FROZEN HEAT

A GLOBAL OUTLOOK ON METHANE GAS HYDRATES

VOLUME TWO

UNEP

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GUEST EDITORS

Scott Dallimore and **Ray Boswell**

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FOREWORD

Growing energy demands, uncertainty about supplies, and the urgent need to reduce emissions of greenhouse gases mean that the world faces an uncertain energy future. Many countries have begun to explore alternative energy sources, including so-called unconventional fossil fuels such as natural gas hydrates.

Gas hydrates generally occur in relatively inaccessible polar and marine environments, which is why they have not been extensively studied until recently. Research about naturally occurring gas hydrates has increased markedly over the past two decades, however, and understanding about where hydrates occur and how they might be exploited is growing rapidly. Japan has recently tested offshore production of natural gas from a hydrate reservoir located more than 1,300 metres below the sea's surface and other countries are also actively exploring production potentials.

Continuing a tradition of identifying emerging issues, the Global Outlook on Methane Gas Hydrates is the result of a rigorous assessment process designed to ensure the availability of scientifically credible and policy-relevant information. This assessment format brings together diverse strands of knowledge and is a key mechanism through which science informs decision-making.

This report provides a basis for understanding how gas hydrates occur and the emerging science and knowledge as to their potential environmental, economic, and social consequences of their use. The intention of this publication is to enable sound policy discourse and choices that take into account a number of important perspectives.

Achim Steiner

Achim Steiner
UN Under-Secretary General
and Executive Director of UNEP

PREFACE

This is the second volume of Frozen Heat: A global outlook on methane gas hydrates, a two-volume examination of the nature and energy potential of gas hydrates. UNEP's purpose in preparing this report is to inform the global discussion about this potential resource by compiling a comprehensive summary of current issues in global gas hydrate research and development. The first volume of Frozen Heat covered the science of gas hydrates and their role in natural systems. This volume examines the potential impact of gas hydrates as a possible new and global energy resource.

Figure 1.1: Natural gas infrastructure in northern Russia. (Courtesy of Lawrence Hislop, GRID-Arendal)

Figure 1.2: Japan, Canada, China, S. Korea, India, the U.S., Germany, Norway and other nations have made significant scientific and technical advances with respect to gas hydrates. (Photo left courtesy of JOGMEC: Photo of operations of the Drill Ship Chikyu in the Nankai Trough, 2013; Photo right courtesy of KIGAM: Scientific party with hydrate recovered from UBGH01 (Ulleng Basin Gas Hydrate 01) Expedition in Ulleung Basin, East sea, Korea, 2007).

Methane gas hydrates – the most common kind of gas hydrate – are solid, ice-like combinations of methane and water that are stable under conditions of relatively high pressure and low temperature. Found mainly in relatively harsh and remote polar and marine environments, gas hydrates occur most commonly beneath terrestrial permafrost and in marine sediments along or near continental margins. Naturally occurring gas hydrates contain most of the world's methane and account for roughly a third of the world's mobile organic carbon.

Gas hydrates were not studied extensively until fairly recently. In the 1930s, they were recognized as an industrial hazard that can form blockages in oil and gas pipelines. In the late 1970s and early 1980s, a series of deep-ocean scientific drilling expeditions confirmed their existence in nature and revealed their abundance. Growing energy demands and climate concerns have focused the attention of both industry and national governments on the potentially immense quantity of methane – a relatively clean-burning fuel – locked in natural gas hydrates.

The result has been significantly increased research into gas hydrates over the past two decades. Several countries have developed national gas hydrate research programs, and the pace of scientific discovery about the nature and extent of gas hydrate deposits is accelerating. Industry is beginning to invest in understanding the hazards that naturally occurring gas hydrates pose to deep-water and Arctic energy development. Academia is making significant progress in understanding the basic physics and chemistry of gas hydrates, their impact on the physical properties of sediments, and the role of gas hydrates in global environmental processes. However, the primary driver for much of the current interest is the potential contribution to energy security that gas hydrates offer to a world with steadily increasing energy demands and uncertain future energy supplies.

