed within the next 15 years:

- A series of extended duration reservoir response tests that progress from controlled scientific experiments of reservoir depressurization to integrated technology demonstration in a variety of geologic settings (including onshore and offshore) would enable an improved assessment of the potential for gas hydrates to provide incremental supplies of natural gas to the U.S. Such testing should occur initially onshore (on the Alaska North Slope) and then progress to a marine field production test.
- Drilling, logging, and coring programs to refine the assessment of viable domestic recoverable resource volumes.
- Documentation of effective pre-drill exploration and characterization technologies.
- Documentation of the role gas hydrates play in the global environment, including long-term carbon cycling and near-term response to ongoing climate change, and full integration of these insights into forward climate models.
- Continued international collaboration so as to assist in accelerating the timelines and broadening the science base for gas hydrate resource appraisal by key allies.

While the primary outcomes of R&D efforts would be long-term, there are a number of key challenges that could be completed or initiated within the next five years to ensure a proper progression toward ultimate resolution of gas hydrate science and technology issues:

Resource Characterization

- Complete field programs in the northern GOM to explore new sites and collect and characterize pressure cores from existing sites.
- Initiate field programs to evaluate gas hydrate occurrence on the Atlantic Margin.

Field Sampling Technology

- Complete testing, development, and deployment of pressure coring and pressure core analysis systems.

Exploration Technology

- Complete geologic and geophysical studies, as well as new data acquisition as needed, to confirm reservoir occurrence on State Lands on the Alaska North Slope (ANS).
- Progress toward confirmation of reservoir occurrence at new sites in the Gulf of Mexico and the Atlantic OCS via development of programs designed to conduct a series of multi-well exploration programs in the U.S. OCS. These expeditions would be designed to select sites and conduct science to address a range of issues, including core acquisition from resource-quality accumulations; development of advanced models of gas hydrate formation and evolution, geohazards, climate interactions; and refinement of resource volume estimates. Primary focus should be on further evaluation of gas hydrate occurrence in areas of high potential as indicated in ongoing BOEM studies, including the northern GOM and the central and northern Atlantic OCS. Focus in the GOM should be on additional sites in the vicinity of existing infrastructure that might provide feasible opportunities for future experimental programs.
- Test exploration concepts through collaborative international drilling programs.

Production Technology

- Complete an initial long-term scientific production test (in Alaska) focused on determining the expected gas and water production profiles to be generated from reservoir depressurization. The test should contain comprehensive environmental monitoring related to gas migration, movement of the dissociation front, geomechanics and land subsidence, water production, air emissions, and water production (volumes and chemistry).
- Analyze the petrophysical/geomechanical characteristics of marine gas hydrates from collected pressure cores, as well as collection of short-duration pressure response data, from gas hydrate reservoirs in the GOM OCS (such as those documented in the 2009 JIP Leg II program) to determine properties required to appropriately assess marine recovery potential and to design future marine production experiments.

Global Carbon Cycle

- Complete ongoing studies to constrain observed natural gas flux, gas hydrate's role, and linkage to long-term and short-term environmental drivers. Continued development and validation of experiment data and numerical simulation tools to enable sound planning of field programs and reliable interpretation of field data with respect to gas hydrate energy development, reservoir geomechanics, environmental impacts, gas hydrate role in global carbon cycling (long term) and past climate events, and gas hydrate role in ongoing climate change (present and near term).
- Expand the integration of gas hydrate science in global climate models.
- Initiate a program of drilling and sampling expeditions in climate-sensitive and geohazard-prone settings (both at high and mid-latitudes) to determine typical gas hydrate occurrences and inventories, the rate and nature of changes in the natural environment and the response of gas hydrate-bearing sediment to those changes, the dynamics of natural gas flux, and the impact of natural gas on oceanic and atmospheric chemistry. It is anticipated that such expedition would target: 1) gas hydrates in permafrost-associated settings (both onshore and shallow water offshore); 2) gas hydrates at the landward margin of deepwater gas hydrate stability; and 3) areas of natural gas seepage within the zone of gas hydrate stability.

Primary Technical Focus Areas

To progress meaningfully toward answering the identified science and technology questions will require further work in the following broad categories: 1) development of tools for reliable marine gas hydrate sampling and analysis; 2) integrated geologic/geophysical characterization methodologies to enable pre-drill assessments of natural gas hydrate systems; 3) development of exploration technologies; 4) development of production technologies; 5) determination of gas hydrate's implications for long-term global carbon cycling and potential near-term feedbacks to ongoing climate change; and 6) development and demonstration of numerical simulation tools to enable the effective design and interpretation of field data related to both production and environmental implications. Each of these areas should integrate supporting laboratory and field experimental studies and numerical simulation as appropriate and feasible.

Marine Sampling Tools/Technology Development: Given the difficulties in preservation and transfer of natural samples into laboratory equipment, and the complexities of creating synthetic samples that sufficiently mimic natural conditions, strong emphasis will continue to be placed on development of *in situ* data collection tools, as well as the improved ability to collect and effectively analyze pressure cores.[138] A primary R&D need over the next five years is to complete the development of a robust coring system that has the flexibility to successfully acquire and analyze cores from a variety of common drilling platforms and across a range of occurrence types, including gas-hydrate-bearing sands. These systems would include both the coring device (for example, the Hybrid Pressure Coring System, including the coring equipment, a compatible bottom-hole assembly, and field-deployable vans to house the equipment) and a suite of compatible analytical devices (for example, IPTC and pressure core characterization tool[139]) that can collect physical and chemical property data from minimally-disturbed samples. Opportunities to further the development of these tools both domestically and through international collaboration should continue to be monitored and pursued as feasible.

Gas Hydrate Systems Characterization: A prerequisite to evaluating the varied implications of naturally-occurring gas hydrates is an improved understanding of the controls on the abundance, occurrence, and nature of gas hydrates in sediments. This work should advance through the collection and analysis of data obtained from a range of environments in which gas hydrates are thermodynamically stable but in which occurrence is highly variable. A primary near-term action should include geologic and geophysical review of gas hydrate occurrence on state lands in Alaska. A second action should be the pursuit of opportunities for deepwater drilling and sampling in the U.S. OCS, most likely to include further evaluation of known sites in the northern GOM as well as exploration of additional, high-priority sites.[140] A third action is continued international engagement in drilling and coring expeditions.

Gas Hydrate Exploration Technologies: Although it appears likely that gas hydrates occur in large volumes globally, it is well established that those specific and anomalous deposits that are feasible recovery targets can best be identified through the use of exploration approaches that fully assess the local petroleum system, including not only the necessary pressure-temperature conditions, but also the nature of local gas sources, the presence of suitable host reservoirs, and the existence of gas migration pathways.[141] Data sufficient to inform the best approaches for successful gas hydrate prospecting thus far exist only in a few locations, most notably Japan's Nankai Trough, the Prudhoe Bay region of the Alaska North Slope, and a handful of sites in the northern Gulf of Mexico. Present approaches appear to be sufficient for the recognition of select gas hydrate accumulations;[142] however, it is likely that many more viable hydrate deposits exist in conditions that will require more sophisticated data acquisition and analysis to delineate. In the near-term, additional prospect development (in Alaska and in the Gulf of Mexico) and subsequent exploratory drilling would be essential to more fully develop sound and effective gas hydrate characterization methods. Longer-term, these insights would need to be applied to the evaluation of gas hydrates in other high-potential (but where resourced volumes are very poorly constrained) regions of the U.S. OCS, such as the Atlantic Margin; or in areas where gas hydrate characterization could better constrain potential geohazards, such as offshore northern Alaska.

Gas Hydrate Production Technology: Short-duration scientific field tests of gas hydrate productivity have been conducted at locations in Arctic Canada,[143] Alaska North Slope,[144] and in the Nankai Trough, offshore Japan.[145] These tests have revealed that the primary technology for gas hydrate production will be reservoir depressurization; although it is expected that local optimization of production would include use of supplemental stimulation technologies—such as heating and chemical injection—as most appropriate for local conditions.[146] While the field tests and allied modeling conducted to date have demonstrated the technical feasibility of production, achieving economic viability—even in the most favorable reservoirs—would require overcoming a range of complex technical and operational challenges.[147] Economic viability will also be strongly influenced by the nature of local energy markets and national energy supply issues.

Given the limited duration of the tests conducted to date, the primary near-term R&D need remains the successful completion of extended-duration scientific field tests that would provide a sound understanding of the physical response of gas hydrate reservoirs to reservoir depressurization. These tests would ideally include comprehensive environmental-impact monitoring to track the development of the dissociation front, the migration and/or release of any free gas, and the geomechanical response of reservoirs and seals. Over the longer-term, additional tests can then be designed to assess the potential long-term gas and water production profiles that can be expected from optimized production systems (including issues of stimulation, well completion design, and well design) across the range of likely gas hydrate occurrences. Because the initial scientific production tests will be most valuable where they can be conducted for extended periods, test locations need to have access to permanent production facilities in which R&D operations will not have an undue effect on ongoing industry operations.[148] While such testing programs would ultimately be needed in every major potential production area, the most favorable locations for initial long-term tests (from a cost and logistical viewpoint) are the well-characterized reservoirs known to exist within the Greater Prudhoe Bay region (including Milne Point, Prudhoe Bay, and Kuparuk River oil fields and adjoining areas) on the Alaska North Slope. Logistical barriers to conducting the testing must be overcome. This effort includes both continued engagement with the Prudhoe Bay working interest owners regarding test sites within the operating units as well as the ongoing evaluation of unleased acreage within the greater Prudhoe Bay area that the State of Alaska has recently set-aside (in association with an MOU between the DOE and that Alaska's Department of Natural Resources) until such time as its usefulness for gas hydrate resource evaluation can be determined.

Gas Hydrate Geohazards: Gas hydrates have been linked to a range of issues collectively described using the term "geohazards." These hazards generally relate to the consequences of gas hydrate dissociation and the destabilizing effects of relatively sudden introduction of large volumes of gas and water into shallow geologic systems. Gas hydrate "geohazards" include events that occur due to natural processes or that are triggered unintentionally by industrial activities.[149] The seepage of gas is common globally and is an ongoing natural phenomenon both within areas of potential gas hydrate occurrence and in shallow water areas where gas hydrates do not occur and is therefore not considered a geohazard. However, gas hydrates may mediate gas migration in such a way as to lead to periodic episodes of large-scale gas venting. One example may be certain large features observed on arctic shelves ("pingo-like features")[150] that may reflect the unique influence of relict permafrost and other lithologic aspects on geologic processes.

"Operational" geohazards include the implications of unintended gas hydrate destabilization while drilling through, or subsequently producing hydrocarbons through, zones of gas hydrate occurrence. At present, there is limited need for R&D related to risks associated with drilling through hydrates as these appear to be readily-managed through established protocols for drill-fluid temperature management[151] and shallow hazard assessment.[152] However, the long-term production of hot fluids through hydrate-bearing sediments may generate pervasive destabilization of shallow, hydrate-bearing sediments, leading to potential risks of gas release (through pathways within the wellbore annulus) and sediment instability that could lead to failure in casing systems. Although this issue has attracted past private industry investment,[153] the DOE is not currently aware of any ongoing research within industry on this topic. The unique setting of gas hydrates on shallow Arctic shelves, and the high environmental sensitivity of those regions, suggests that further research on this topic should be a priority. Primary near-term actions, therefore, should focus on the desire to design various field programs to assess natural geohazard issues that may arise in both deepwater (sediment instability in response to natural dissociation) and the arctic (actively dissociating gas hydrates in areas of shallow-water "relict" permafrost).

