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Methane Hydrates in Nature—Current Knowledge and Challenges

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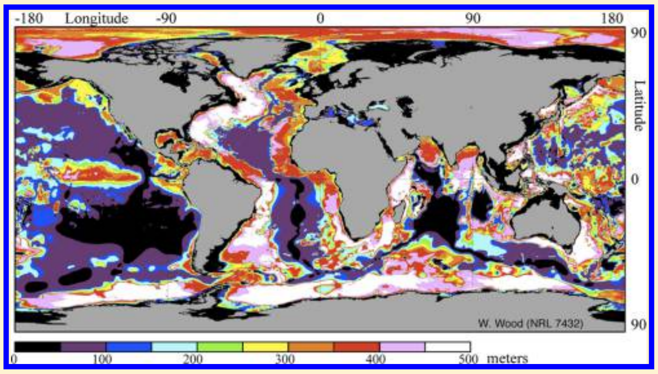

ABSTRACT: Recognizing the importance of methane hydrate research and the need for a coordinated effort, the United States Congress enacted the Methane Hydrate Research and Development Act of 2000. At the same time, the Ministry of International Trade and Industry in Japan launched a research program to develop plans for a methane hydrate exploratory drilling project in the Nankai Trough. India, China, the Republic of Korea, and other nations also have established large methane hydrate research and development programs. Government-funded scientific research drilling expeditions and production test studies have provided a wealth of information on the occurrence of methane hydrates in nature. Numerous studies have shown that the amount of gas stored as methane hydrates in the world may exceed the volume of known organic carbon sources. However, methane hydrates represent both a scientific and technical challenge, and much remains to be learned about their characteristics and occurrence in nature. Methane hydrate research in recent years has mostly focused on: (1) documenting the geologic parameters that control the occurrence and stability of methane hydrates in nature, (2) assessing the volume of natural gas stored within various methane hydrate accumulations, (3) analyzing the production response and characteristics of methane hydrates, (4) identifying and predicting natural and induced environmental and climate impacts of natural methane hydrates, (5) analyzing the methane hydrate role as a geohazard, (6) establishing the means to detect and characterize methane hydrate accumulations using geologic and geophysical data, and (7) establishing the thermodynamic phase equilibrium properties of methane hydrates as a function of temperature, pressure, and gas composition. The U.S. Department of Energy (DOE) and the Consortium for Ocean Leadership (COL) combined their efforts in 2012 to assess the contributions that scientific drilling has made and could continue to make to advance our understanding of methane hydrates in nature. COL assembled a Methane Hydrate Project Science Team with members from academia, industry, and government. This Science Team worked with COL and DOE to develop and host the Methane Hydrate Community Workshop, which surveyed a substantial cross section of the methane hydrate research community for input on the most important research developments in our understanding of methane hydrates in nature and their potential role as an energy resource, a geohazard, and/or as an agent of global climate change. Our understanding of how methane hydrates occur in nature is still growing and evolving, and it is known with certainty that field, laboratory, and modeling studies have contributed greatly to our understanding of hydrates in nature and will continue to be a critical source of the information needed to advance our understanding of methane hydrates.

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1. INTRODUCTION

In 2012, the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL), in partnership with the Consortium for Ocean Leadership (COL), initiated a new field-focused methane hydrate research project that would inform, and potentially lead to, future offshore drilling expeditions. The primary objective of this project was to identify how scientific drilling could be most effectively conducted to advance the evaluation of methane hydrate resource, geohazard, and climate-change implications. To implement and help guide this effort, COL assembled a Methane Hydrate Project Science Team consisting of representatives from academia, industry, and government. Two of the major elements of this COL-led science planning effort were (1) the authoring of a Historical Methane Hydrate Project Review Report[1] and (2) the hosting of a Methane Hydrate Community Workshop.[2] The historical review report was used as a guide to develop the agenda for the Methane Hydrate Community Workshop and provide the foundation for the Methane Hydrate Research Science Plan.[3]

The COL-hosted Methane Hydrate Community Workshop focused on identifying and assessing specific scientific challenges that must be addressed to advance our understanding of methane hydrates and how these challenges could be resolved with the support of scientific drilling. The workshop also provided an excellent venue for the exchange of ideas among a highly interdisciplinary group of scientists. Workshop discussions provided detailed reviews of our current understanding of the geologic controls on the occurrence of methane hydrate in nature and how these factors may impact the energy, hazard, and climate change aspects of methane hydrate research. It was concluded that the most significant advancements in methane hydrate research have included:

-Documenting the geologic parameters that control the occurrence and stability of hydrates in nature—Methane Hydrate System;

-Assessing the volume of natural gas stored as hydrates within various geologic settings—Methane Hydrate Assessments;

-Analyzing the production response and characteristics of methane hydrates—Methane Hydrate Production;

-Identifying and predicting natural and induced environmental and climate impacts of natural methane hydrates—Methane Hydrate Climate Change Issues;

-Analyzing the impact and response of methane hydrates to external forcing—Methane Hydrate Geohazard Issues;

-Development of advanced methane hydrate modeling, laboratory and field characterization capabilities—Pressure Core Field and Laboratory Studies, Downhole Measurements Systems, Reservoir Modeling, Drill Site Geologic and Geophysical Characterization.

In this report we summarize our most current understanding of methane hydrates in nature and further document the technical and scientific challenges that will be the likely focus of methane hydrate research in the next decade.

2. STATE OF METHANE HYDRATE SCIENCE

The study of methane hydrates in nature has been ongoing for over 40 years. Significant strides have been made in our understanding of the occurrence, distribution, and characteristics of marine methane hydrates (Figures 1 and 2), but knowledge of the role they may play as an energy resource, geologic hazard, and possible agent in climate change is incomplete. In this section, we review some of the most important recent developments in the study of methane hydrates in nature and explore future methane hydrate research opportunities.