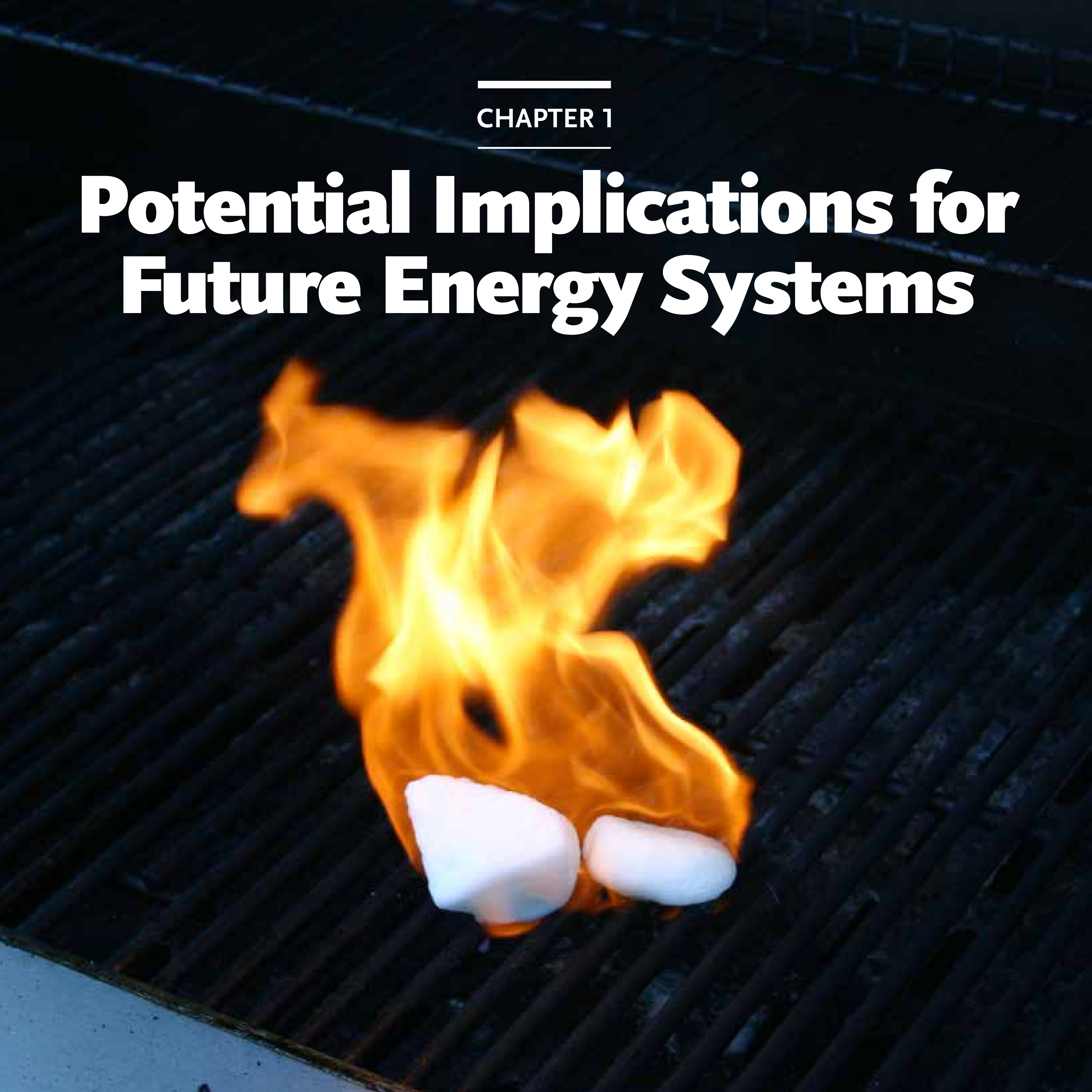
This volume of Frozen Heat examines the current state of knowledge about the distribution and availability of gas hydrates, the status of recovery technology, the potential environmental impacts of gas hydrate development, and the potential role of methane from gas hydrates in a future energy system, particularly as part of the necessary transition to low-carbon and, ultimately, no-carbon energy sources. It also looks at the role gas hydrates might play in future economic development worldwide – especially in the development of greener, more sustainable and environmentally friendly economies.

The central message in Volume 2 is that gas hydrates could potentially represent a large global energy resource. Even if no more than a small subset of the global resource is accessible through existing technologies, that portion still represents a very large quantity of natural gas. Moreover, the accessible subset could occur in places where conventional hydrocarbon production is already planned and/or underway and in areas with strong societal motivations for developing domestic energy resources. However, the commercial viability and environmental impacts of gas hydrate development are still very poorly known. Substantial additional basic science, engineering, and technology development will be needed to enable well-informed decisions.

Although commercial production of methane from gas hydrates is still in the future, that future is moving closer. Ultimately, a combination of technological advances and favourable global/regional market conditions will likely make gas hydrate production economically viable, at least in some regions or for some deposits. This volume attempts to pull together the information people will need to evaluate future energy resource options and the role gas hydrates might play in those options.

CHAPTER 1

Potential Implications for Future Energy Systems



1.1 INTRODUCTION

Energy is essential to achieving the economic, social, and environmental goals of sustainable human development. The combination of services that acquires energy and delivers it where it is needed to serve those goals is called an energy system. That system consists of an energy supply sector and commercial, industrial, or household end-use technologies (WEA 2000). The global energy system is currently facing a number of challenges. Some are related to increasing consumption levels, limited access, and energy security, while others are environmental concerns, such as climate change and pollution of air and water resources (surface and groundwater).

Gas hydrates, ice-like combinations of water and natural gases (most commonly methane), are a hitherto untapped energy resource. Recent scientific drilling and evaluation programs suggest that gas hydrates occur in abundance, primarily in marine settings, with about 1% of the global gas hydrate distribution occurring in permafrost environments. (See Volume 1 Chapter 1 of this report for a detailed discussion.) Global resources of methane in gas hydrates are enormous. In fact, some estimates suggest that the amount of hydrocarbons bound in the form of gas hydrates may rival the total energy resources contained in other conventional hydrocarbon sources such as coal, natural gas, and oil. Given the advances in scientific knowledge about gas hydrates over the past few decades, as well as continuing innovation in oil and gas recovery techniques, it is likely that large-scale production of natural gas from gas hydrates will become viable in the next several decades. This could have profound implications for the future global energy system.