Gas Hydrate Linkages to Global Carbon Cycling and Climate Change: Recent years have seen a number of publications indicating that methane venting from the seafloor may be a very common global occurrence.[154] This phenomena, particularly as it may relate to events in the Arctic,[155] has fueled concerns that escalating gas hydrate destabilization and methane release pose a substantial risk as a deleterious feedback to ongoing climate change.[156] The concerns include changes to the chemical makeup of both the oceans (acidification) and the atmosphere (increased in GHG concentrations and exacerbation of ongoing climate change).

While there is abundant discussion about a potential "methane catastrophe" focused on the arctic, it remains that no observed methane releases have as yet been clearly linked to gas hydrates from among the variety of potential natural sources. Further, the actual presence of gas hydrates in significant volumes has not yet been demonstrated for climate-sensitive settings, either in the Arctic or at mid-latitudes. Therefore, current information and models are simply not sufficient to meaningfully assess the climate risks of gas hydrates. To do so, they would need to be based on: 1) accurate depictions of gas hydrate occurrence and distribution in climate sensitive settings; 2) proper accounting for the timescales needed to destabilize gas hydrates given specific climatic changes; and 3) full integration of the potential sinks that may mediate the delivery of any released natural gas to either the ocean or the atmosphere.[157] Therefore, near-term actions to address this would include the initiation of a systematic program of field study to delineate those areas most prone to climate-induced destabilization and to better constrain the assessment of the distribution of gas hydrates within those regions. These field-based efforts should ultimately investigate a variety of gas hydrate-bearing areas and the resulting data should be fully integrated in various process models and ultimately into forward climate models as appropriate. The overall goal is to contribute to the development of a general scientific consensus regarding the potential response of gas hydrates to different future climate scenarios and the resulting environmental implications. This work should include shallow arctic shelves as well as the landward limit of hydrate stability throughout the U.S. OCS and may be elucidated by studies of past gas hydrate-climate linkages as appropriate.

DOE Technology Transfer and Outreach

Critical to the ultimate success of any R&D effort in gas hydrates will be a rigorous scientific vetting of the economic and environmental implications of gas hydrates and the effective communication of those findings to the public. Gas hydrates may represent a new fossil energy resource, and given 1) the strong links between fossil fuels and potential anthropogenic climate change and 2) the role gas hydrates may have played in global climate events in geologic history, it is important that any research should both investigate and report on the environmental implications of potential utilization of gas hydrates as a bridging fuel to the sustainable sources of the future. To be credible, this outreach must include demonstration that the science community has a good understanding of the role that naturally-occurring gas hydrates have in ongoing global environmental processes, as well as how gas hydrates respond to environmental changes—both natural and induced. To this end, publically supported research should be maintained on comprehensive websites that provide detailed overviews of both past and ongoing projects, with access to all public-domain, project-related reports and presentations, programmatic and outreach documents, past interagency planning documents, and newsletters such as NETL's *Fire in the Ice*, which continues to be a leading source of international information for the gas hydrate community, and other materials.

DOE, the USGS, and international scientific organizations have also collaborated with external organizations such as the United Nations Environmental Programme[158] and the SBC Energy Institute[159] to produce scientific reviews of gas hydrate science. Field data and initial scientific reports from major field projects should continue to be made available to the public on an expedited basis, and peer-reviewed articles outlining key findings and implications are needed (such as the three Thematic Volumes within the *Journal of Marine and Petroleum Geology* edited by DOE and USGS scientists that served to compile scientific results for the 2005 JIP Leg I program;[160] the 2007 Mt. Elbert Program;[161] and the 2009 JIP Leg II program[162]).

Although the industry-led field efforts in the past have received high-visibility, universities have also played a major role in gas hydrate R&D program, both as key parts of the industry-led research teams and in conducting their own competitively-awarded R&D projects. In future years, this contribution is expected to increase. To further support the training of future scientists, the DOE established in 2006 a formal, competitive, merit-based Fellowship program in collaboration with the National Academies of Science. That program has since selected seven "National Methane Hydrate R&D Program Fellows."

Summary

Recent assessments have identified extensive evidence for gas hydrate occurrence throughout the ANS[163] and the U.S. OCS.[164] These assessments have been aided and validated by field programs that have demonstrated the validity of the gas hydrate exploration and characterization methods developed within the DOE Program. Successful field programs in Canada and offshore Japan, in addition to those undertaken by DOE in Alaska, have confirmed the technical feasibility of natural gas recovery utilizing depressurization and provided the first field trials of complementary technologies that could improve the overall carbon footprint of extraction. However, significant additional field validation and calibration opportunities are needed before the U.S. gas hydrate resource potential can be understood with confidence. Further, gas hydrates present potential unconstrained risks to global climate that should be properly assessed and evaluated. Recent trends in unconventional gas production have impacted the ability of the private industry to participate in gas hydrate R&D. Until private industry re-engages in this effort, gas hydrate R&D private-public partnerships could be augmented through cross-agency collaboration and engagement with international partners.

The fundamental needs in gas hydrate R&D are the development of science and technology that enable: 1) an accurate assessment of the nature and occurrence of gas hydrates within the U.S.; 2) refinement and demonstration of technologies that can achieve production in an economically-viable and environmentally-responsible manner; and 3) determination and effective public communication of the role of gas hydrate deposits in natural geohazards and in the natural sequestration and cycling of carbon in response to both long-term (global carbon cycle) and short term (potential feedbacks to ongoing climate change) time-scales. Success in these efforts would provide a full scientific evaluation of the potential for gas hydrates to provide an additional option to address potential future energy needs both for the U.S. and for key international allies. This evaluation should include the assessment and demonstration of safe and efficient exploration and production technologies, as well as an understanding of potential environmental impacts and mitigation strategies. An additional outcome would be an improved understanding of our natural environment, providing more informed decision-making on a wide variety of issues ranging from ocean policy to global climate change. Other benefits are also expected, including successful collaboration with key international partners, fuller understanding of gas hydrate-related geohazards, and contributions to the education and training of the next generation of scientists.

Endnotes

[1] Consortium for Ocean Leadership, 2013. Marine methane hydrate field reserach plan. US DOE/NETL Topical Report, 60 pp. http://oceanleadership.org/wp-content/uploads/2013/01/MH_Science_Plan_Final.pdf

[2] Boswell, R., Collett, T., 2011. Current perspectives on gas hydrate resources. *Energy and Env. Sci.*, 4, 1206-1215.

[3] Ruppel, C., Boswell, R., Jones, E., 2008. Scientific results from Gulf of Mexico gas hydrates joint industry project Leg 1 drilling: Introduction and overview. *J. Mar. Pet. Geology*, 25 (9), 819-829.

[4] McConnell, D., Zhang, Z., Boswell, R., 2012. Review of progress in evaluating gas hydrate drilling hazards, *J. Mar. Pet. Geol.*, 34 (1), 209-223.

[5] Hadley, C., Peters, D., Vaughn, A., Bean, D., 2008. Gumusut-Kakap project: geohazard characterization and impact on field development plans: *Proceedings* IPTC Conference, IPTC #12554; Kuala Lumpur, Malaysia.

[6] Peters, D., Hatton, G., Mehta, A., Hadley, C., 2008. Gas hydrate geohazards in shallow sediments and the impact on the design of subsea systems. *Proceedings*, Int'l Conf. on Gas Hydrates, Vancouver, BC, July 6-10, 7 pp.

[7] Collett, T., 1993., Natural gas hydrates of the Prudhoe Bay and Kuparuk River area, North Slope, Alaska. AAPG, *Bulletin* 77 (5), 793-812.

[8] Boswell, R., Shelander, D., Latham, T., Lee, M., Collett, T., Guerin, G., Moridis, G., Reagan, M., Goldberg, D., 2009. Occurrence of gas hydrate in Oligocene Frio Sand: Alaminos Canyon block 818: northern Gulf of Mexico. *J. Mar. Pet. Geo.* 26 (8), 1499-1512.

[9] Stevens, J., Howard, J., Baldwin, B., Ersland, G., Husebo, J., Graue, A., 2008. Experimental hydrate formation and gas production scenarios based on CO_2 sequestration. *Proceedings*, 6th International conference on gas hydrates (ICGH-6). http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/methane%20hydrates/NT06553_StevensEtAl.pdf

[10] Reichel T., Gallagher, J., 2014. Global screening of gas hydrates. *Proceedings*, Offshore Technology Conference, OTC-25144, 4 pp.

[11] Calle, A. E., 2013. Geological evidences of a petroleum system of gas hydrates in the Colombian Caribbean Sea., *Proceedings* AAPG ACE, Pittsburgh PA, May 19-22.

[12] Kadaster, A., Milheim, K., Thompson, T., 2005. The planning and drilling of Hot Ice #1 – Gas hydrate exploration well in the Alaskan Arctic. *Proceedings*, SPE/AIDC, SPE-92764-MS.

[13] Boswell, R., Collett, T., Anderson, B., Hunter, R., eds., 2011. Thematic set on scientific results of the Mount Elbert Gas Hydrate Stratigraphic Test Well, Alaska North Slope, *J. Mar. Pet. Geol.* 28 (2), 279-605.

[14] Schoderbek, D., Martin, K., Howard, J., Silpngarmlert, S., Hester, K., 2012. North Slope Hydrate Field trial: CO_2/CH_4 exchange. *Proceedings*, SPE Arctic Technology Conference, OTC-2375, 13 pp.

[15] Anderson, B., Boswell, R., Collett, T., Farrell, H., Ohtsuki, M., White, M., Zyrianova, M., 2014. Review of the findings of the 2012 Iġnik Sikumi CO_2-CH_4 gas hydrate exchange field trial. *Proceedings*, ICGH-8, Beijing, China, 14 pp. http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/methane%20hydrates/nt0006553-field-trial-review.pdf

[16] Boswell, R., Collett, T., Frye, M., Shedd, W., McConnell, D., Shelander, D., 2012. Subsurface gas hydrates in the northern Gulf of Mexico. *J. Mar. Pet. Geol.* 34 (1), 4-30.

[17] Anderson, B., Wilder, J., Kurihara, M., White, M., Moridis, G., Wilson, S., Pooladi-Darvish, M., Masuda, Y., Collett, T., Hunter, R., Narita, H., Rose, K., Boswell, R., 2011. Analysis of Modular Dynamic Formation Test results from the "Mount Elbert" stratigraphic test well, Milne Point, Alaska; *J. Mar. Pet. Geol.* 28 (2), 493-501;

- Anderson, B., Boswell, R., Collett, T., Farrell, H., Ohtsuki, M., White, M., Zyrianova, M., 2014. Review of the findings of the 2012 Iġnik Sikumi CO_2-CH_4 gas hydrate exchange field trial. *Proceedings*, ICGH-8, Beijing, China, 14 pp.

[18] Haines, S., Hart, P., Shedd, W., Frye, M., 2014. Seismic investigation of gas hydrates in the Gulf of Mexico: 2013 multi-component and high-resolution 2D acquisition at GC955 and WR313. *Proceedings*, OTC-25318, 18 pp.

[19] Dallimore, S., Yamamoto, K., Wright, J., Bellefleur, G., eds. 2012. Scientific results from the JOGMEC/NRCan/Aurora Mallik 2007-2008 Gas Hydrate Production Research Well Program, Mackenzie Delta, Northwest Territories, Canada. Geological Survey of Canada *Bulletin* 601.