2A. Methane Hydrate System. In recent years, significant progress has been made in addressing key issues on the formation, occurrence, and stability of methane hydrate in nature. The concept of a methane hydrate system, similar to the concept that guides conventional oil and gas exploration, has been developed to systematically assess the geologic controls on the occurrence of methane hydrate in nature (Figure 3).[6,7] In a methane hydrate system, the individual factors that contribute to the formation of methane hydrate in nature can be identified and assessed; the most important factors include: (1) methane hydrate pressure−temperature stability conditions, (2) gas charge—the combination of gas source and migration, and (3) the presence of suitable host sediment or "reservoir".

In terms of methane hydrate as a potential energy resource, the concept of a methane hydrate system has been developed to systematically assess the occurrence, distribution, and richness of gas hydrate accumulations in nature from the reservoir to a basin scale.[7] The methane hydrate system concept has been used to guide the site selection process for numerous recent national and international methane hydrate scientific drilling programs.[8] The methane hydrate system concept can also be used to characterize the geologic controls on the occurrence and stability of methane hydrates in natural systems with respect to geohazard and climate-change response assessments.

Most methane hydrate system studies have focused on describing hydrates as static deposits rather than building a better appreciation of them as part of a dynamic system. Fundamental questions remain as to the residence time of methane hydrates near the seafloor and deeper within the sediment column, the sources of methane and the pathways for its transport, the nature and mechanisms driving fluid flow, and changes in these variables through time (Figure 3). Consequently, there is a growing imperative to develop integrated time-dependent models to understand the controls on the formation, occurrence, and stability of methane hydrates in nature, as well as the forcing mechanisms that modulate the processes responsible for methane generation, consumption, and potential discharge from the methane hydrate system.

2B. Methane Hydrate Assessments. Methane hydrate resource assessments indicating enormous global volumes of methane within hydrate accumulations have been one of the primary driving forces behind the growing interest in methane hydrates.[9] For the most part, these estimates range over several orders of magnitude, creating great uncertainty in the role methane hydrates may play as an energy resource or as a factor in global climate change. In recent years, field production tests combined with advanced numerical simulation have shown that hydrates in sand reservoirs are the most feasible initial targets for energy recovery. It has also been shown that, with regard to the climate implications of methane hydrates, there is growing need to accurately assess the portion of the global methane hydrate endowment that is most prone to disturbance under future warming scenarios.

Over the last 10 years, a number of new quantitative estimates of in-place methane hydrate volumes have been reported.[10−13] In most cases, hydrate assessments include the analysis of a set of minimum source-rock criteria such as organic richness, sediment thickness, and methane generation as they apply to both microbial and thermogenic gas sources (Figure 4). In several of the more recent assessments, the hydrate resource volume estimates have also considered the nature of the