Energy resources are sometimes measured in joules, an expression of the amount of energy contained in the resource. In terms of electrical generation, one joule produces one watt of power for one second. A decade ago, largely due to lack of field data, estimates of global gas hydrate resources ranged from 0.1 to 300 million exajoules (EJ, with 1 EJ equal to 10^{18}) (Collett and Kuuskraa 1998; Max *et al.* 1997). As an indication of the scale of these resources, annual global energy consumption is currently about 500 EJ. In recent years, as more information has become available, estimates of the global in-place hydrate resources have tended to fall into a narrower range: between 0.1 and 1.1 million EJ, or 3 000 to 30 000 trillion cubic metres (Tcm) (Boswell and Collett 2011). How much of this resource is suitable for practical and affordable recovery, however, remains uncertain.

Chapter 2 of this volume describes the current state of the assessment of gas hydrates from an energy resource perspective. Most of the earlier assessments focused on quantifying in-place resources, with little attention paid to how much methane might ultimately be recoverable. The first efforts to assess the practical resource potential of gas hydrates are now appearing, both at the global scale (Johnson 2011) and as detailed geological assessments of specific, well-characterized regions (Saeki *et al.* 2008; Collett *et al.* 2008; Frye 2008; Frye *et al.* 2011). While these findings are clearly preliminary and await confirmation from industrial production tests, they are supported by the findings of initial scientific field-testing programs (Yamamoto *et al.* 2011; Dallimore *et al.* 2012). The results are consistent with the potential for substantial, widespread, recoverable gas resources in gas hydrates.

Given the enormous potential methane resource contained in gas hydrates, the lack of any clear technical hurdles (Paull *et al.* 2010; Moridis *et al.* 2009), and the need for secure energy in many parts of the world, it is plausible that economically attractive extraction methods will eventually be developed. Preliminary evaluations of gas hydrate potential in the World Energy Assessment report (WEA 2000) and by the International Panel on Climate Change (IPCC) (Nakicenovic and Swart 2000) suggested that gas hydrate resources, as part of an expansion in unconventional gas resources, could support a tripling of gas usage globally through 2040. More recently, gas hydrate potential has been considered within the Global Energy Assessment (GEA) (Johnson 2011; GEA 2012). However, gas hydrates have generally been excluded from consideration in global energy system projections, such as those conducted by the International Energy Agency (IEA) and, in particular, those with medium-term time frames (IEA 2011a).

This chapter explores the range of environmental and economic issues likely to be raised with growing awareness of the potential of gas hydrates as a significant new source of natural gas. We reference, in particular, the general findings of the IEA's 2011 World Energy Outlook Special Report Are We Entering a Golden Age of Gas? (IEA 2011b), which amends prior IEA energy outlooks in light of the recent expansion in unconventional gas production. Another important source is the 2012 Global Energy Assessment report (GEA 2012), which sheds light on the question of how future energy systems can address multiple challenges and sustainability goals (Riahi *et al*. 2012). While the latter assessment assumes that gas hydrates are unlikely to have any significant impact over the 2015-2035 time frame, it outlines the major issues and opportunities raised by an expansion in natural gas availability. Finally, we discuss a number of points for policy-makers to consider in relation to gas hydrates and how they might help ease the transition to the sustainable energy systems of the future.

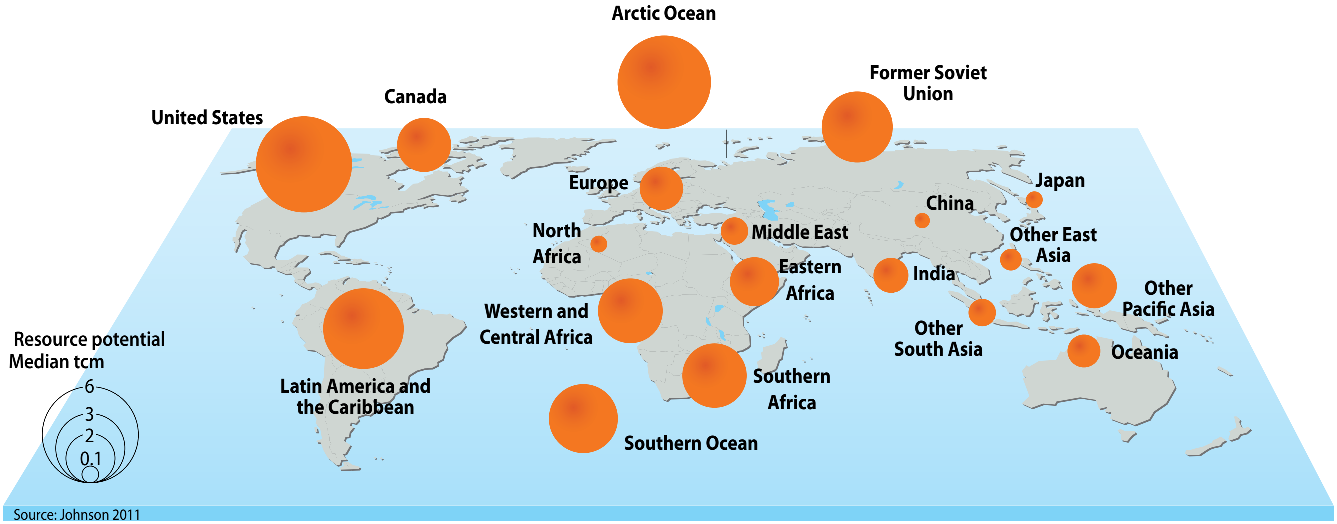
This chapter introduces global energy resources, the evolution of the energy system, and the potential implications of gas hydrate development. Section 1.2 provides the latest assessments of energy resources. Section 1.3 outlines the historic evolution of the global energy system. Section 1.4 presents global energy system projections with a focus on natural gas. Finally, Section 1.5 discusses the implications of developing gas hydrates.