[20] Tsuji, Y., Fujii, T., Hayashi, M., Kitamura, R., Nakamizu, M., Ohbi, K., Saeki, T., Yamamoto, K., Namikawa, T., Inamori, T., Oikawa, N., Shimizu, S., Kawasaki, M., Nagakubo, S., Matsushima, J., Ochiai, K., Okui,T., 2009. Methane-hydrate occurrence and distribution in the eastern Nankai trough, Japan: Findings of the Tokai-oki to Kumano-nada methane-hydrate drilling program., in Collett, T.; A. Johnson; C. Knapp; and R. Boswell, eds., Natural Gas Hydrates -- Energy Resource Potential and Associated Geologic Hazards: AAPG *Memoir* 89, 228-246;

- Fujii, T., Namikawa, T., Okui, T., Kawasaki, M., Ochiai, K., Nakamizu, M., Nishimura, M., Takano, O., Tsuji, Y., 2009. Methane hydrate occurrence and saturation confirmed from core samples, eastern Nankai Trough, Japan, in Collett, T.; A. Johnson; C. Knapp; and R. Boswell, eds., Natural Gas Hydrates -- Energy Resource Potential and Associated Geologic Hazards: AAPG Memoir 89, 385-400;
- Yamamoto, K., Terao, Y., Fujii, T., Ikawa, T., Seki, M., Matsuzawa, M., Kanno, T., 2014. Operational overview of the first offshore production test of methane hydrates in the Eastern Nankai Trough., OTC-25243, 11 pp.

[21] Collett, T., Boswell, R., Cochran, J., Kumar, P., Lall, M., Mazumdar, A., Ramana, M., Ramprasad, T., Riedel, M., Sain, K., Sathe, A., Vishwanath, K., 2014. Geologic implications of gas hydrates in the offshore of India: results of the National Gas Hydrate Program Expedition 01: *J. Mar. Pet. Geo.*, 58, 1-28;

- Kumar, P., Collett, T., Boswell, R., Lall, M., Mazumdar, A., Ramana, M., Ramprasad, T., Riedel, M., Sain, K., Sathe, A., Vishwanath, K., 2014. Geologic implications of gas hydrates in the offshore of India: Krishna-Godovari Basin, Mahanadi Basin, Andaman Sea, Kerala-Konkan Basin. *J. Mar. Pet Geol.*, 58, 29-98.

22 Ryu, B., Riedel, M., Kimm J-H., Hyndman, R., Lee, Y-J., Chung, B-H., Kim, I-S., 2009. Gas hydrates in the western deep-water Ulleung Basin, East Sea of Korea. *J. Mar. Pet Geol.*, 26, 1483-1498.

23 Zhang, H., Yang, S., Wu, N., Su, X., Holland, M., Schultheiss, P., Rose, K., Butler, H., Humphrey, G., and GMGS-1 Science Team. 2007. Successful and surprising results for China's first gas hydrate drilling expedition. USDOE-NETL Newsletter, *Fire in the Ice*, Fall 2007, pp. 6-9; http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/methane%20hydrates/HMNewsFall07.pdf

- Zhang, G., Yang, S., Ming, Z., Liang, J., Lu, J., Holland, M., Schultheiss, P., 2014. GMGS-2 Expedition investigates rich and complex gas hydrate environment in the South China Sea. USDOE-NETL Newsletter, *Fire in the Ice*, 14 (1) 1-5. http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/methane%20hydrates/MHNews_2014_February.pdf#Page=1

24 Lu, Z., Zhu, Y., Zhang, Y., Wen, H., Li, Y., Lui, C., 2011. Gas hydrate occurrences in the Qilian Mountain permafrost, Qinghai Province, China. *Cold Regions Science and Technology* 66 (2-3), 93-104.

25 Zhao, X., Deng, J., Li, J., Lu, C., Song, J., 2012. Gas hydrate formation and its accumulation potential in Mohe permafrost, China. *J. Mar. Pet. Geol.*, 35 (1), 166-175.

26 National Petroleum Council, 2011. Prudent Development: Realizing the Potential of North America's Abundant Natural Gas and Oil Resources. National Petroleum Council, 68 pp; http://www.npc.org/nard-execsummvol.pdf

- National Academies, 2010. Realizing the Energy Potential of Methane Hydrate for the United States. Committee on assessment of the Department of Energy's methane hydrate research and development program: evaluating methane hydrate as a future energy resource (Paull, C., Chair). National Academies Press, Washington, D.C., 184 pp; http://www.nap.edu/catalog/12831/realizing-the-energy-potential-of-methane-hydrate-for-the-united-states
- MIT Energy Initiative, 2011, The Future of Natural Gas: an interdisciplinary MIT study. Massachusetts Institute of Technology. https://mitei.mit.edu/system/files/NaturalGas_Report.pdf

27 Shellenberger, M., Nordhaus, T., Trembath, A., Jenkins, J., 2012. Where the shale gas revolution came from. Breakthrough Institute, 25 pp. http://thebreakthrough.org/blog/Where_the_Shale_Gas_Revolution_Came_From.pdf

28 Collett, T., Johnson, A., Knapp, C., Boswell, R., 2009. Ch. 1. Natural gas hydrates – a review, in Collett T., et al., eds, Natural gas hydrates—Energy resource potential and associated geologic hazards: AAPG *Memoir* 89, 146-220.

- Boswell, R., Collett, T., 2011. Current perspectives on gas hydrate resources. *Energy and Env. Sci.*, 4, 1206-1215;
- Ruppel, C., 2011. Methane hydrates and the future of natural gas. Supplemental Paper 4; in The Fugure of Natural gas, MIT Energy Initiative. http://www.circleofblue.org/waternews/wp-content/uploads/2013/09/Supplementary_Paper_SP_2_4_Hydrates.pdf
- Boswell, R., Yamamoto, K., Lee, S-R., Collett, T., Kumar, P., Dallimore, S., 2014. Methane Hydrates – ch. 8. In Letcher, T., ed., Future Energy, 2nd Ed., Elsevier, pp. 159-178.

29 Tsuji, Y., Ishida, H., Nakamizu, M., Matsumoto, R., Shimizu, S., 2004. Overview of the MITI Nankai Trough wells: a milestone in the evaluation of methane hydrate resources: *Resource Geology* 54 (1), 3-10.

30 Tsuji, Y., Fujii, T., Hayashi, M., Kitamura, R., Nakamizu, M., Ohbi, K., Saeki, T., Yamamoto, K., Namikawa, T., Inamori, T., Oikawa, N., Shimizu, S., Kawasaki, M., Nagakubo, S., Matsushima, J., Ochiai, K., Okui,T., 2009. Methane-hydrate occurrence and distribution in the eastern Nankai trough, Japan: Findings of the Tokai-oki to Kumano-nada methane-hydrate drilling program., in Collett, T.; A. Johnson; C. Knapp; and R. Boswell, eds., Natural Gas Hydrates -- Energy Resource Potential and Associated Geologic Hazards: AAPG *Memoir* 89, 228-246.

31 Saeki, T., Fujii, T., Inamori, T., Kobayashi, T., Hayashi, M., Nagakubo, S., Takano, O. 2008. Delineation of methane hydrate concentrated zone using 3-D seismic data in the eastern Nankai Trough: *Proceedings,* 6th International conference on gas hydrates (ICGH-6).

32 Hutchinson, D.R., C. Ruppel, H. Roberts, R. Carney, and M. Smith, 2011, Gas hydrates in the Gulf of Mexico, in: Gulf of Mexico Origin, Waters, and Biota, vol. 3, ed. by N.A. Buster and C.W. Holmes, Texas A&M University Press;

- McConnell, D., Zhang, Z., Boswell, R., 2012. Review of progress in evaluating gas hydrate drilling hazards. , *J. Mar. Pet. Geol.*, 34 (1), 209-223.

33 Ruppel, C., Boswell, R., Jones, E., 2008. Scientific results from Gulf of Mexico gas hydrates joint industry project Leg 1 drilling: Introduction and overview: *J. Mar. Pet. Geo.*, 25 (9), 819-829.

- Collett, T., Boswell, R., eds., 2012, Thematic set on resource and hazard implications of gas hydrates in the Northern Gulf of Mexico: results of the 2009 Joint Industry Project Leg II drilling expedition. *J. Mar. Pet. Geol.* 34 (1), 223 pp.

34 Boswell, R., Collett, T., Frye, M., Shedd, W., McConnell, D., Shelander, D., 2012. Subsurface gas hydrates in the northern Gulf of Mexico. *J. Mar. Pet. Geol.* 34 (1), 4-30.

35 Cook, A., Malinverno, A., 2013. Short migration of methane into a gas-hydrate-bearing sand layer at Walker Ridge, Gulf of Mexico. *Geochemistry, Geophysics, Geosystems* 14 (2), 283-291.

36 Macelloni, L., Brunner, C., Caruso, S., Lutken, C., D'Emidio, M., Lapham, L., 2013. Spatial distribution of seafloor bio-geological and geochemical processes as proxies of fluid flux regime and evolution of a carbonate/hydrates mound, northern Gulf of Mexico. *Deep Sea Research Part 1: Oceanography Research Papers* 74, 25-38.

[37] Holbrook, W., 2001. Seismic studies of the Blake Ridge: Implications for hydrate distribution, methane expulsion, and free gas dynamics. In: Paull, C.A. & Dillon, W.P. (eds) Natural Gas Hydrates Occurrence, Distributions, and Detection. American Geophysical Union, Geophysical Monograph, 124, 235–256.

[38] Hornbach, M., Lavier, L., Ruppel, C., 2007. Triggering mechanism and tsunamogenic potential of the Cape Fear slide complex, U.S. Atlantic margin. *Geochem. Geophys. Geosys.* 8 (12).

[39] BOEM (Bureau of Ocean Energy Management), 2012. Assessment of in-place gas hydrate resources of the Lower 48 United States Outer Continental Shelf. *BOEM Fact Sheet* RED-2012-01. 4 pp. http://www.boem.gov/uploadedFiles/BOEM/Oil_and_Gas_Energy_Program/Resource_Evaluation/Gas_Hydrates/BOEM-FactSheetRED_2012-01.pdf

[40] Skarke, A., Ruppel, C., Kodis, M., Brothers, D., Lobecker, E., 2014. Widespread methane leakage from the seafloor on the northern US Atlantic Margin. *Nature Geoscience*, 7, 657-661.

[41] Riedel, M., Collett, T., Malone, M., Expedition 311 Scientists, 2006. Cascadia margin gas hydrates, *Proceedings* IODP, 311, Washington, DC;

- Torres, M., Trehu, A., Cespedes, N., Kastner, M., Wortmann, U., Kim, J., Long, P., Malinverno, A., Pohlman, J., Riedel, M., Collett, T., 2008. Methane hydrate formation in turbidite sediments of northern Cascadia, IODP Expedition 311, *Earth and Planetary Science Letters* 271, 170-180.

[42] Collett, T., Boswell, R., Cochran, J., Kumar, P., Lall, M., Mazumdar, A., Ramana, M., Ramprasad, T., Riedel, M., Sain, K., Sathe, A., Vishwanath, K., 2014. Geologic implications of gas hydrates in the offshore of India: results of the National Gas Hydrate Program Expedition 01: *J. Mar. Pet. Geo.*, 58, 1-28. ;

- Kumar, P., Collett, T., Boswell, R., Lall, M., Mazumdar, A., Ramana, M., Ramprasad, T., Riedel, M., Sain, K., Sathe, A., Vishwanath, K., 2014. Geologic implications of gas hydrates in the offshore of India: Krishna-Godovari Basin, Mahanadi Basin, Andaman Sea, Kerala-Konkan Basin. *J. Mar. Pet Geol.* 58, 29-98.

[43] Cook, A. Anderson, B. Maliverno, A., Mrozewski, S., Goldberg, D. , 2010. Electrical anistrophy due to gas hydrate-filled fractures. *Geophysics*, 75 (6), F173-F185.