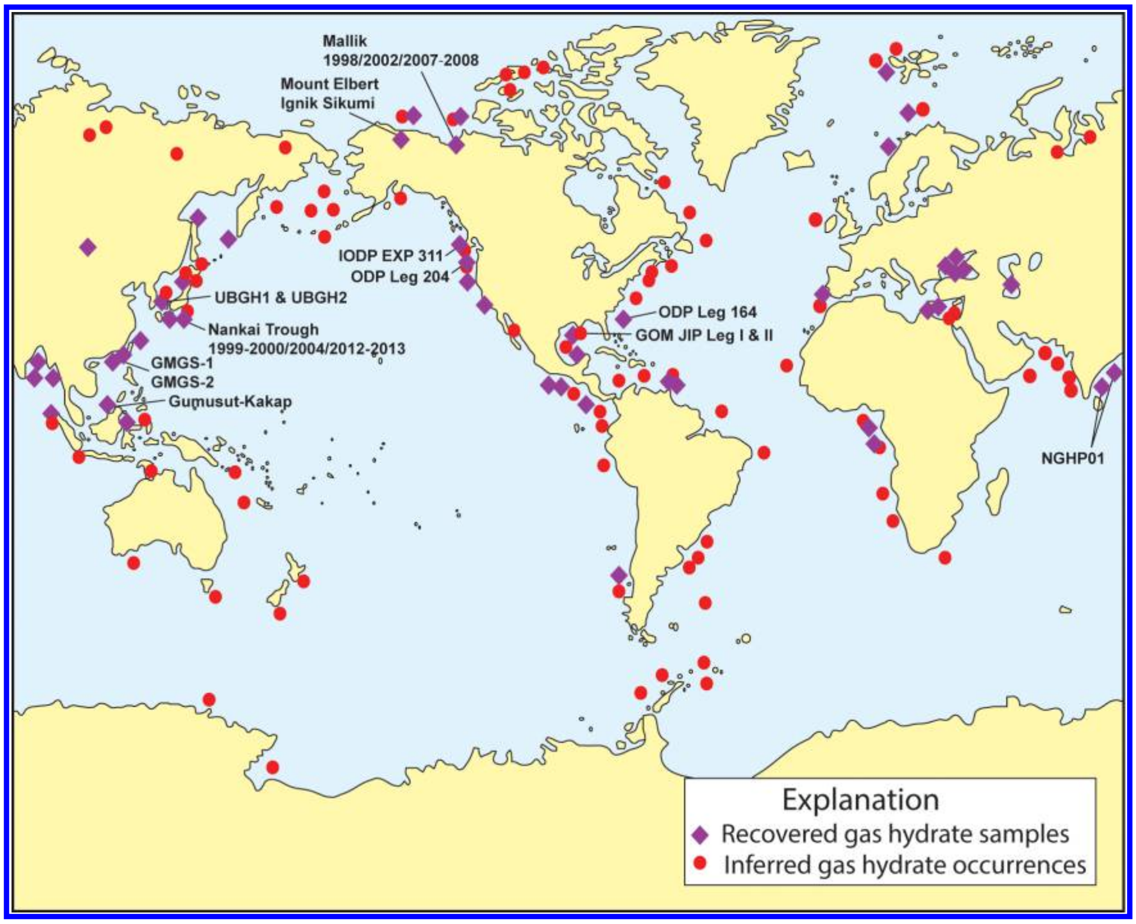

Figure 1. Location of sampled and inferred methane hydrate occurrences in oceanic sediment of outer continental margins and permafrost regions.[4] Most of the recovered methane hydrate samples have been obtained during deep coring projects or shallow seabed coring operations. Most of the inferred methane hydrate occurrences are sites at which bottom simulating reflectors (BSRs) have been observed on available seismic profiles. The methane hydrate research drilling projects and expeditions reviewed in this report have also been highlighted on this map.

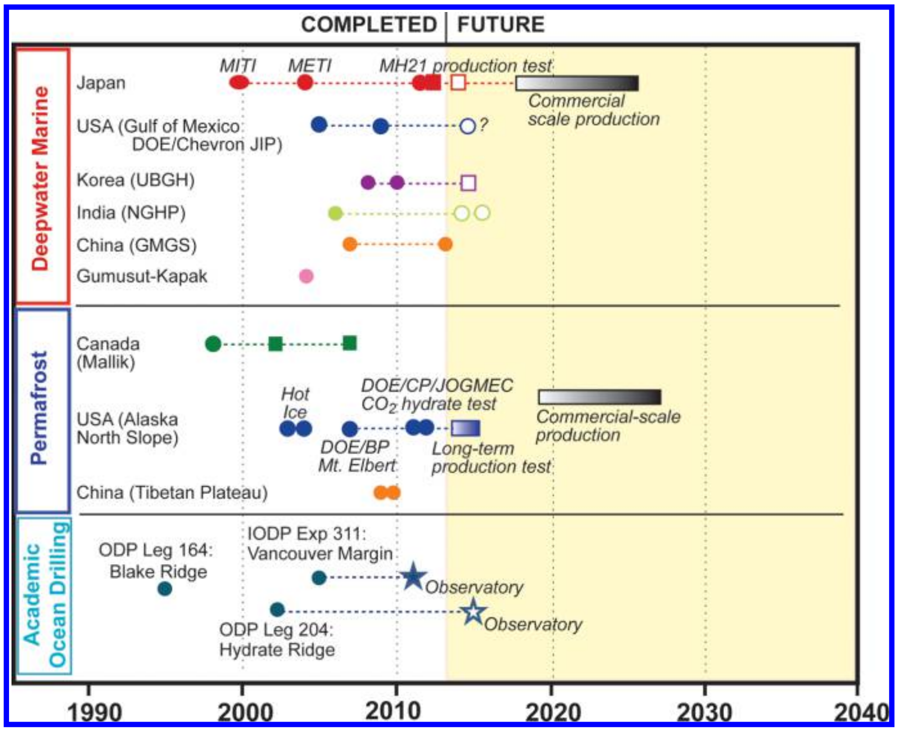

Figure 2. Timeline chart showing the deepwater marine, Arctic permafrost, and academic ocean drilling scientific drilling expeditions dedicated to the research on naturally occurring methane hydrates.[5]