1.2 GLOBAL ENERGY RESOURCES AND GAS HYDRATES

Resource occurrences and potential for recovery are not amenable to an easy or simple quantification. Energy resource assessments typically include at least three interrelated components: geological knowledge, economics, and technology. Increases in geological knowledge and improvements in technology, motivated largely by increasing prices, have contributed to an increase in the fossil energy resource base. The additional resources include new fields discovered within already-established resource elements, as well as entirely new resource elements (such as ultra-deep-water hydrocarbon resources and a variety of unconventional resources) that were previously unknown or considered non-recoverable.

A number of terms related to resources and reserves have specific meaning in connection with hydrocarbons. The total volume of a resource, often called the in-place resource, includes all hydrocarbons present within a given geologic unit or geographic area. The subset of in-place resources that is practically producible is often called the technically recoverable resource (TRR). Those technically recoverable resources that can be produced at a profit are economically recoverable resources (ERR). Economically recoverable resources that have been confirmed and quantified by hydrocarbon production are called reserves (see Text Box 1.1 for more detail).

Gas hydrates resource potential by global regions



Source: Johnson 2011

Figure 1.1: Gas hydrates resource potential by global regions. This figure includes only that subset of global in-place gas hydrates that appear to occur at high concentrations in sand-rich reservoirs, the most likely candidates for development. Source: Johnson 2011.

Box 1.1 **What is a Resource?**

To understand the resource potential of gas hydrate, it is important to distinguish among the various sub-categories of resource in common usage in the energy industry.

- **In-place resource:** The total volume of a resource present. An estimate of in-place resource attempts to account for the entire amount of hydrocarbons (in the case of gas hydrates, almost exclusively methane) present within a given geologic unit or geographic area, without consideration of their recovery potential.
- **Recovery factor:** The percentage of the in-place resource that is technically extractable. In the case of conventional oil and gas, the recovery factor can sometimes exceed 80 per cent. However, recovery factors may be very low for many unconventional resources such as shales. As a consequence, estimation of total in-place resources is of limited relevance to the discussion of energy supply potential.
- **Technically recoverable resource (TRR):** That subset of the in-place resource that is practically producible. Although the definition of TRR is not precise, it generally refers to just those accumulations from which recovery is possible at non-trivial rates, given the expected capacity of industry to apply known or evolving technologies over a specific time frame, such as 30 years. Assessments of TRR are, however, only snapshots in time. Technological advances have a long history of providing access to resources that were previously considered unobtainable (see Volume 2 Chapter 2).
- **Economically recoverable resource (ERR):** That subset of the TRR that can be produced at a profit. ERR describes only those volumes that are economically viable under prevailing regulatory and market conditions, including the costs of recovering and delivering the gas and its market value. Key to assessing ERR are data on how wells will produce, both in terms of total volumes and in the time profile of production rate. At present, little of this information is available for gas hydrates, and economic evaluations conducted thus far are highly speculative (Masuda *et al.* 2010; Walsh *et al.* 2009). Equally important to understanding ERR are regional markets and societal and national drivers for gas production, which vary substantially around the globe. Resources that are not ERR in one region may be viable somewhere else.
- **Reserve:** A gas volume that has been confirmed by drilling and is available for production from existing wells or through development drilling projects. At present, as the long-term production potential of gas hydrates has not yet been demonstrated, there are no documented gas hydrate reserves anywhere in the world.

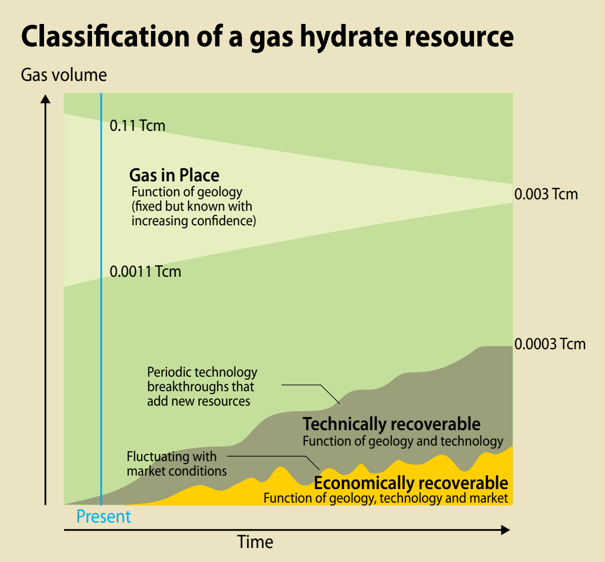


Figure TB-1.1: Example of the classification of a gas hydrate resource. Estimates of the total resource of gas associated with gas hydrates currently range over several orders of magnitude, but this volume is likely to become better known with time. More significant in assessing gas hydrate resource potential, however, are the volumes that are technically recoverable (green) and economically recoverable (orange). At present, these volumes are low due to the limited field demonstration of production technologies, but will likely grow. (Figure modified from Boswell and Collett 2011).