[44] Zhang, H., Yang, S., Wu, N., Su, X., Holland, M., Schultheiss, P., Rose, K., Butler, H., Humphrey, G., and GMGS-1 Science Team. 2007. Successful and surprising results for China's first gas hydrate drilling expedition. USDOE-NETL Newsletter, *Fire in the Ice*, 7 (3), 6-9; http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/methane%20hydrates/HMNewsFall07.pdf

- Zhang, G., Yang, S., Ming, Z., Liang, J., Lu, J., Holland, M., Schultheiss, P., 2014. GMGS-2 Expedition investigates rich and complex gas hydrate environment in the South China Sea. USDOE-NETL Newsletter, *Fire in the Ice*, 14 (1) 1-5. http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/methane%20hydrates/MHNews_2014_February.pdf#Page=1

[45] Wang, X., Collett, T., Lee, M., Yang, S., Guo, Y., Wu, S., 2014. Geological controls on the occurrence of gas hydrate from core, downhole log, and seismic data in the Shenhu area, South China Sea. *Marine Geology* 357, 272-292.

[46] Ryu, B-J., Collett, T., Riedel, M., Kim, G-Y., Chun, J-H., Bahk, J-J., Lee, J., Kim, J-H., Yoo, D-G., 2013. Scientific results of the second gas hydrate drilling expedition in the Ulleung Basin (UBGH2), *J. Mar. Pet. Geo.* 47, 1-20.

[47] Matsumoto, R., Ryu, B-J., Lee, S-R., Lin, S., Wu, S., Sain, K., Pecher, I., Riedel, M., 2011. Occurrence and exploration of gas hydrate in the marginal seas and continental margin of the Asia and Oceania region. *J. Mar. Pet. Geo.* 28 (10), 1751-1767.

[48] Westbrook, G., Thatcher, K., Rohling, E., Piotrowski, A., Palike, H., Osborne, A., Nisbet, E., Minshull, T., Lanoiselle, M., James, R., Huhnerbach, V., Green, D., Fisher, R., Crocker, A., Chabert, A., Bolton, C., Beszczynski-Moller, A., Berndt, C., Aguilina, A., 2009. Escape of methane gas from the seabed along the West Spitsbergen continental margin. *Geophys. Res. Lett.* 36 (15).

[49] Bunz, S., Polyanov, S., Vadakkepuliyambatta, S., Consolaro, C., Mienert, J., 2012. Active gas venting through hydrate-bearings sediments on the Vestnesa Ridge, offshore W-Svalbard, *Marine Geology* 332-334; 189-197;

- Rajan, A., Mienert, J., Bunz, S., 2012. Acoustic evidence for a gas migration and release system in Arctic continental margins offshore NW-Svalbard. *J. Mar. Pet. Geo.,* 32, 36-49.

[50] Brothers, L., Hart, P., Ruppel, C., 2012. Minimum distribution of subsea ice-bearing permafrost on the US Beaufort Sea Continental Shelf, *Geoph. Res. Lett.*, 39 (15).

[51] Shakhova, N., Semiletov, I., Salyuk, A., Yusupov, V., Kosmach, D., Gustafsson, O., 2010. Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic Shelf: *Science* 327, 1246-1250;

- Whiteman, G., Hope, C., Wadhams, P., 2013. Climate Science, Vast Costs of Arctic Change, *Nature* 499, 401-403.

[52] Collett, T., Johnson, A., Knapp, C., Boswell, R., 2009. Ch. 1. Natural gas hydrates – a review, in Collett T., et al., eds, Natural gas hydrates—Energy resource potential and associated geologic hazards: *AAPG Memoir* 89, 146-220.

[53] Collett, T, Lee, M., Agena, W., Miller, J., Lewis, K., Zyrianova, M., Boswell, R., Inks, T., 2012. Permafrost associated natural gas hydrate occurrences on the Alaskan North Slope. *J. Mar. Pet. Geo.*, 28 (2), 279-294.

[54] Lee, M., Collett, T., Inks, T., 2009. Seismic-attribute analysis for gas hydrate and free-gas prospects on the North Slope of Alaska. In Collett, T., et al., eds., Natural Gas Hydrates – Energy Resource Potential and Associated Geologic Hazards, *AAPG Memoir* 89, 541-555.

[55] Inks, T., Lee, M., Agena, W., Taylor, D., Collett, T., Hunter, R., Zyrianova, M., 2009. Seismic prospecting for gas hydrate and associated free-gas prospects in the Milne Point area of northern Alaska, in T. Collett, A. Johnson, C. Knapp, and R. Boswell, eds.,Natural gas hydrates—Energy resource potential and associated geologic hazards: *AAPG Memoir* 89, 555-583.

[56] Boswell, R., Collett, T., Anderson, B., Hunter, R., eds., 2011. Thematic set on scientific results of the Mount Elbert Gas Hydrate Stratigraphic Test Well, Alaska North Slope, J. Mar. Pet. Geol. 28 (2), 279-605.

[57] Schoderbek, D., Martin, K., Howard, J., Silpngarmlert, S., Hester, K., 2012. North Slope Hydrate Field trial: CO_2/CH_4 exchange. *Proceedings*, SPE Arctic Technology Conference, OTC-2375, 13 pp.

[58] Santamarina, C., Dai, S., Jang, J., Terzariol, M., 2012. Pressure core characterization tools for hydrate-bearing sediments. *Scientific Drilling* 14, 44-48. http://www.pmrl.ce.gatech.edu/papers/Santamarina_2012a.pdf

[59] Waite, W., Santamarina, C., Cortes, D., Dugan, B., Espinoza, D., Germaine, J., Jang, J., Jung, J., Kneafsey, T., Shin, H., Soga, K., Winters, B., Yun, T., 2010. Physical Properties of Hydrate-bearing sediments. *Reviews of Geophysics* 47, 38 pp;

- Choi, J., Dai, S., Cha, J., Seol, Y., 2014. Laboratory formation of non-cementing hydrates in sandy sediments. *Geochemistry, Geophysics, Geosystems* 15 (4), 1648-1656;
- Spangenberg, E., Priegnitz, M., Heeschen, K., Schicks, J., 2014. Are laboratory-formed hydrate-bearing sediments analogous to those in nature? *J. Chemical & Engineering Data*, 60 (2), 258-268.

[60] Riedel, M., Willoughby, E., Chopra, S., 2010. Gas hydrates – geophysical exploration techniques and methods, in Riedel, M., Willoughby, E., Chopra, S., eds., *Geophysical Characterization of Gas Hydrates*; Society of Exploration Geophysicists *Geophysical Developments Series* 14, Ch. 2; 1-22.

[61] Shelander, D., Dai, J., Bunge, G., Singh, S., Eissa, M., Fisher, K., 2012. Estimating saturation of gas hydrates using conventional 3-D seismic data, Gulf of Mexico Joint Industry Project Leg II. *J. Mar. Pet. Geol.* 34 (1), 96-110.

[62] Haines, S., Hart, P., Shedd, W., Frye, M., 2014. Seismic investigation of gas hydrates in the Gulf of Mexico: 2013 multi-component and high-resolution 2D acquisition at GC955 and WR313. *Proceedings* OTC-25318, 18 pp.

[63] Weitermeyer, K., Constable, S., Key, K., 2013, Mapping marine gas hydrate systems in the Gulf of Mexico with electromagnetic methods: AGU Fall Meeting, 2013 Abstract GP23A-0991.

[64] Shedd, W., Boswell, R., Frye, M., Godfriaux, P., Kramer, K., 2012. Occurrence and nature of "bottom simulating reflectors" in the northern Gulf of Mexico. *J. Mar. Pet. Geol.*, 34 (1), 31-40.

[65] Holbrook, W., 2001. Seismic studies of the Blake Ridge: Implications for hydrate distribution, methane expulsion, and free gas dynamics. In: Paull, C. and Dillon, W. eds Natural Gas Hydrates Occurrence, Distributions, and Detection. *American Geophysical Union, Geophysical Monograph*, 124, 235–256.

[66] Tsuji, Y., Fujii, T., Hayashi, M., Kitamura, R., Nakamizu, M., Ohbi, K., Saeki, T., Yamamoto, K., Namikawa, T., Inamori, T., Oikawa, N., Shimizu, S., Kawasaki, M., Nagakubo, S., Matsushima, J., Ochiai, K., Okui,T., 2009. Methane-hydrate occurrence and distribution in the eastern Nankai trough, Japan: Findings of the Tokai-oki to Kumano-nada methane-hydrate drilling program., in Collett, T.; A. Johnson; C. Knapp; and R. Boswell, eds., Natural Gas Hydrates -- Energy Resource Potential and Associated Geologic Hazards: AAPG *Memoir* 89, 228-246.

[67] Saeki, T., Fujii, T., Inamori, T., Kobayashi, T., Hayashi, M., Nagakubo, S., Takano, O. 2008. Delineation of methane hydrate concentrated zone using 3-D seismic data in the eastern Nankai Trough: *Proceedings*, 6th International conference on gas hydrates (ICGH-6).

[68] Lee, M., Collett, T., Inks, T., 2009. Seismic-attribute analysis for gas hydrate and free-gas prospects on the North Slope of Alaska. In Collett, T., et al., eds., Natural Gas Hydrates – Energy Resource Potential and Associated Geologic Hazards., AAPG *Memoir* 89, 541-555;

- Inks, T., Lee, M., Agena, W., Taylor, D., Collett, T., Hunter, R., Zyrianova, M., 2009. Seismic prospecting for gas hydrate and associated free-gas prospects in the Milne Point area of northern Alaska, in T. Collett, A. Johnson, C. Knapp, and R. Boswell, eds.,Natural gas hydrates—Energy resource potential and associated geologic hazards: AAPG *Memoir* 89, 555-583.

[69] Boswell, R., Collett, T., Frye, M., Shedd, W., McConnell, D., Shelander, D., 2012. Subsurface gas hydrates in the northern Gulf of Mexico. *J. Mar. Pet. Geol.* 34 (1), 4-30.

[70] Collett, T., Johnson, A., Knapp, C., Boswell, R., 2009. Natural gas hydrates – a review, in Collett T., et al., eds, Natural gas hydrates—Energy resource potential and associated geologic hazards: AAPG *Memoir* 89; 146-220;

- Boswell, R., Shipp, C., Reichel, T., Saeki, T., Frye, M., Shedd, W., Collett, T., McConnell, D., Shelander, D., 2015. Prospecting for Marine Gas Hydrate Resources. *Interpretation*, 4 (1), SA13-SA24;
- Max, M., Johnson, A., 2014. Hydrate petroleum system approach in natural gas hydrate exploration. *Petroleum Geoscience* 20 (2), 187-199.

[71] Boswell, R., Shipp, C., Reichel, T., Saeki, T., Frye, M., Shedd, W., Collett, T., McConnell, D., Shelander, D., 2015. Prospecting for Marine Gas Hydrate Resources. *Interpretation*, 4 (1), SA13-SA24.

[72] Boswell, R., Collett, T., 2011. Current perspectives on gas hydrate resources. *Energy and Env. Sci.*, 4, 1206-1215.

[73] Ruppel, C., 2015. Permafrost-associated gas hydrate: is it really approximately 1% of the global system. *J. Chem & Eng Data* 60, 429-436.

[74] Ruppel, C., 2011. Methane Hydrates and Contemporary Climate Change, *Nature Education Knowledge*, 3 (10), 29.