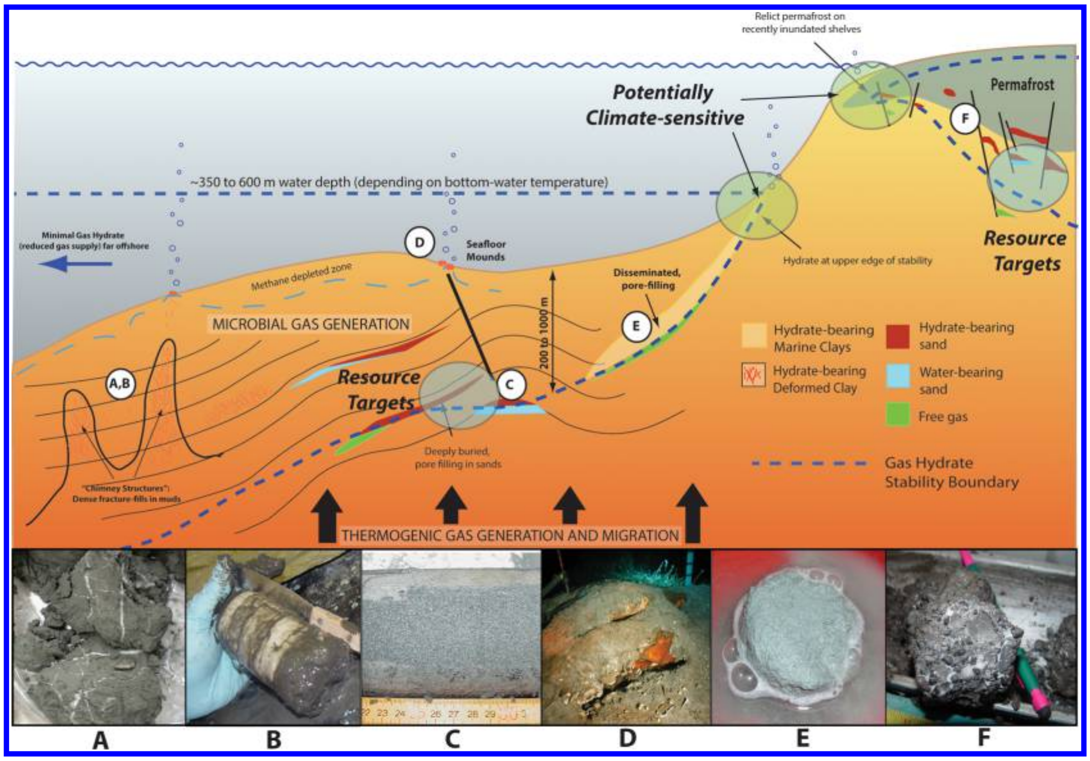

Figure 3. A schematic depiction of the components of various types of methane hydrate systems.[6] Typical methane hydrate reservoir morphologies including (A) networks of hydrate-filled veins; (B) massive hydrate lenses; (C) grain-filling methane hydrate in marine sands; (D) massive sea-floor mounds; (E) grain-filling methane hydrate in marine clays; (F) grain-filling methane hydrate in onshore Arctic sands/conglomerates. The general location of the most resource relevant (blue circles) and most climate relevant (green circles) methane hydrate occurrences are also shown. Images as shown are (A) courtesy UBGH-01 (Korea); (B) courtesy NGHP Expedition 01 (India); (E) courtesy GMGS Expedition 1 (China); (F) courtesy Mallik 2002 Science Program (Canada). Other parts of the methane hydrate system as depicted include the relationship between microbial and thermogenic gas sources and gas migration controls.

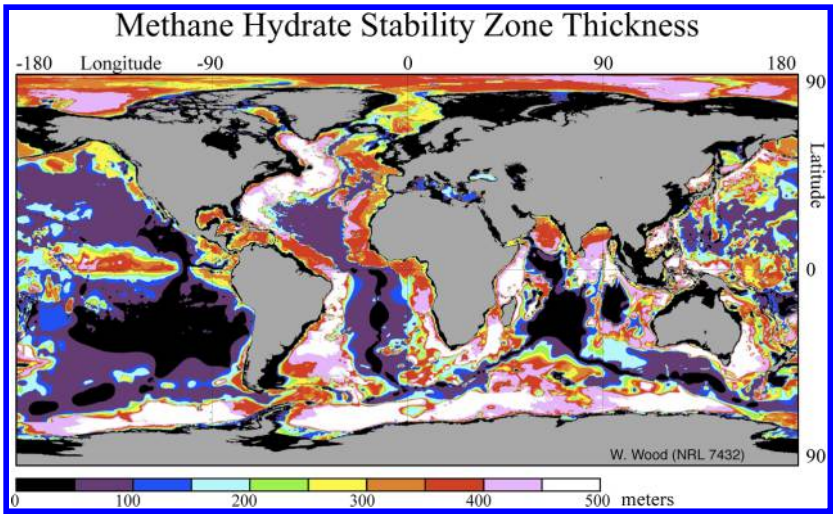

Figure 4. Map of the methane hydrate stability zone thickness used to limit the area assessed for the occurrence of methane hydrate within the worldwide methane hydrate assessment conducted by Wood and Jung.[12]

sediments that host the hydrates. For example, in 2012, the Bureau of Ocean Energy Management (BOEM) reported that the "United States Lower-48 Outer Continental Shelf" contains about 1454 trillion cubic meters (51 338 trillion cubic feet) of in-place gas within hydrates. BOEM further estimated that 190 trillion cubic meters (6700 trillion cubic feet) of the total amount of gas within methane hydrates of the Gulf of Mexico occurred as highly concentrated hydrate accumulations within sand reservoirs. Similarly, BOEM estimated the volume of gas within sand reservoirs along the Atlantic margin of the United States at 447 trillion cubic meters (15 785 trillion cubic feet). Fujii et al.[14] also reported on a resource assessment of methane hydrates in which they estimated the volume of gas within the hydrates of the eastern Nankai Trough at about 1.1 trillion cubic meters (40 trillion cubic feet), with about half of the estimated volume concentrated in sand reservoirs. Collectively, the recent hydrate assessments in the United States and Japan indicate that reservoir-quality sands may be more common in methane hydrate systems than previously thought.

One of the most important emerging goals of methane hydrate research and development activities is the identification and quantification of the amount of technically and economically recoverable natural gas that might be stored within methane hydrate accumulations. In 2008, the U.S. Geological Survey used the methane hydrate system concept for the first time to assess amount of the technically recoverable methane hydrate resources on the North Slope of Alaska;[15] this assessment indicated that there are about 2.42 trillion cubic meters (85.4 trillion cubic feet) of technically recoverable methane gas resources within concentrated, sand-dominated, methane hydrate accumulations in northern Alaska.

A variety of models have been developed to predict methane hydrate occurrence on local, regional, and global scales. But to properly constrain predictive assessment models, it is critical to have a comprehensive understanding of the model input parameters, in particular, variables that control the input and output of methane over time. Additionally, while sensitivity studies can identify the most important components in any one model, it is often uncertain which of the many critical parameters and conditions are the primary driving forces for the accumulation of methane hydrate in the natural environment at any specific site.