Table 1.1: Global Energy Consumption, 1860–2009, Fossil Fuel Reserves and Resources, and Renewable Energy Potential

	Consumption				**Reserves**	**Resources**
	1860–2009 (cumulative)		**2009**			
	EJ	**GtC**	**EJ**	**GtC**	**EJ**	**EJ**
	Oil					
Conventional	6 580	131	170	3.3	4 000–7 600	4 200–6 200
Unconventional	NA	NA	NA	NA	3 800–5 600	11 300–14 900
	Natural gas					
Conventional	3 450	50	110	1.5	5 000–7 100	7 200–8 900
Unconventional	NA	NA	NA	NA	20 100–67 100	40 200–122 000
	Coal					
All	7 210	183	140	3.7	17 300–21 000	291 000–435 000
	All fossil fuels					
Total occurrences	17 200	355	420	8.5	50 000–108 400	354 000–587 000
	Renewable Energy Sources					
	Deployment potential in 2050 (EJ/year)				**Technical potential (EJ/year)**	
Bioenergy	145–170				160–270	
Hydro	18.7–2.8				5–6	
Wind	170–344				1 250–2 250	
Solar	1 650–1 741				62 000–280 000	
Geothermal	23				8 100–1 400	

Sources: GEA(2012), WEC(1998), IEA (2012)

Top: Energy consumption versus reserves and estimated resources of oil, natural gas, and coal. Consumption is given in ZJ (zettajoules; 1 ZJ = 1000 exajoules, EJ) and GtC (gigatonnes of carbon released to the atmosphere). Conventional sources of oil and gas are those exploited to date. Unconventional are potential sources not currently exploited.

Bottom: Potential energy from renewable sources with current technology, including approximations of the degree to which each might feasibly be implemented by 2050.

Note: Numbers shown as ranges indicate the lowest and highest published estimates.

A major consideration in estimating oil and gas resources is the difference between conventional and unconventional hydrocarbons. The term unconventional lacks a standard definition, but it generally refers to resources that require stimulation treatments or special recovery processes and technologies in order to economically produce oil and gas. Each unconventional type (e.g., oil shale, tar sands, coal bed methane, and gas hydrates) requires unique strategies, such as fracture stimulation in the case of shale oil and gas. Each also presents individual environmental challenges. The recoverability of unconventional resources depends greatly on technological development. Combined with variations in demand and price, this means that the line between economically recoverable and uneconomical unconventional resources is constantly shifting.

Estimates of gas reserves and resources are revised continuously as information, technology, and economics change. Many parts of the world currently lack the infrastructure for distribution or are too remote to make natural gas extraction economically viable at present. Because of this, exploration has often been limited in certain parts of the world. There still remains, however, potential for discovery of new resources in these areas.

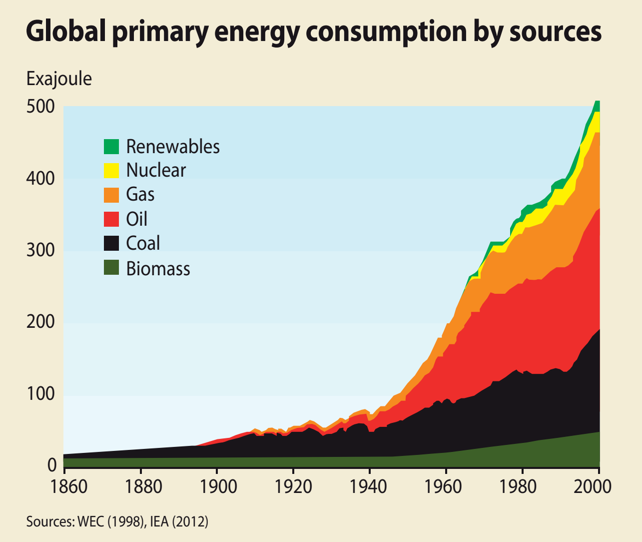
A large amount of the gas currently identified as unconventional or not economically recoverable would need to be transferred into the reserves category to meet predicted future demand. The GEA (2012) estimates conventional gas reserves at 130 to 190 Tcm, or 5000 to 7000 EJ. According to the GEA, unconventional gas types include coal bed methane, tight formation gas, and gas hydrates. The total global reserves and resources of this category are estimated to be in the range of 1600 to 5040 Tcm or 60 000 to 189 000 EJ. This represents, potentially, one of the largest reserves of all fossil fuels, exceeding even known coal reserves.

Reviews of the literature indicate very substantial global gas hydrate occurrences. For example, WEA (2000) estimates the global in-place resource potential for gas hydrates at 350 000 EJ (9 400 Tcm). Moreover, gas hydrates appear to be widely distributed around the world in many marine and permafrost environments. This makes them very attractive to countries that are not naturally endowed with conventional domestic energy resources, as well as to the world's largest and most-rapidly growing economies. Figure 1.1 shows the resource potential of gas hydrates by global region.

1.3 EVOLUTION OF THE GLOBAL ENERGY SYSTEM

For most of modern history, the energy system has been central to economic development and social progress. In addition, the energy system is now recognized as an important part of humanity's impact on the global environment. It is also critical to achieving major societal objectives, such as sustainable economic development.

Energy demand has been growing rapidly in many parts of the world. Figure 1.2 shows global annual primary energy consumption by source since 1860, and Figure 1.3 shows the relative shares of each source in total primary energy. With the emergence of the coal age and steam power, the global energy system changed from a reliance on traditional energy sources, such as firewood, to fossil energy. Annual global energy demand has grown from around 19.4 EJ in 1860 (WEC 1998) to 515 EJ in 2009 (IEA 2012), an increase of about 2.2 per cent per year. The composition of the global fuel mix has become much more diverse over time. However, the consumption of oil, coal, and biomass continues to grow in absolute terms – despite experiencing a declining share in the total energy mix – due to the energy needs of an increasing population and a growing global economy.