[75] Johnson, A., 2012. Global resource potential of gas hydrate – a new calculation. DOE/NETL *Fire in the Ice* Newsletter, 11 (2). http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/methane%20hydrates/MHNews-2011-12.pdf#Page=1

[76] Riedel, M., Bahk, J., Kim, H., Scholz, N., Yoo, G., Kim, W., Ryu, B., Lee, S., 2013. Seismic facies analysis as aid in regional gas hydrate assessments, Part II: Prediction of reservoir properties, gas hydrate petroleum system analysis, and Monte Carlo simulation. *J. Mar. Pet. Geol.* 47, (269-290).

77 Fujii, T., Saeki, T., Kobayashi, T., Inamori, T., Hayashi, M., Takano, O., Takayama, T., Kawasaki, T., Nagakubo, S., Nakamizu, M., Yokoi, K. 2008. Resource assessment of methane hydrate in the eastern Nankai Trough, Japan: *Proceedings*, 6th International conference on gas hydrates (ICGH-6).

78 MMS (Minerals Management Service), 2008, Preliminary evaluation of in-place gas hydrate resources: Gulf of Mexico outer continental shelf: M. Frye (compiler) Minerals Management Service Report 2008-004: http://www.mms.gov/revaldiv/GasHydrateAssessment.htm.

79 BOEM (Bureau of Ocean Energy Management), 2012. Assessment of in-place gas hydrate resources of the Lower 48 United States Outer Continental Shelf. *BOEM Fact Sheet* RED-2012-01. 4 pp. http://www.boem.gov/uploadedFiles/BOEM/Oil_and_Gas_Energy_Program/Resource_Evaluation/Gas_Hydrates/BOEM-FactSheetRED_2012-01.pdf

80 Collett, T., 1995. Gas Hydrate Resources of the United States, in Gautier, D., et al., eds., 1995 Assessment of US Oil and Gas Resources. USGS DDS-30.

81 Ruppel, C., 2015. Permafrost-associated gas hydrate: is it really approximately 1% of the global system. *J. Chem & Eng Data* 60, 429-436.

82 Collett, T., Agena, W., Lee, M., et al., 2008. Assessment of gas hydrate resources on the North Slope, Alaska. U.S. Geological Survey *Fact Sheet* 2008-3073. 4 pp. http://pubs.usgs.gov/fs/2008/3073/pdf/FS08-3073_508.pdf

83 Inks, T., Lee, M., Agena, W., Taylor, D., Collett, T., Hunter, R., Zyrianova, M., 2009. Seismic prospecting for gas hydrate and associated free-gas prospects in the Milne Point area of northern Alaska, in T. Collett, A. Johnson, C. Knapp, and R. Boswell, eds., Natural gas hydrates—Energy resource potential and associated geologic hazards: AAPG *Memoir* 89, 555-583.

84 Osadetz, K., Chen, Z., 2010., A re-evaluation of Beaufort Sea-Mackenzie Delta basin gas hydrate resource potential: petroleum system approaches to non-conventional gas resource appraisal and geologically-sourced methane flux: *Bulletin of Canadian Petroleum Geology* 58 (1), 56-71.

85 Majorowicz, J., Osadetz, K., 2001. Gas hydrate distribution and volume in Canada. *AAPG Bulletin* 85 (7), 1211-1230.

86 Ruppel, C., 2015. Permafrost-associated gas hydrate: is it really approximately 1% of the global system. *J. Chem. & Eng. Data* 60, 429-436.

87 Moridis, G., Collett, T., Boswell, R., Kurihara, M., Reagan, M., Koh, C., Sloan, D., 2009. Toward production from gas hydrates: current status, assessment of resources, and simulation-based evaluation of technology and potential, *SPE Reservoir Eval. and Eng.* 14 (1), 76-112;

- Moridis, G., Sloan, D., 2007. Gas production of disperse, low-saturation hydrate accumulations in oceanic sediments. *Energy Conservation and Management* 48: 1834-1849.

88 Moridis, G., Collett, T., Boswell, R., Kurihara, M., Reagan, M., Koh, C., Sloan, D., 2009. Toward production from gas hydrates: current status, assessment of resources, and simulation-based evaluation of technology and potential, *SPE Reservoir Eval. and Eng.* 14 (1), 76-112.

89 Park, Y., Kim, D., Lee, J., Huh, D., Park, K., Lee, J., Lee, H., 2006. Sequestering carbon dioxide into complex structures of naturally-occurring gas hydrates. *PNAS* 102 (34), 12690-12694.

90 Ersland, G., Husebo, J., Graue, A., Baldwin, B., Howard, J., Stevens, J., 2010. Measuring gas hydrate formation and exchange with CO_2 in Bentheim Sandstone using MRI tomography. *Chem. Eng. J.*, 158 (1), 25-31.

91 Schoderbek, D., Martin, K., Howard, J., Silpngarmlert, S., Hester, K., 2012. North Slope Hydrate Field trial: CO_2/CH_4 exchange. *Proceedings*, SPE Arctic Technology Conference, OTC-2375, 13 pp.

92 Anderson, B., Boswell, R., Collett, T., Farrell, H., Ohtsuki, M., White, M., Zyrianova, M., 2014. Review of the findings of the 2012 Iġnik Sikumi CO_2-CH_4 gas hydrate exchange field trial. *Proceedings*, ICGH-8, Beijing, China, 14 pp. http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/methane%20hydrates/nt0006553-field-trial-review.pdf

93 National Energy Technology Laboratory, “2012 Iġnik Sikumi gas hydrate field trial”, http://www.netl.doe.gov/research/oil-and-gas/methane-hydrates/co2_ch4exchange/

94 Hancock, S., Dallimore, S., Collett, T., Carle, D., Weatherhill, B., Satoh, T., Inoue, T., 2005. Overview of pressure-drawdown production-test results for the JAPEX/JNOC/GSC et al., Mallik 5L-38 gas hydrate production research well. in Dallimore, S., and Collett, T., (eds), Scientific results from Mallik 2002 Gas Hydrate Production Research Well Program, Mackenzie delta, Northwest Territories, Canada, *GSC Bulletin* 585.

95 Anderson, B., Wilder, J., Kurihara, M., White, M., Moridis, G., Wilson, S., Pooladi-Darvish, M., Masuda, Y., Collett, T., Hunter, R., Narita, H., Rose, K., Boswell, R., 2011. Analysis of Modular Dynamic Formation Test results from the “Mount Elbert” stratigraphic test well, Milne Point, Alaska; *J. Mar. Pet. Geol.* 28 (2), 493-501.

96 Dallimore, S., Yamamoto, K., Wright, J., Bellefleur, G., eds. 2012. Scientific results from the JOGMEC/NRCan/Aurora Mallik 2007-2008 Gas Hydrate Production Research Well Program, Mackenzie Delta, Northwest Territories, Canada. Geological Survey of Canada *Bulletin* 601., 292 pp.

97 Kurihara, M., Sato, A., Funatsu, K., Ouchi, H., Yamamoto, K., Fujii, T., Numasawa, M., Masuda, Y., Narita, H., Dallimore, S., Wright, J., Ashford, D., 2012. Analysis of 2007 and 2008 gas hydrate production tests on the Aurora/JOGMEC/NRCAN Mallik 2L-38 well through numerical simulation. Dallimore et al., eds., Geol. Survey of Canada *Bulletin* 601, 217-260.

98 Yamamoto, K., Terao, Y., Fujii, T., Ikawa, T., Seki, M., Matsuzawa, M., Kanno, T., 2014. Operational overview of the first offshore production test of methane hydrates in the Eastern Nankai Trough., *Proceedings*, OTC-25243, 11 pp.

99 Hancock, S., Moridis, G., Wilson, S., Robertson, A., 2010. Well design requirements for deepwater and arctic onshore gas hydrate production wells. Proceedings, Offshore Technology Conference, *Proceedings*, OTC-21015, 7 pp;

- Boswell, R., Yamamoto, K., Lee, S-R., Collett, T., Kumar, P., Dallimore, S., 2014. Methane Hydrates . In Letcher, T., ed., Future Energy, 2nd Ed., Elsevier, 159-178.

[100] Boswell, R., Collett, T., 2011. Current perspectives on gas hydrate resources. *Energy and Env. Sci.*, 4, 1206-1215.

[101] National Energy Technology Laboratory, "Software", http://www.netl.doe.gov/research/oil-and-gas/software/

[102] Rutqvist, J., Grover, T., Moridis, G., 2008. Coupled hydrological, thermal, and geomechanical analysis of wellbore stability in hydrate-bearing sediments: *Proceedings*, SPE Offshore Technology Conference; OTC 19572.

[103] Reagan, M., Moridis, G., Johnson, J., Pan, L., Freeman, C., Boyle, K., Keen, N., Husebo, J., 2015. Field-scale simulation of production from oceanic gas hydrate deposits. *Transport in Porous Media* 108, 151-169.

[104] Reagan, M., Moridis, G. 2008. Dynamic response of oceanic hydrate deposits to ocean temperature change; *Journal of Geophysical Research* 113.

[105] White, M., Wurstner, S., McGrail, B., 2011. Numerical studies of methane production from Class 1 gas hydrate accumulations enhanced with carbon dioxide injection. *J. Mar. Pet. Geo.* 28 (2), 546-560.

[106] Wilder, J., Moridis, G., Wilson, S., Kurihara, M., White, M., Masuda, Y., Anderson, B., Collett, T., Hunter, R., Narita, H., Pooladi-Darvish, M., Rose, K., Boswell, R., 2008. An international effort to compare gas hydrate reservoir simulators, in Englezos, P., Ripmeester, J., eds. *Proceedings*, 6th Int'l Conf.on gas hydrates (ICGH-6);

- Anderson, B., Wilder, J., Kurihara, M., White, M., Moridis, G., Wilson, S., Pooladi-Darvish, M., Masuda, Y., Collett, T., Hunter, R., Narita, H., Rose, K., Boswell, R., 2011. Analysis of Modular Dynamic Formation Test results from the "Mount Elbert" stratigraphic test well, Milne Point, Alaska; *J. Mar. Pet. Geol.* 28 (2), 493-501.

[107] Gaddipati, M., Anderson, B., 2012. 3D Reservoir Modeling of Depressurization-Induced Gas Production from Gas Hydrate Reservoirs at the Walker Ridge Site, Northern Gulf of Mexico, *Proceedings*, OTC, OTC 23582-MS.

[108] Rutqvist, J., Moridis, G., Grover, T., Silpngarmlert, S., Collett, T., Holditch, S., 2012. Coupled multi-phase flow and wellbore stability analysis associated with gas production from oceanic hydrate-bearing sediments. *J. Pet. Sci. Eng,* 92-93, 65-81.

[109] Walsh, M., Hancock, S., Wilson, S., Patil, S., Moridis, G., Boswell, R., Collett, T., Koh, C., Sloan, D., 2009. Preliminary report on the economics of gas production from natural gas hydrates. *Journal of Energy Economics* 31, 815-823;

- Moridis, G., Collett, T., Boswell, R., Kurihara, M., Reagan, M., Koh, C., Sloan, D., 2009. Toward production from gas hydrates: current status, assessment of resources, and simulation-based evaluation of technology and potential, *SPE Reservoir Eval. and Eng.* 14 (1), 76-112.

[110] Boswell, R., Collett, T., Frye, M., Shedd, W., McConnell, D., Shelander, D., 2012. Subsurface gas hydrates in the northern Gulf of Mexico. *J. Mar. Pet. Geol.* 34 (1), 4-30.