2C. Methane Hydrate Production. Methane hydrates are known to occur at high concentrations in sand-dominated reservoirs in both permafrost[16] and deep marine settings.[8,17] These settings have been the focus of recent methane hydrate exploration and production studies in northern Alaska and Canada, in the Gulf of Mexico, off the southeastern coast of Japan, in the Ulleung Basin off the east coast of the Korean Peninsula, and along the eastern margin of India (Figure 1).[6] Production testing and modeling have shown that concentrated methane hydrate occurrences in sand reservoirs are conducive to existing well-based production technologies (Figure 5).[9] Because conventional production technologies favor sand-dominated methane hydrate reservoirs, sand reservoirs are considered to be the most viable economic target for methane hydrate production and will be the prime focus of most future methane hydrate exploration and development projects, with depressurization techniques, optimized through tailored applications of thermal and/or chemical stimulation, being the primary basis for initial production experiments.[6,18]

Over the last 10 years, national methane hydrate research programs, along with industry interest, have led to the development and execution of major methane hydrate production field test experiments. Three of the most important field testing programs have been conducted at the Mallik site in the Mackenzie River Delta of Canada[19,20] and in the Eileen methane hydrate accumulation (i.e., Mount Elbert and Ignik Sikumi tests) on the North Slope of Alaska.[21] Most recently, we have also seen the completion of the world's first marine methane hydrate production test in the Nankai Trough offshore of Japan.[22] The recent production tests in Alaska, northern Canada, and offshore Japan have collectively shown that natural gas can be produced from methane hydrates with existing conventional oil and gas production technology.

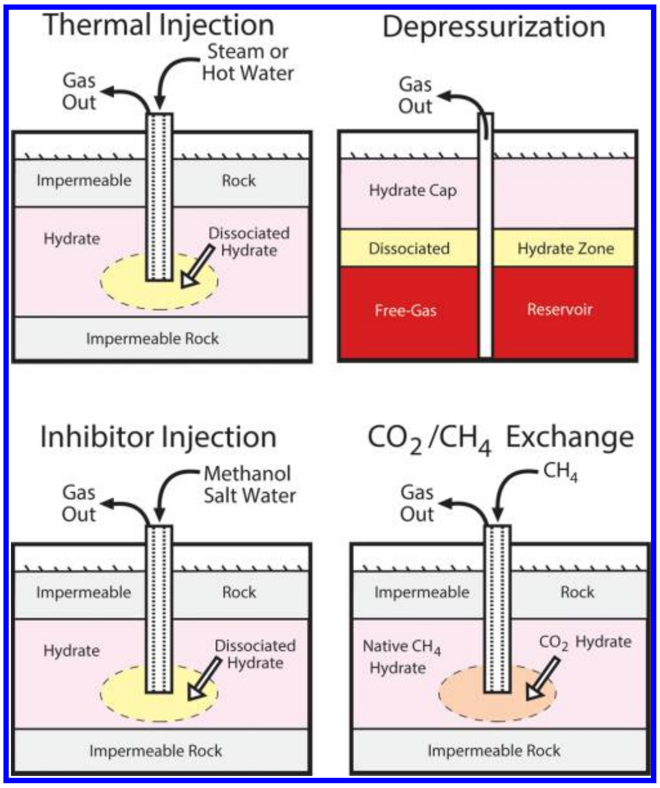

Figure 5. Schematic of proposed methane hydrate production methods.[7]

In general, the completed field methane hydrate production tests have been of limited duration, from 6 to 25 days. These tests support the technical proof-of-concept for gas production from hydrate reservoirs, but they fall short of proving the economic viability of the resource. Longer-duration production tests that rigorously test a wide range of production technologies are needed to investigate the viability of economic gas production from methane hydrate. The need for future methane hydrate production testing at the experimental and industry-scale to understand the ultimate economic resource potential of methane hydrates is critical. To prepare for future field production testing, more information is needed (1) on the properties/characteristics of methane hydrate reservoirs, (2) the production response of various methane hydrate accumulations measured in the laboratory and quantified through production modeling, and (3) the environmental issues controlling the ultimate resource potential of methane hydrates. Numerical models that can accurately represent observed phenomena in field and laboratory experiments also need to be further developed and improved.

2D. Methane Hydrates and Climate Change. Methane hydrates are only recently being incorporated into global environmental concepts and processes, including carbon cycling[23] and global climate.[24] For example, the atmospheric concentration of methane, like that of carbon dioxide, has increased over the past century. Methane in the atmosphere comes from many sources, including wetlands, rice cultivation, termites, cows and other ruminants, forest fires, and fossil fuel production. Some researchers have estimated that up to two percent of atmospheric methane may originate through dissociation of global methane hydrates.[25] It has been shown that methane is an important component of Earth's carbon cycle on geologic time scales. Whether methane once stored as methane hydrate has contributed to past climate change or will play a role in the future global climate remains unclear. A given volume of methane causes 15 to 20 times more greenhouse gas warming than carbon dioxide, so the release of large quantities of methane could exacerbate warming and cause more methane hydrate to destabilize. Extreme warming during the

Paleocene−Eocene Thermal Maximum about 55 million years ago may have been related to a large-scale release of global methane hydrates.[23] The impact of modern climate warming on methane hydrate deposits does not appear to have led to catastrophic breakdown of methane hydrates or major leakage of methane to the ocean-atmosphere system from destabilized hydrates. The vast majority of methane hydrates would require a sustained warming over thousands of years to trigger dissociation, and the released methane would encounter many potential sinks before being emitted to the atmosphere. However, methane hydrates, particularly those associated with relict permafrost, may yet persist on arctic shelves that have been inundated by post ice-age sea-level rise and are now dissociating in response to longer-term climate processes.[25]

The controls on the inventory and flux of methane in marine systems are poorly constrained; methane hydrate is a component of a complex system, with inputs and outputs of methane over time. Ultimately, methane generation is closely tied to the inputs of organic carbon, although it is not yet clear how to best evaluate the relationship between the amount and type of organic carbon deposited on the seafloor and the quantity of methane generated. In terms of outputs, it is important to quantify the amount of methane lost from the system through naturally occurring gas seeps and the amount consumed by anaerobic methane oxidation in the sediments.