Sources: WEC (1998), IEA (2012)

Figure 1.2: Global primary energy consumption by sources: 1860-2009. Sources: WEC (1998), IEA (2012).

The evolution of the energy system is a slow process. The introduction and market deployment of new and advanced energy technologies take a long time. Figure 1.3 shows that competition among the six sources of primary energy is a dynamic substitution process. Any new resource, regardless of its attractiveness, might require 30 to 50 years to replace 80 per cent of energy capital stock. For example, it took about half a century for crude oil to replace coal as the dominant global energy source. Energy conversion changed fundamentally with each new technology: internal combustion, electricity generation, steam and gas turbines, and chemical and thermal energy conversion. At the global level, the time constant for fundamental energy transitions has been about 50 years.

Coal reached its maximum market share of the global energy supply in 1910 to 1920, and it maintained a dominant position until 1965 (WEF, 2013). Oil fields were initially developed in the late 19th century, but it was not until 1960 to 1965 that oil began to take the lead in the global primary energy mix (WEF, 2013). Since 1965, oil has dominated the mix, as the automotive, petrochemical, and other industries have matured. Growth in natural gas consumption has been less rapid, but steady. Gas has doubled its share in the global primary energy mix since the mid-1950s (WEF, 2013).

The shift from a fuel with high carbon content (such as coal) to energy carriers with lower carbon content (such as natural gas), along with the introduction of zero-carbon energy sources, such as hydropower and nuclear, has led to a decline in the carbon intensity of the primary energy supply (Ausubel 1995).

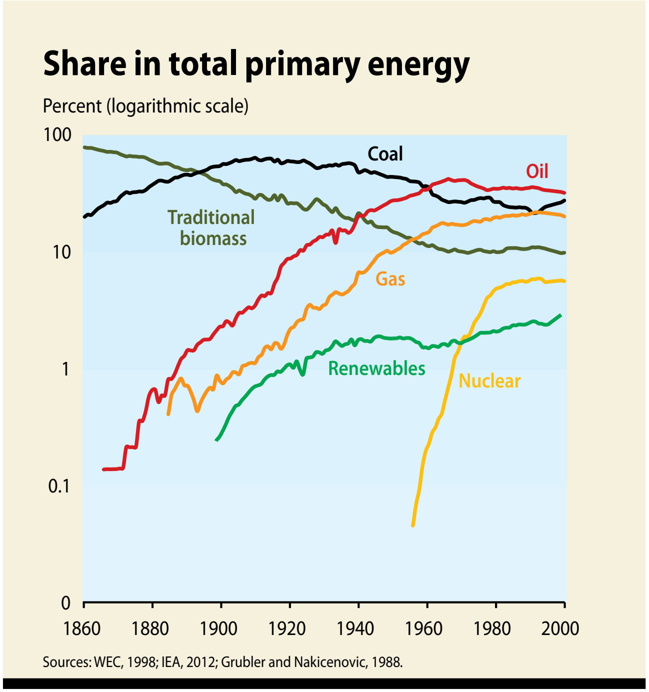


Figure 1.3: Global primary energy substitution 1860-2009, expressed in fractional market shares. Sources: WEC (1998), IEA (2012), Grubler and Nakicenovic (1988).

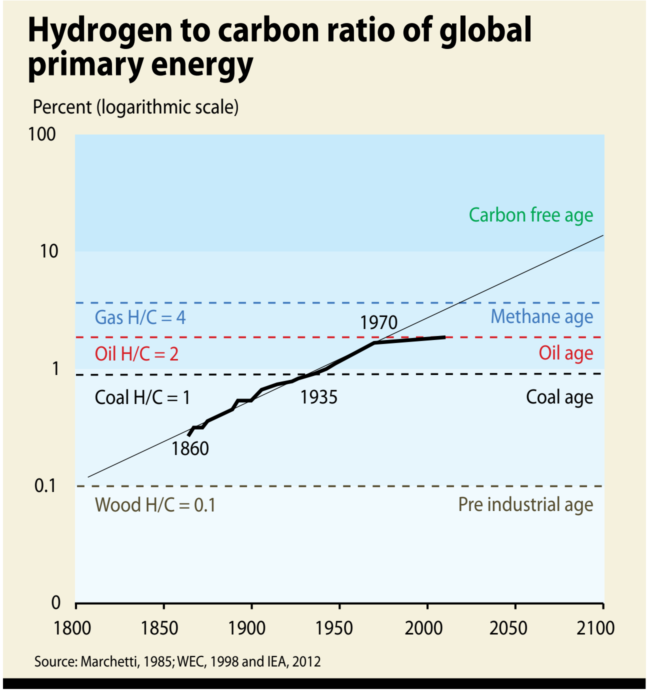


Figure 1.4: Hydrogen to carbon ratio of global primary energy, 1860-2009. The ratio is expressed in fractional shares of hydrogen and carbon in average primary energy consumed. Source: Marchetti (1985), WEC (1998), IEA (2012).