[111] Balczewski, J., Boswell, R., Collett, T., Baker, R., 2008. International collaboration on deepwater natural gas hydrate continues – Gulf of Mexico gas hydrate JIP: past, present, and future. 6th International Conference on Gas Hydrates, Edinburgh, Scotland, 6 pp;

- Birchwood, R., Noeth, S., Tjengdrawira, M., Kisra, S., Elisabeth, F., Sayers, C., Singh, R., Hooyman, P., Plumb, R., Jones, E., Bloys, B., 2007. Modeling the mechanical and phase change stability of wellbores drilled in gas hydrates by the Joint Industry Project (JIP) Gas hydrate project, Phase II., *Proc*. SPE Annual Technical Conference - SPE 110796;
- Birchwood, R., Noeth, S., Jones, E., 2008. Safe drilling in gas-hydrate prone sediments: Findings from the 2005 drilling campaign of the Gulf of Mexico gas hydrates Joint Industry Project (JIP). USDOE-NETL *Fire in the Ice* Newsletter, 8 (1), 1-4.

[112] Peters, D., Hatton, G., Mehta, A., Hadley, C., 2008. Gas hydrate geohazards in shallow sediments and the impact on the design of subsea systems. *Proceedings*, Int'l Conf. on Gas Hydrates, Vancouver, BC, July 6-10, 7 pp.

[113] Kvalstad, T., Andersen, L., Forsberg, C., Berg, K., 2005. The Storegga Slide: evaluation of triggering sources and slide mechanics, *J. Mar. Pet.* Geol., 22, 245-256;

[114] Hornbach, M., Lavier, L., Ruppel, C., 2007. Triggering mechanism and tsunamogenic potential of the Cape Fear slide complex, U.S. Atlantic margin. *Geochem. Geophys. Geosys.* 8, (12).

[115] Ryu, B., Riedel, M., Kimm J-H., Hyndman, R., Lee, Y-J., Chung, B-H., Kim, I-S., 2009. Gas hydrates in the western deep-water Ulleung Basin, East Sea of Korea. *J. Mar. Pet Geol.*, 26, 1483-1498.

[116] Skarke, A., Ruppel, C., Kodis, M., Brothers, D., Lobecker, E., 2014. Widespread methane leakage from the seafloor on the northern US Atlantic Margin. *Nature Geoscience*, 7, 657-661.

[117] Paull, C., Ussler, W., Dallimore, S., Blasco, S., Lorenson, T., Melling, H., Medioli, B., Nixon, F., McLaughlin, F., 2007. Origin of pingo-like features on the Beaufort Sea shelf and their possible relationship to decomposing methane gas hydrates. *Geoph. Res., Lett.* 34 (1).

[118] Dickens, G., 2003. Rethinking the global carbon cycle with a large, dynamic, and microbially-mediated gas hydrate capacitor. *Earth and Planetary Sci Lett*. 213, 169-183.

[119] Gu G., Dickens, G., Bhatnagar, G., Colwell, R., Hirasaki, G., Chapman, W., 2011. Abundant early Paleogene marine gas hydrates despite warm deep-ocean temperatures. *Nature Geoscience* 4, 848-851.

[120] Intergovernmental Panel on Climate Change, Fifth Assessment Report (AR5) Working Group 1 (WG1), *"Climate Change 2013: The Physical Science Basis - Anthropogenic and Natural Radiative Forcing Supplementary Material*", Cambridge University Press, 2013. http://www.ipcc.ch/report/ar5/wg1/

[121] Archer, D., 2007. Methane hydrate stability and anthropogenic climate change. *Biogeosciences* 4, 521-544.

[122] Sowers, T., 2006. Late Quaternary atmospheric CH4 isotope record suggests marine clathrates are stable. *Science* 311, 838-840.

[123] Archer, D., Buffett, B., Brovkin, V., 2009. Ocean methane hydrate as a slow tipping point in the global carbon cycle: *PNAS* 106 (49), 20596-20601.

[124] Dickens, G., 2011. Down the rabbit hole: toward an appropriate discussion of methane release from gas hydrate systems during the Paleocene-Eocene thermal maximum and other past hyper-thermal events. *Clim. Past* 7, 831-846.

[125] Bowen, Gabriel J.; Maibauer, Bianca J.; Kraus, Mary J.; Rohl, Ursula; Westerhold, Thomas; Steimke, Amy; Gingerich, Philip D.; Wing, Scott L.; Clyde, William C., 2014, "Two massive, rapid releases of carbon during the onset of the Palaeocene-Eocene thermal maximum", *Nature Geoscience* 8 (1), 44-47.

[126] Kennedy, M., Mrofka, D., von der Borch, C., 2008. Snowball Earth termination by destabilization of equatorial permafrost methane clathrate. *Nature* 453, 642-645.

[127] Bristow, T., Bonifacie, M., Derkowski, A., Eiler, J., Grotzinger, J., 2011. A hydrothermal origin for isotopically anomalous cap dolostone cements from south China. *Nature* 474, 68-71.

[128] Cui, Y., Kump, L., Ridgwell, A., Charles, A., Junium, C., Diefendorf, A., Freeman, K., Urban, N., Harding, I., 2011. Slow release of fossil carbon during the Palaeocene-Eocence Thermal Maximum., *Nature Geoscience* 4 (7), 481-485.

[129] Shakhova, N., Semiletov, I., Salyuk, A., Yusupov, V., Kosmach, D., Gustafsson, O., 2010. Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic Shelf: *Science* 327, 1246-1250.

[130] Westbrook, G., Thatcher, K., Rohling, E., Piotrowski, A., Palike, H., Osborne, A., Nisbet, E., Minshull, T., Lanoiselle, M., James, R., Huhnerbach, V., Green, D., Fisher, R., Crocker, A., Chabert, A., Bolton, C., Beszczynski-Moller, A., Berndt, C., Aguilina, A., 2009. Escape of methane gas from the seabed along the West Spitsbergen continental margin. *Geophys. Res. Lett.* 36 (15).

[131] Berndt, C., Feseker, T., Treude, T., Krastel, S., Liebetrau, V., Niemann, H., Bertics, V., Dumke, I., Dunnbier, K., Ferre, B., Graves, C., Gross, F., Hissman, K., Huhnerbach, V., Krause, S., Lieser, K., Schauer, J., Steinle, L., 2014. Temporal constraints on hydrate-controlled seepage off Svalbard. *Science* 343 (6168), 284-287.

[132] Hautala, Susan L.; Solomon, Evan A.; Johnson, H. Paul; Harris, Robert N.; Miller, Una K., 2014, Dissociation of Cascadia margin gas hydrates in response to contemporary ocean warming, *Geophysical Research Letters* 41 (23), 8486-8494.

[133] Ruppel, C., 2011. Methane Hydrates and Contemporary Climate Change, *Nature Education Knowledge*, 3 (10), 29.

[134] Reagan, M., Moridis, G. 2008. Dynamic response of oceanic hydrate deposits to ocean temperature change; *Journal of Geophysical Research* 113;

- Biastoch, A., Treude, T., Rupke, L, Riebesell, U., Roth, C., Burwicz, R., Park, W., Boning, C., Latif, M., Madec, G., Wallman, K., 2011. Rising Arctic Ocean temperatures cause gas hydrate destabilization and ocean acidification. *Geophy. Res. Lett*. 38 (8);
- Marin-Moreno, H., Minshull, T., Westbrook, G., Sinha, B., Sarkar, S., 2013. The response of methane hydrate beneath the seabed offshore Svalbard to ocean warming during the next three centuries. *Geoph. Res. Lett*. 40 (19), 5159-5163.

[135] Biastoch, A., Treude, T., Rupke, L, Riebesell, U., Roth, C., Burwicz, R., Park, W., Boning, C., Latif, M., Madec, G., Wallman, K., 2011. Rising Arctic Ocean temperatures cause gas hydrate destabilization and ocean acidification. *Geophy. Res. Lett*. 38 (8).

[136] Spangenberg, E., Priegnitz, M., Heeschen, K., Schicks, J., 2014. Are laboratory-formed hydrate-bearing sediments analogous to those in nature? *J. Chemical & Engineering Data* 60 (2), 258-268.

[137] Collett, T., Johnson, A., Knapp, C., Boswell, R., 2009. Natural gas hydrates – a review, in Collett T., et al., eds, Natural gas hydrates—Energy resource potential and associated geologic hazards: AAPG *Memoir* 89., 146-220.

[138] Schultheiss, P., Holland, M., Humphrey, G., 2009. Wireline coring and analysis under pressure: recent use and future developments of the HYACINTH system; *Scientific Drilling* 7, 44-47;

- Consortium for Ocean Leadership, 2013. Marine methane hydrate field reserach plan. US DOE/NETL Topical Report, 60 pp. http://oceanleadership.org/wp-content/uploads/2013/01/MH_Science_Plan_Final.pdf

[139] Santamarina, C., Dai, S., Jang, J., Terzariol, M., 2012. Pressure core characterization tools for hydrate-bearing sediments. *Scientific Drilling* 14, 44-48.

[140] Consortium for Ocean Leadership, 2013. Marine methane hydrate field reserach plan. US DOE/NETL Topical Report, 60 pp. http://oceanleadership.org/wp-content/uploads/2013/01/MH_Science_Plan_Final.pdf

[141] Collett, T., Johnson, A., Knapp, C., Boswell, R., 2009. Natural gas hydrates – a review, in Collett T., et al., eds, Natural gas hydrates—Energy resource potential and associated geologic hazards: AAPG *Memoir* 89, 146-220;

- Max, M., Johnson, A., 2014. Hydrate petroleum system approach in natural gas hydrate exploration. Petroleum Geoscience, 20 (2), 187-199.

[142] Boswell, R., Shipp, C., Reichel, T., Saeki, T., Frye, M., Shedd, W., Collett, T., McConnell, D., Shelander, D., 2015. Prospecting for Marine Gas Hydrate Resources. *AAPG-SEG Interpretation*, 4 (1), SA13-SA24.

[143] Dallimore, S., Collett, T., eds., 2005. Scientific results from the Mallik 2002 gas hydrate production research well program, Mackenzie delta, Northwest Territories, Canada; Geological Survey of Canada *Bulletin* 585;

- Dallimore, S., Yamamoto, K., Wright, J., Bellefleur, G., eds. 2012. Scientific results from the JOGMEC/NRCan/Aurora Mallik 2007-2008 Gas Hydrate Production Research Well Program, Mackenzie Delta, Northwest Territories, Canada. Geological Survey of Canada *Bulletin* 601.

[144] Schoderbek, D., Martin, K., Howard, J., Silpngarmlert, S., Hester, K., 2012. North Slope Hydrate Field trial: CO_2/CH_4 exchange. *Proceedings*, SPE Arctic Technology Conference, OTC-2375, 13 pp.

[145] Yamamoto, K., Terao, Y., Fujii, T., Ikawa, T., Seki, M., Matsuzawa, M., Kanno, T., 2014. Operational overview of the first offshore production test of methane hydrates in the Eastern Nankai Trough., *Proceedings*, OTC-25243, 11 pp.

[146] Moridis, G., Collett, T., Boswell, R., Kurihara, M., Reagan, M., Koh, C., Sloan, D., 2009. Toward production from gas hydrates: current status, assessment of resources, and simulation-based evaluation of technology and potential, *SPE Reservoir Eval. and Eng.* 14 (1), 76-112;

- Boswell, R., Yamamoto, K., Lee, S-R., Collett, T., Kumar, P., Dallimore, S., 2014. Methane Hydrates. In Letcher, T., ed., Future Energy, 2nd Ed., Elsevier, 159-178.