In addition to understanding the dynamics of carbon flux associated with hydrate systems, strong interest exists in understanding how methane hydrate systems respond to natural and anthropogenic perturbations. Dissociation of methane hydrate due to warming or sea-level change can release methane into the ocean system, affecting ocean chemistry (for example, "ocean acidification") and, potentially, climate and marine slope stability. Past warming has been hypothesized to be responsible for global methane hydrate dissociation events that have played a critical role in climate change.[23,25] However, the nature, mechanisms, and extent of methane escape due to perturbations are poorly understood. Moreover, the fate and extent to which methane reaches the atmosphere is not well-constrained even in active vents and seeps overlying modern methane hydrate systems. These unknowns result in uncertainties in carbon cycle and climate models.

2E. Methane Hydrates as Geohazards. Geohazards associated with the occurrence of methane hydrates in nature are generally classified as "naturally occurring" geohazards that emerge wholly from geologic processes and "operational" geohazards that may be triggered by human activity (Figure 6).[26] As a geohazard, the dissociation of methane hydrate replaces a rigid sediment component (i.e., methane hydrate) with free gas and excess pore water, which may substantially reduce the geomechanical stability of the affected sediment.

The two most important naturally occurring geohazards associated with methane hydrate dissociation are slope instability and wide-scale gas venting. The concept that methane hydrate dissociation causes extensive slope instability has been around for over three decades,[27] and it has received further support with the recognition that methane hydrates may play an important role in the global carbon cycle.[28] Several investigators have argued that lowering global sea level and/or ocean warming establishes new equilibrium conditions for marine methane hydrate stability, which induces seafloor slope instability.[29,30] However, evidence has emerged that methane hydrate dissociation does not occur in such a manner as to cause widespread slope instability. Field investigations at the sites of major mass wasting events, such as the Storegga[31] and Cape Fear[32] slides have addressed this topic with inconclusive results. However, these studies suggest that methane hydrate impact on seafloor stability in recent geologic history may be small.

Continuous methane gas venting occurs in many marine settings and may in some cases represent a naturally occurring geohazard. Large concentrations of gas chimneys have been documented in certain settings,[33] which may cause widespread gas releases or even sediment expulsion. Gas venting was initially thought to have caused a collapse feature on the crest of Blake Ridge, but later this feature was found to have resulted from sedimentological processes.[34] Compelling evidence for gas and sediment expulsions was found in the "pingo-like features" observed on the shallow Canadian Beaufort shelf.[35] These features appear to be a result of methane hydrate dissociation related to melting of permafrost due to post ice-age sea level rise.

In comparison to most conventional hydrocarbon accumulations, methane hydrates occur at relatively shallow depths, representing an operational geohazard to shallow drilling and well completions. Mechanical disturbance and/or heating of these shallow reservoirs through, for example, drilling or emplacement of seafloor infrastructure such as pipelines can cause the hydrates to dissociate, thus reducing the host sediment strength and adversely impacting drilling operations and well installations.

Results from several methane hydrate drilling programs, including Ocean Drilling Program (ODP) Legs 164 and 204, and more recently the Chevron-led Gulf of Mexico Joint Industry Project (GOM-JIP) Legs I and II, Integrated Ocean Drilling Program (IODP) Expedition 311, and National Gas Hydrate Program (NGHP) Expedition 01 have shown that drilling hazards associated with methane hydrate-bearing sections can be managed through the careful control of drilling parameters.[36,37] However, a longer-term and perhaps more difficult-to-constrain risk is the potential for hydrate dissociation and sediment-wellbore instability caused by the heating of sediment around production wells due to sustained flow of deeper, warmer fluids.[38,39]

There is a significant lack of quantitative understanding of operational geohazards because of the general lack of practical field experience with methane hydrate systems. There is even a greater lack of experience when dealing with operational geohazards associated with the direct exploitation of methane hydrates as a potential resource. More work is needed to understand the complete range of operational geohazards associated with various types of methane hydrate occurrences in nature.

3. ADVANCEMENTS IN METHANE HYDRATE MODELING, LABORATORY, AND FIELD CHARACTERIZATION

To advance methane hydrate science and properly draw generalized interpretations from site-specific field data requires accurate laboratory and field data, and the development of advanced laboratory and field measurement tools. These data and tools are critical to the development of accurate and reliable pore-scale and transport models, physical property and geochemical field and laboratory measurements, and reservoir prediction models. The technical developments below describe both routine and specialized needs for laboratory and field measurements and modeling developments in the support of methane hydrate research.

3A. Integrated Field and Laboratory Measurements and Experiments. To assess the in situ nature of methane