In 1985, Marchetti presented the concept of the hydrogen to carbon ratio (H/C), which can be used as a proxy for environmental quality (Marchetti 1985; Ausubel 1998). Firewood has the highest carbon content and lowest H/C ratio, with about one hydrogen atom per ten carbon atoms. Among fossil energy sources, coal has the lowest H/C ratio at roughly one hydrogen atom to one carbon atom. Oil has, on average, two hydrogen atoms to one carbon atom, and natural gas or methane, four hydrogen atoms to one carbon atom. Figure 1.4 shows the changes in the H/C ratio resulting from global primary energy substitution in the period from 1860 to 2009 and the continuous decarbonization from 1860 to 1970. At this point, the H/C ratio has become approximately constant.

Many energy analysts agree that this trend points to a future increasingly fuelled by natural gas, which could serve as a bridge towards a low- to no-carbon long-term energy outlook (Nakicenovic *et al.*, 2011; MIT 2010). That is consistent with the dynamics of primary energy substitution, as well as with the steadily decreasing carbon intensity of primary energy and the increasing hydrogen to carbon ratio.

As non-fossil energy sources are introduced into the primary energy mix, new energy conversion systems will be required to provide low- to no-carbon energy carriers, in addition to growing shares of electricity. Ideal candidates might be conversion systems with carbon capture and storage technologies. With the implementation of such technologies, the methane economy would lead to a greater role for energy gasses and, over time, hydrogen. An analysis of primary energy substitution and market penetration suggests that natural gas could become the dominant energy source and that the methane economy could provide a bridge toward a carbon-free future (Grubler and Nakicenovic 1988, IPCC 2007).

1.4 ENERGY SCENARIOS AND THE ROLE OF GAS IN SUSTAINABLE DEVELOPMENT

Scenarios are representations of ways the future might unfold. They assist in understanding possible developments in complex systems. Projecting the future of energy production, transportation, and consumption (the energy system) is subject to numerous uncertainties. These uncertainties include – but are not limited to – future energy prices, economic growth, demographic changes, technological advances, and government policies. Energy system scenarios have been developed by many international and national organizations and institutions. These include the International Energy Agency (IEA), the U.S. Energy Information Administration (EIA), the Intergovernmental Panel on Climate Change (IPCC), World Energy Council (WEC), and Energy Modelling Forum (EMF).

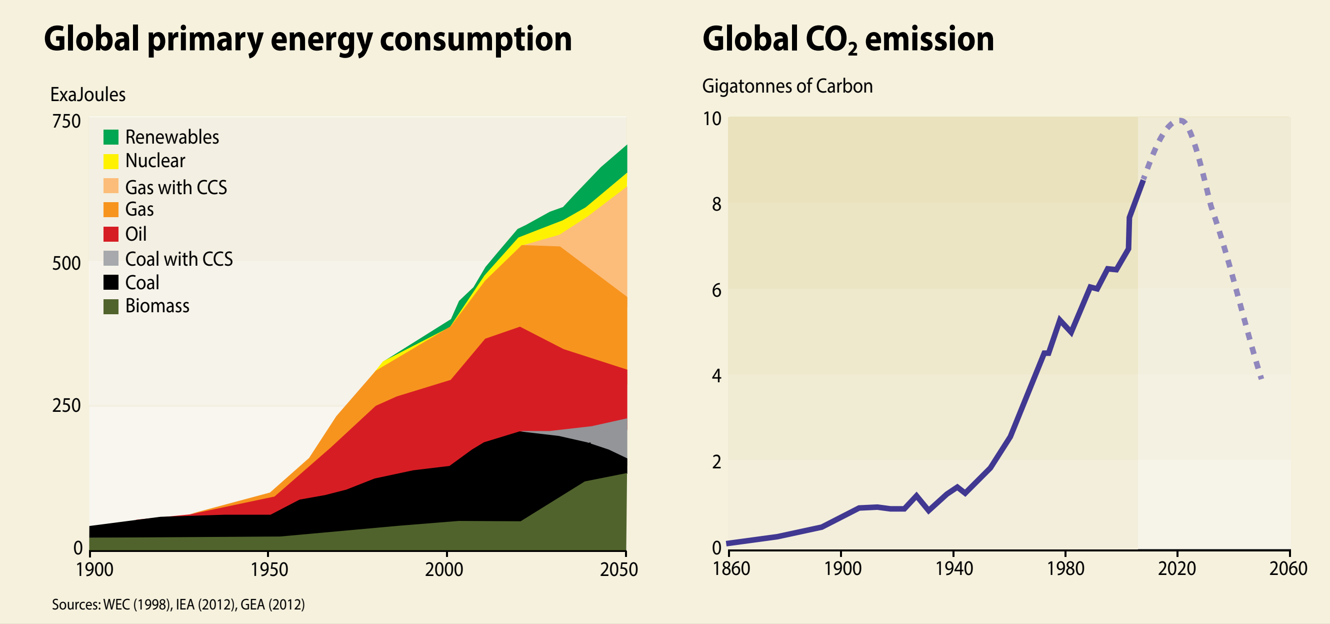
The majority of global energy scenarios predict a substantial increase in global energy demand by 2050. Long-term business-as-usual energy system projections, such as those conducted by the IEA, uniformly predict steady increases in the use of fossil fuels, including natural gas, over the next several decades. For example, the IEA's 2010 Energy Technology Perspectives (ETP) presents a Baseline 2050 scenario that assumes no changes in existing carbon-management policies. This scenario projects that use of all fossil fuels, particularly coal, will increase dramatically to keep pace with future demand (IEA 2010). In contrast, the BLUE Map 2050 scenario, also presented in ETP 2010 (IEA 2010), is designed to depict one possible least-cost path to cutting global carbon dioxide emissions in half by 2050. The BLUE Map 2050 scenario shows that energy demands can still be met with decreases in coal and oil use, unchanging production of natural gas, and expansion of nuclear, renewables, energy efficiency, and carbon capture and storage technologies.