[147] Walsh, M., Hancock, S., Wilson, S., Patil, S., Moridis, G., Boswell, R., Collett, T., Koh, C., Sloan, D., 2009. Preliminary report on the economics of gas production from natural gas hydrates. *Journal of Energy Economics* 31, 815-823;

- Hancock, S., Moridis, G., Wilson, S., Robertson, A., 2010. Well design requirements for deepwater and arctic onshore gas hydrate production wells. *Proceedings*, OTC-21015, 7 pp.

[148] Collett, T., Boswell, R., Lee, M., Anderson, B., Rose, K., Lewis, K., 2012. Evaluation of long-term gas-hydrate-production testing locations on the Alaska North Slope. *SPE Reservoir Evaluation and Eng.* 15 (2), 243-264.

[149] Boswell, R., Collett, T., Frye, M., Shedd, W., McConnell, D., Shelander, D., 2012. Subsurface gas hydrates in the northern Gulf of Mexico. *J. Mar. Pet. Geol.* 34 (1), 4-30.

[150] Paull, C., Ussler, W., Dallimore, S., Blasco, S., Lorenson, T., Melling, H., Medioli, B., Nixon, F., McLaughlin, F., 2007. Origin of pingo-like features on the Beaufort Sea shelf and their possible relationship to decomposing methane gas hydrates. *Geoph. Res., Lett.* 34 (1).

[151] Birchwood, R., Noeth, S., Jones, E., 2008. Safe drilling in gas-hydrate prone sediments: Findings from the 2005 drilling campaign of the Gulf of Mexico gas hydrates Joint Industry Project (JIP). USDOE-NETL *Fire in the Ice* Newsletter, 8 (1), 1-4.

[152] McConnell, D., Zhang, Z., Boswell, R., 2012. Review of progress in evaluating gas hydrate drilling hazards. , *J. Mar. Pet. Geol.*, 34 (1) 209-223.

[153] Peters, D., Hatton, G., Mehta, A., Hadley, C., 2008. Gas hydrate geohazards in shallow sediments and the impact on the design of subsea systems. *Proceedings*, Int'l Conf. on Gas Hydrates, Vancouver, BC, July 6-10, 7 pp;

- Hadley, C., Peters, D., Vaughn, A., Bean, D., 2008. Gumusut-Kakap project: geohazard characterization and impact on field development plans: *Proceedings* IPTC Conference, IPTC #12554; Kuala Lumpur, Malaysia.

[154] Skarke, A., Ruppel, C., Kodis, M., Brothers, D., Lobecker, E., 2014. Widespread methane leakage from the seafloor on the northern US Atlantic Margin. *Nature Geoscience* 7 (9), 657-661 , 5 pp.

[155] Shakhova, N., Semiletov, I., Salyuk, A., Yusupov, V., Kosmach, D., Gustafsson, O., 2010. Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic Shelf: *Science* 327, 1246-1250.

[156] Whiteman, G., Hope, C., Wadhams, P., 2013. Climate Science, Vast Costs of Arctic Change, *Nature* 499, 401-403.

[157] Ruppel, C., 2011. Methane Hydrates and Contemporary Climate Change, *Nature Education Knowledge*, 3 (10), 29.

[158] Beaudoin, Y., Boswell, R., Dallimore, S., Waite, W., eds., 2015. Frozen Heat: A Global Outlook on Methane Gas Hydrates. United Nations Environmental Programme, 2 volumes. http://www.netl.doe.gov/research/oil-and-gas/methane-hydrates/gas-hydrate-global-assessment

[159] DeCourt, B., Alias, S., DeBarre, R., 2015. Gas Hydrates; taking the heat out of the burning-ice debate: Potential and future of gas hydrates. Natural Gas Series Factbook, SBC Energy Institute. https://www.sbc.slb.com/~/media/Files/SBC%20Energy%20Institute/SBC%20Energy%20Institute_Gas%20Hydrates_FactBook.pdf

[160] Ruppel, C., Boswell, R., Jones, E., 2008. Scientific results from Gulf of Mexico gas hydrates joint industry project Leg 1 drilling: Introduction and overview: *J. Mar. Pet. Geol.* 25 (9), 819-829.

[161] Boswell, R., Collett, T., Anderson, B., Hunter, R., eds., 2011. Thematic set on scientific results of the Mount Elbert Gas Hydrate Stratigraphic Test Well, Alaska North Slope, *J. Mar. Pet. Geol.* 28 (2), 279-605.

[162] Collett, T., Boswell, R., eds., 2012, Thematic set on resource and hazard implications of gas hydrates in the Northern Gulf of Mexico: results of the 2009 Joint Industry Project Leg II drilling expedition. *J. Mar. Pet. Geol.* 34 (1), 223 pp.

[163] Collett, T., Agena, W., Lee, M., et al., 2008. Assessment of gas hydrate resources on the North Slope, Alaska. *U.S. Geological Survey Fact Sheet* 2008-3073. 4 pp. http://pubs.usgs.gov/fs/2008/3073/pdf/FS08-3073_508.pdf

[164] BOEM (Bureau of Ocean Energy Management), 2012. Assessment of in-place gas hydrate resources of the Lower 48 United States Outer Continental Shelf. *BOEM Fact Sheet* RED-2012-01. 4 pp. http://www.boem.gov/uploadedFiles/BOEM/Oil_and_Gas_Energy_Program/Resource_Evaluation/Gas_Hydrates/BOEM-FactSheetRED_2012-01.pdf

Acronyms

ANS	Alaska North Slope
BLM	Bureau of Land Management
BOEM	Bureau of Ocean Energy Management
COL	Consortium for Ocean Leadership
CSEM	Controlled source electromagnetics
DOE	Department of Energy
DOI	Department of Interior
E&P	Exploration and production
EM	Electromagnetic
FAC	Federal Advisory Committee
FWP	Field work proposal
FY	Fiscal year
GHR&D	Gas hydrate research and development
GHSZ	Gas hydrate stability zone
GMGS	Guangzhou Marine Geological Survey
GOM	Gulf of Mexico
HRC	HYACE (hydrate autoclave coring equipment) rotary corer
ICC	Interagency Coordination Committee
ICGH	International Conference on Gas Hydrates
IODP	Integrated Ocean Drilling Program
IPTC	Integrated pressure temperature chamber
JIP	Joint Industry Project
LBNL	Lawrence Berkeley National Laboratory
MMS	Minerals Management Service
MPU	Milne Point Unit (Alaska)
NETL	National Energy Technology Laboratory
NGHP	National Gas Hydrate Program (India)
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
NSF	National Science Foundation
PCS	Pressure coring system

PTSC	Pressure-temperature coring system
QTR	Quadrennial Technology Review
R&D	Research and development
TCT	Technical Coordination Team
UBGH	Ulleung Basin Gas Hydrate
USGS	United States Geological Survey

Glossary

Accretionary Wedge Sediments	A mass of sea floor sediment that accumulates at the boundary between a converging oceanic plate and continental plate. This sediment is being scraped off the top of the oceanic plate as it is forced under the continental plate. It "accretes" at the point of plate collision, and that is where the name originates. Source: Geology.com (http://geology.com/dictionary/glossary-a.shtml)
Alaska North Slope	The Alaska North Slope is the region of the U.S. State of Alaska located on the northern slope of the Brooks Range along the coast of two marginal seas of the Arctic Ocean, the Chukchi Sea being on the western side of Point Barrow, and the Beaufort Sea on the eastern. The North Slope contains half a dozen of the 100 largest oil fields in the United States and one of the 100 largest natural gas fields. Most of Alaska's oil production takes place on the North Slope. Source: Arctic Governance Project (http://www.arcticgovernance.org/north-slope-borough.4745156-137746.html) and EIA's Alaskan State Energy Profile (http://www.eia.gov/state/print.cfm?sid=AK)
Anthropogenic	Made or generated by a human or caused by human activity. The term is used in the context of global climate change to refer to gaseous emissions that are the result of human activities, as well as other potentially climate-altering activities, such as deforestation. Source: EIA Online Glossary (http://www.eia.gov/tools/glossary/)
Arctic Shelves	Continental shelves at high latitudes.
Bioclasts	Fragmental or broken remains of organisms in sedimentary rocks.
Biota	The animal and plant life specific to a region, habitat, or interval of geologic time.

Chemical Injection	A general term for wellbore injection processes that use special chemical solutions to improve oil recovery, remove formation damage, clean blocked perforations or formation layers, reduce or inhibit corrosion, upgrade crude oil, or address crude oil flow-assurance issues. With respect to gas hydrates, chemical injection is a potential production mechanism whereby destabilizing chemical inhibitors are placed in contact with the hydrate deposit matrix to liberate methane gas. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/c/chemical_injection.aspx)
Chemosynthetic Communities	Ecosystems that rely on chemosynthesis rather than photosynthesis to maintain life. Chemosynthesis is the process by which certain microbes create energy by mediating chemical reactions. These microbes then become a local food source for other organisms. Hydrothermal vents or methane hydrate deposits can provide a foundation for chemosynthetic communities. Source: NOAA (http://oceanexplorer.noaa.gov/explorations/02mexico/background/communities/communities.html).
CO_2 "Exchange"	A specific type of chemical injection whereby carbon dioxide (CO_2) is placed in contact with the hydrate deposit matrix in order for the CO_2 molecules to "exchange" with the methane molecules; thereby liberating the methane gas.
Coal Bed Methane	Methane located within and produced from coal seams. Coal-bed (or coalbed) methane is formed during coalification, which is the geologic process that transforms organic material into coal.
Cold Vent Site	Cold vent sites or seeps are regions of the sea floor where reduced compounds (mainly methane and sulfides) are released from sediments. Through chemosynthesis (activities of chemoautotrophic bacteria), these compounds support rich assemblages of organisms sometimes distinct from those in surrounding sediments. Source: Research Italy (https://www.researchitaly.it/uploads/8451/Seep.pdf?v=cff8b89)
Continental Slope	The gently-sloping portion of the continental margin between the continental shelf and the abyssal ocean plain.
Conventional Oil and Gas	Crude oil and natural gas that is produced by a well drilled into a geologic formation in which the reservoir and fluid characteristics permit the oil and natural gas to readily flow to the wellbore. Source: EIA Online Glossary (http://www.eia.gov/tools/glossary/)

Coring	The process of taking a cylindrical sample of geologic rock formation, usually reservoir rock, either during (full core) or after (sidewall core) the drilling of a well. Gravity coring involves dropping a weighted steel core barrel overboard to collect sediment core from the sea bottom.
Deepwater	The offshore exploration and development environment characterized by water depths between 4000 feet and 7000 feet is one definition. Greater than 7000 feet is termed "ultra-deepwater." This definition is not standardized and has changed over time as both exploration and production have been extended to deeper and deeper water depths. Source: OilPro (http://oilpro.com/q/714/water-depth-differences-cut-offs-for-ultra-deepwater-vs-midwater-etc)
Depressurization	Depressurization is a production mechanism through which an oil or gas reservoir is produced through a differential pressure that drives fluids from the reservoir into the wellbore. The process is initiated by reducing a well's bottom hole pressure below the fluid pressure within the pores of the reservoir, which is a function of the hydrostatic pressure exerted by the column of water extending upwards from the reservoir depth to the water table (or sea level) and in some cases geologic processes that can lead to elevated pore pressures.
Drilling	The act of boring a hole into the earth.
Electromagnetic Data	Data collected through a group of techniques in which natural or artificially generated electric or magnetic fields are measured at the Earth's surface or in boreholes in order to map variations in the Earth's electrical properties (resistivity, permeability or permittivity). Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/e/electromagnetic_method.aspx?p=1)
Facies	The overall characteristics of a rock unit that reflect its origin and differentiate the unit from others around it. Mineralogy and sedimentary source, fossil content, sedimentary structures and texture distinguish one facies from another. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/en/Terms/f/facies.aspx?p=1)
Flow Assurance	The technologies, strategies, and principles for ensuring that there is uninterrupted hydrocarbon flow from the reservoir to the point of sale. Impediments to hydrocarbon flow in wellbores and flowlines include many phenomena, including the spontaneous formation of solid gas hydrates when mixtures of natural gas and water are exposed to reduced temperatures (e.g., in deepwater flowlines).