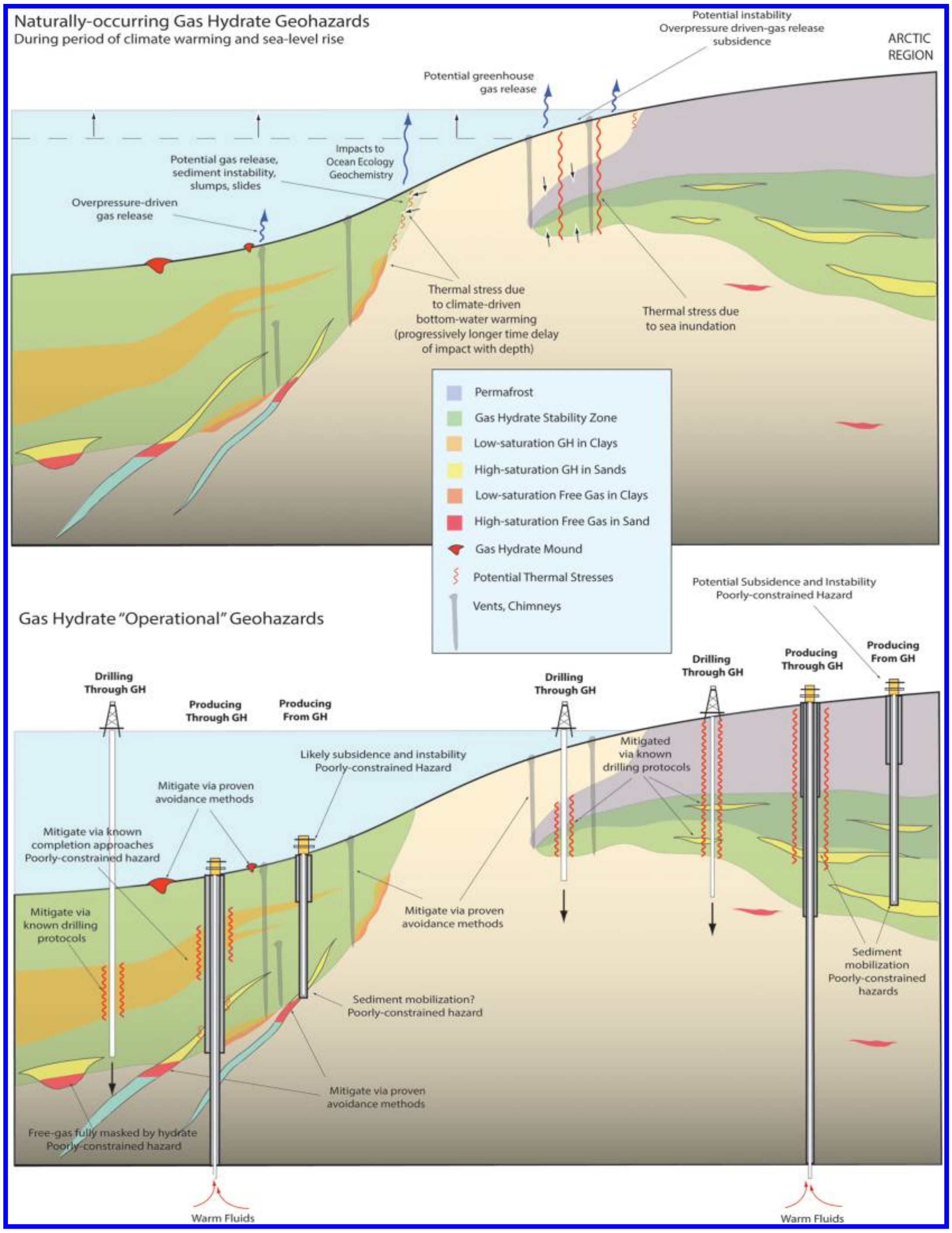

Figure 6. Geohazards associated with the occurrence of methane hydrate encompasses any condition that has the potential to negatively impact human activity or the natural environment. In this review, "natural-occurring" geohazards refer to conditions associated with natural processes. "Operational" geohazards are conditions triggered by human activities.[26]

hydrates requires the retrieval and analysis of hydrate-bearing sediment cores that closely represent in situ conditions, which has led to the development of advance hydrate pressure coring systems. One of the first pressure core systems used to study methane hydrates was the pressure core sampler (PCS). The PCS is sealed in an autoclave core barrel that can withstand the hydrostatic pressure at the coring depth and remains sealed as it is brought to the surface. In the past, pressure core systems were used to determine the in situ gas volume and composition of recovered hydrate-bearing cores, and in some configurations, the pressurized cores were analyzed using X-ray imaging systems.[40]

Significant advances have been made in the development and implementation of pressure coring tools for hydrate drilling expeditions.[41,42] Systems include the Fugro Pressure Corer, which is suitable for use in unlithified sediments, and the Fugro Rotary Pressure Corer, which was designed to sample lithified sediment or rock. A new generation of pressure coring systems has also been developed, including the Pressure−Temperature Coring System (PTCS) and the Hybrid Pressure−Coring System (Hybrid-PCS), which deliver longer cores and feature robust ball-valve sealing systems.

Further developments have been made to enable the hydrate-bearing cores retrieved under pressure to be transferred and measured without depressurizing the recovered cores. These new systems include the HYACINTH Pressure Core Analysis and Transfer System (PCATS) that enables acoustic P-wave velocity, gamma ray attenuation, and X-ray imaging of recovered pressure cores all under in situ pressure conditions.[40,41] Pressure Core Characterization Tools (PCCT) have been developed[43] that include core manipulation tools and characterization chambers to enable hydrological, thermal, chemical, biological, and mechanical properties to be measured under pressure and effective stress conditions.

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

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

Significant progress has been made in developing synthesis methods for methane hydrate formation in a range of hydrate-bearing sediment systems. These synthesis methods include: (1) hydrate formation from dissolved gas, which leads to heterogeneous nucleation and more uniform growth in the pore space; (2) from partial water saturation, which results in preferential formation at grain contacts; and (3) from hydrate particles and ice seeds where the hydrate-bearing sediment properties depend on the relative size of the hydrate particles and sediment grains as well as hydrate saturation.[44] To date, only a few studies have been performed to characterize hydrate-bearing sediment samples (both synthetic and a limited number of natural core samples) using CT-X-ray imaging, porosity–permeability petrophysical analysis, or acoustic measurements. There have only been a limited number of laboratory studies to investigate gas production from methane hydrate-bearing sediments by depressurization, thermal stimulation,[45] and CO_2 injection.[46] In summary, laboratory analyses of well-characterized synthetic hydrate-bearing sediment cores have been shown to be an important source of information on occurrence and behavior of methane hydrates in nature.

3B. Downhole Measurement Systems. Advanced downhole wireline and logging-while-drilling conveyed tools are now routinely used to examine the petrophysical properties of methane hydrate reservoirs and the distribution and concentration of methane hydrates within various reservoir systems.[47] The most established and well-known use of well logs in methane hydrate research are those that provide electrical resistivity and acoustic velocity data (both compressional- and shear-wave data) to estimate methane hydrate content (i.e., methane hydrate pore-volume saturation) in various types of reservoirs. Recent integrated sediment coring and well log studies have confirmed that electrical resistivity and acoustic velocity data can yield accurate methane hydrate saturations in sediment grain-supported (isotropic) systems such as sand reservoirs, but more advanced log-analysis models are required to characterize methane hydrate in fractured (anisotropic) reservoir systems.[48−50] New well logging tools designed to make directionally oriented acoustic and propagation resistivity log measurements provide the data needed to analyze the acoustic and electrical anisotropic properties of highly interbedded and fracture-dominated methane-hydrate reservoirs.

Advancements in nuclear magnetic resonance (NMR) logging and wireline formation testing have also allowed for the characterization of methane hydrate at the pore scale. Integrated NMR and formation testing studies from northern Canada and Alaska have yielded valuable insight into how methane hydrates are physically distributed in sediments and the occurrence and nature of pore fluids (i.e., free water along with clay- and capillary-bound water) in methane hydrate-bearing reservoirs.[47] Information on the distribution of methane hydrate at the pore scale has provided invaluable insight on the mechanisms controlling the formation and occurrence of methane hydrate in nature along with data on methane hydrate reservoir properties (i.e., porosities and permeabilities) needed to accurately predict gas production rates for various methane hydrate production schemes.

It is necessary to continue to develop and widely implement existing advanced field characterization tools to obtain reliable and accurate field data on hydrate-bearing reservoirs during predrilling, drilling, and postdrilling phases and production programs. In particular, NMR and wireline formation testing tool deployments are needed for detailed reservoir characterization.[47] In addition, downhole tools such as cone penetrometers and in situ formation pressure and temperature measurement devices need to be included in future drilling expeditions to address the outstanding methane hydrate related science challenges.

3C. Methane Hydrate Reservoir Modeling. Multiscale models (pore-scale and reservoir-scale) development and validation are needed to provide reliable assessment of the methane hydrate resource potential, gas production rates, and geomechanical/environmental impacts of methane hydrate systems during production. Hydrate reservoir models that have been developed include TOUGH+HYDRATE/TOUGH, Fx/Hydrate (DOE-LBNL), CMG STARS (Computer Modeling Group), HydrateResSim (DOE-NETL), MH-21 (National Institute of Advanced Industrial Science and Technology, Japan Oil Engineering Company, University of Tokyo), HYDRES, and STOMP-HYD (PNNL, University of Alaska Fairbanks). These reservoir model prediction tools have been applied in numerous resource studies to estimate gas production rates and reservoir response to depressurization, thermal stimulation, and chemical injections.[18,51,52]

Simulating methane hydrate production requires solving a complex combination of coupled heat, mass, and fluid-transport equations, together with assessment of the formation and dissociation of multiple solid phases in the reservoir. The available simulation models use different approaches to solve the problems, which can lead to discrepancies between some of the models. Reservoir simulators are being further developed to assess gas recoverability from hydrate-bearing sediments in oceanic and Arctic environments using different production methods and the geomechanical properties of hydrate-bearing reservoir systems. To ensure the model predictions are accurate and reliable, it is important to incorporate the correct physics into the models, including accurate pore-scale, thermodynamic, and transport information. The correct physics can only be obtained by acquiring more laboratory and field characterization data sets and by conducting more production tests.

Critical to the assessment of methane hydrate occurrence, stability, and the resource production potential of methane hydrate accumulations is the accurate determination of the methane hydrate stability conditions. The thermodynamic phase equilibria stability conditions for pure methane hydrate are well-established for a wide range of moderate pressure and temperature conditions.[53] However, the thermodynamic stability data and models are less established for methane hydrate-bearing sediment systems, where the sediment system and pore-water chemistry can have a significant impact on the phase equilibria properties. When the pore-size distribution of the sediment system is above around 55 nm, the methane hydrate phase equilibria curves are indistinguishable from that of bulk methane hydrate, without the presence of the porous media.[54] Conversely, smaller sediment pore-size distributions can result in a significant increase in the dissociation pressure of methane hydrate at a given temperature. For example, methane hydrate dissociation pressures in 7 nm pores (of silica gel) were decreased by 20% to 100% compared to the corresponding dissociation pressures for bulk methane hydrate.[55] Similarly, as the pore-water chemistry increases in complexity by containing different salt ions, there will be a significant impact on the methane hydrate stability conditions, with data and models for higher concentrations and more complex salt systems being less reliable.

3D. Methane Hydrate Drill Site Review and Characterization. In recent years, there have been important advances in the approaches and data used in predrilling site surveys. For example, building on the results of Gulf of Mexico Joint Industry Project (JIP) Leg I, a key objective of JIP Leg II drilling program was to address the hypotheses that methane hydrate occurs in sand reservoirs within the deepwater Gulf of Mexico and that specific methane hydrate-in-sand accumulations can be identified and characterized prior to drilling through an integrated geophysical-geological prospecting approach.[8]

The site selection review process for JIP Leg II consisted of simultaneously integrating advanced seismic inversion results with the geological−geophysical analyses to evaluate the presence of gas sources and sand-rich lithofacies linked by migration pathways. JIP Leg II was launched with a total of 20 drill locations permitted within the Gulf of Mexico.[8] Ultimately, the downhole logging data acquired during JIP Leg II confirmed reservoir-quality sands within the methane hydrate stability zone in all seven wells drilled during the expedition, with methane hydrate occurrences closely matching predrill predictions in six of the wells. For most drilling projects, however, not all of the data needed for a comprehensive predrill site survey are readily available.

4. CONCLUSION

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

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

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