Foraminifera	Microscopic, single celled organisms (protists) having shells. Analysis of these shells found in sediments can be used to understand past depositional environments.
Fracture	A crack or surface of breakage within rock or sediment along which there has been no movement. When walls of a fracture have moved only normal to each other, the fracture is called a joint. Fractures can enhance permeability of rocks greatly, and for that reason, fractures are induced mechanically in some reservoirs in order to boost hydrocarbon flow. Fractures may also be referred to as natural fractures to distinguish them from fractures induced as part of a reservoir stimulation or drilling operation. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/f/fracture.aspx)
Free Gas	The gaseous phase present in a reservoir or other contained area. Gas may be found either dissolved in reservoir fluids or as free gas that tends to form a gas cap beneath the top seal on the reservoir trap. Both free gas and dissolved gas play important roles in the reservoir-drive mechanism. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/f/free_gas.aspx)
Free Water	Water that is mobile, available to flow, and not bound to surfaces of grains or minerals in rock. (Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/f/free_water.aspx)
Gas Flux	The rate of gas flow at a specific location compared to background emission measurements.
Gas Hydrates	Solid, crystalline substances composed of water, methane, and usually a small amount of other gases, with the gases being trapped in the interstices of a water-ice lattice. They form beneath permafrost and in deepwater sediments under conditions of moderately high pressure and low temperatures. Source: EIA Online Glossary (http://www.eia.gov/tools/glossary/index.cfm)
Gas Hydrate Geohazard	A hazard associated with gas hydrate formation or decomposition within sediments, whether initiated by natural or industrial processes. Induced gas hydrate destabilization can negatively impact the mechanical stability of the host sediments (e.g., as a result of heat supplied during drilling or production, leading to a reduction in wellbore stability or casing support).

Gas Hydrate Reservoirs	Deposits of methane hydrates which exist due to the temperature and pressure conditions suitable for the formation and stability of gas hydrate. These environments are: 1) sediment and sedimentary rock units below Arctic permafrost; 2) sedimentary deposits along continental margins; 3) deep-water sediments of inland lakes and seas; and 4) under Antarctic ice. With the exception of the Antarctic deposits, methane hydrate accumulations are not very deep below Earth's surface; in most instances within a few hundred meters of the sediment surface. In these environments methane hydrate occurs in the sediment as layers, nodules, and inter-granular cements. Source: Geology.com (http://geology.com/)
Gas Hydrate Stability Zone	The depth range within which both pressure and temperature are suitable for gas hydrate to remain stable. The extent of a gas hydrate stability zone (GHSZ) can depend on local sediment and fluid characteristics.
Geochemical	A process related to the study of the chemistry of the Earth and within solid bodies of the solar system, including the distribution, circulation, and abundance of elements (and their ions and isotopes), molecules, minerals, rocks, and fluids. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/en/Terms/g/geochemistry.aspx?p=1)
Geochemical and Thermal Regimes	Basic climatic parameters related to the amount of heat available or the chemistry including the distribution, circulation, and abundance of elements (and their ions and isotopes), molecules, minerals, rocks, and fluids that can be used to distinctly define one environment from the next. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/en/Terms/g/geochemistry.aspx?p=1)
Geomechanical	A process related to how rocks, stresses, pressures, and temperatures interact. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/g/geomechanics.aspx)
Geophysical Surveys	Investigation of subsurface geology via measurement of electrical, gravitational, and magnetic fields, and propagation of elastic (seismic) waves. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/g/geophysics.aspx)

Global Carbon Cycling	The process by which carbon moves between rocks, oceans, and the atmosphere over various time-scales. The four reservoirs that absorb or take up released carbon from one another are the atmosphere, terrestrial biosphere (usually including freshwater systems), oceans, and sediments (including fossil fuels). Exchanges of carbon from one of these "carbon sinks" to another by various chemical, physical, geological, and biological processes, is termed the carbon cycle. Source: EIA Online Glossary (http://www.eia.gov/tools/glossary/index.cfm?id=C#carb_cycle)
Hydrocarbons	An organic chemical compound of hydrogen and carbon in the gaseous, liquid, or solid phase. The molecular structure of hydrocarbon compounds varies from the simplest (methane, a constituent of natural gas) to the very heavy and very complex oils. Source: EIA Online Glossary (http://www.eia.gov/tools/glossary/index.cfm)
Hydrostatic Pressure	The normal, predicted pressure for a given depth; or the pressure exerted per unit area by a column of freshwater from sea level to a given depth. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/h/hydrostatic_pressure.aspx)
In Situ	A Latin phrase meaning "in the original location or position." Tests can be performed *in situ* in a reservoir to determine its pressure and temperature and its fluid properties. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/i/in_situ.aspx)
Joint Industry Project	A consortium of companies formed to address some specific issue or problem, often of a technical or scientific nature, for mutual benefit.
Leased Lands	Lands encompassed by an agreement wherein a mineral interest owner (lessor) conveys to another party (lessee) the rights to explore for, develop, and produce specified minerals. The lessee acquires a working interest and the lessor retains a non-operating interest in the property, referred to as the royalty interest, each in proportions agreed upon. Source: EIA Online Glossary (https://www.eia.gov/tools/glossary/index.cfm)
Lithology	The macroscopic nature of the mineral content, grain size, texture, and color of rocks. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/l/lithology.aspx)

Logging	The process of lowering instruments into a borehole or an oil or gas well and recording measurements of various physical parameters that can be analyzed to provide useful information about the character of the rocks, fluids or other conditions present. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/l/logging_run.aspx)
Liquefied Natural Gas (LNG)	Natural gas (primarily methane) that has been liquefied by reducing its temperature to -260 degrees Fahrenheit at atmospheric pressure. EIA Online Glossary (https://www.eia.gov/tools/glossary/index.cfm)
Methane Hydrate	An occurrence of hydrocarbon in which molecules of methane are trapped in ice molecules. More generally, hydrates are compounds in which gas molecules are trapped within a crystal structure. Hydrates form in permafrost zones and in deep water. Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/m/methane_hydrate.aspx)
Natural Flux	The observed fluid flow rate of a specific environment.
Nodules	Non-planar mineral masses, the formation of which displaces surrounding sediments.
Numerical Modeling	A rendering of a model of a reservoir or field in entirely numerical formats. Numerical models, once built, may be used to perform many mathematical operations, including calculations of available reserves and simulations of the behavior of the reservoir. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/n/numerical_model.aspx)
Organic Carbon	Naturally-occurring carbon derived from the decomposition of plants and animals as well as from a soil's parent material/geology. "Inorganic carbon", on the other hand, would include dissolved carbon dioxide or carbonic acid salts.
Outer Continental Shelf	Federal domains, located seaward of the coastline. Source: EIA Online Glossary (http://www.eia.gov/pub/oil_gas/natural_gas/data_publications/historical_natural_gas_annual/current/pdf/glossary.pdf)
Oxidize	To chemically transform a substance by combining it with oxygen. Source: EPA Glossary (http://www3.epa.gov/climatechange/glossary.html#num4)

Paleocene-Eocene Thermal Maximum (PETM)	During the Paleocene-Eocene Thermal Maximum (PETM), which occurred around 56 million years ago, global temperatures rose at least 5°C (9°F), and the period of warmth lasted 200,000 years before the Earth system was able to remove the extra CO_2 from the atmosphere. The PRTM marked the transition from the Paleocene to Eocene epochs. Source: Weather Underground (https://www.wunderground.com/climate/PETM.asp)
Permafrost	The permanently frozen subsoil that lies below the upper layer (the upper several inches to feet) of soil in arctic regions. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/p/permafrost.aspx)
Polarity	The nature of the positive and negative portions of the seismic wavelet, the positive and negative aspects of electrical equipment, or the north and south orientations of magnets and the Earth's magnetic field. A polarity standard refers to the convention applied to seismic data that determines how reflections are displayed in graphical depictions of the data. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/p/polarity.aspx)
Relict Hydrates	Permafrost-associated gas hydrates that exist in shallow-shelf settings, associated with relict permafrost (see next entry).
Relict Permafrost	Permafrost that persists in places where it could not presently form. Relict permafrost reflects past climatic conditions, usually colder temperatures that differ from current conditions (e.g., areas previously exposed as dry land but that are now covered by shallow water due to post-ice-age sea-level rise). Source: TAPS EIS (http://tapseis.anl.gov/glossacro/dsp_wordpopup.cfm?word_id=885)
Salt Tectonics	Salt is a ductile, soluble evaporate mineral that is less dense than many sedimentary rocks and is relatively buoyant and can form salt domes, pillars, or curtains by flowing and breaking through or piercing overlying sediments. Salt tectonics refers to how salt structures form and deform the sediments surrounding it.
Seafloor Slumps	Marine landslides.
Seismic Data	Data measuring the variable acoustic velocity of formations in order to infer the geologic structure, lithology, and nature of pore fluids. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms.aspx?LookIn=term%20name&filter=seismic+data)

Sequestration	The permanent isolation of some substance from a protected portion of the environment. Typically used in relation to the permanent storage of carbon dioxide when it is injected for into underground geologic reservoirs, such as oil and natural gas fields, saline aquifers, or abandoned coal mines.
Shale Gas	Natural gas produced from shale formations. A fine-grained, fissile, detrital sedimentary rock formed by consolidation of clay- and silt-sized particles into thin, relatively impermeable layers. The shale acts as both the source and the reservoir for natural gas. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/s/shale.aspx)
Slide Feature	A feature of a submarine seafloor slope failure (slide).
State Lands	Lands under the jurisdiction of one of the 50 states, including adjacent outer continental shelf areas, or the District of Columbia, but excluding Puerto Rico and other U.S. territories.
Stratigraphic Unit	A volume of rock of identifiable origin and relative age range that is defined by the distinctive and dominant, easily mapped and recognizable petrographic, lithologic or paleontologic features (facies) that characterize it. Source: Wikipedia (https://en.wikipedia.org/wiki/Stratigraphic_unit)
Thermal Stimulation	Injection processes that introduce heat into a reservoir to restore or enhance the productivity of a well. Examples include steam injection to enable the production of high viscosity crude oil or the injection of hot water to promote dissociation of methane hydrate and release of methane.
Thermogenic Gas	Natural gas that has been generated via the heating (thermal cracking) of organic matter, as opposed to biogenic produced by the actions of methanogenic organisms.
Thin Bed Analysis	Geophysical analyses that attempt to discern stratigraphic features (e.g., the thicknesses of sedimentary layers) that are typically below the resolution of the data acquisition method.
Up-Dip	Located up the slope of a dipping plane or surface. In a dipping (not flat-lying) hydrocarbon reservoir that contains gas, oil, and water, the gas is updip, the gas-oil contact is downdip from the gas, and the oil-water contact is still farther downdip. Source: Schlumberger Oilfield Glossary (http://www.glossary.oilfield.slb.com/Terms/u/updip.aspx)
Veins	A distinct sheet-like body of crystallized minerals within a rock. Veins form when mineral constituents carried by an aqueous solution within the rock mass are deposited through precipitation. Source: Wikipedia (https://en.wikipedia.org/wiki/Vein_%28geology%29)
Venting	The release of natural gas to the ocean or atmosphere.