The potential for natural gas to be part of a practical solution to global carbon management has gained greater attention in recent years. The unexpected expansion of unconventional gas commerciality, particularly in North America, has tapped resource volumes previously considered technically and economically unrecoverable. This has increased the potential that global natural gas resources might serve as a bridge fuel to the sustainable energy systems of the future. This new outlook is reflected in the IEA's Golden Age of Gas report (IEA 2011b), which was developed to adjust prior IEA baseline scenarios to reflect rapidly changing perspectives on the global availability of unconventional gas resources. This report indicates that expanded unconventional gas could drive global gas utilization from 3.3 to 5.1 Tcm/y by 2035, eclipsing coal use by 2030 and mitigating expected increases in energy costs. Further expansion and diversification of the energy supply (in terms of both fuel types and geographic sources) are also positive developments with respect to global energy security. From an environmental standpoint, a greater market share of gas at a given level of energy demand generally results in modest decreases in global greenhouse gas emissions associated with energy production and use (IEA 2011b).

The projected greenhouse gas reduction due to expanded gas use derives primarily from the partial displacement of coal or oil use. However, the additional potential displacement by nuclear and renewable energy sources must also be considered. In the IEA gas study (IEA 2011b), this interaction resulted in a net reduction in greenhouse gas emissions, but these reductions alone were not sufficient to achieve the desired total carbon emissions levels (Figure 1.5). Cumulative environmental impacts, which include other land, air, and water impacts beyond greenhouse gases, are much more complex to resolve.

The IEA report explicitly excluded consideration of gas hydrates in its analysis of the period up to 2035, assuming that they were unlikely to have any significant impact within that time frame (IEA 2011b). A recent report by the U.S. National Petroleum Council agreed with this assessment, but said that some portion of the U.S. gas hydrate resource "could be available for development in the long term, beginning in the 2030-2050 period…and with the potential for sustained growth over the remainder of the century" (NPC 2011). It seems reasonable to extend this conclusion as a conservative view of the time frame for gas hydrate production in several other nations, particularly Japan, Korea, China, and India, which are aggressively pursuing gas hydrate research and development.

The recently published Global Energy Assessment report (GEA 2012) explores possible transformational pathways for the future global energy system and includes gas hydrates in


Global primary energy consumption

Global CO_2 emission

Sources: WEC (1998), IEA (2012), GEA (2012)

Figure 1.5: Global primary energy consumption by source. The figure on the left shows historical consumption from 1900 to 2009 and the GEA scenario's projections for the period 2010 to 2050. The figure on the right shows global carbon dioxide emissions, both historical since 1860 and projected. The projections are based on one of three illustrative GEA pathways that were interpreted by two different modelling frameworks: IMAGE and MESSAGE. This figure shows IMAGE modelling results (IMAGE - GEA_med_450). Sources: WEC (1998), IEA (2012), GEA (2012).

its assessment of unconventional resources. Unlike previous energy systems projections, which have mostly focused on either specific topics or single objectives, the GEA report attempts to consider the technological feasibility and economic implications of meeting a range of sustainability goals (Riahi *et al*. 2012). The GEA assessment of different pathways suggests that it is technically possible to achieve improved energy access, air quality, and energy security simultaneously, while avoiding dangerous climate change.

Within each of the groups analysed, one pathway was selected as "illustrative" in order to represent alternative ways to move the energy system toward sustainability. Figure 1.5 shows the primary energy mix and carbon dioxide emissions historically, as well as an illustrative GEA pathway under the assumption of intermediate energy demand. The modelling results show a significant increase in natural gas consumption after 2020, with the share of gas in the primary energy mix reaching almost 50 per cent by 2050. The largest part of gas extraction shown in the figure results from the development of unconventional resources. Figure 1.5 also illustrates the desired carbon dioxide emissions curve, peaking at 10 GtC in 2020 and declining rapidly thereafter.

To achieve this pathway, the rapid and simultaneous growth of many advanced technologies is required. A potentially important technology is carbon capture and storage. Indeed, the sustainability target of limiting global temperature change to less than 2°C over preindustrial levels may only be achievable with very substantive global efforts to advance these technologies. In this pathway, the most attractive option for generating electricity after 2020 is natural gas combined with carbon capture and storage. This option provides cleaner fuel supply chains, lower upstream greenhouse gas emissions, higher conversion efficiencies, and significantly lower capital intensity.

Figure 1.4 also shows the historic H/C ratio and projects the ratio as far as 2050, based on the same GEA scenario as Figure 1.5. The expansion of natural gas use envisaged by this scenario (3 per cent annually) results in continuous improvement of the H/C ratio after 2015. We have chosen 2050 as a reasonable time horizon for discussing the implications of commercial gas hydrate production. As described in Chapter 3, it is generally accepted that technical barriers to gas hydrate extraction can be overcome before or by that date, and that national governments will be in a position to choose whether and how to exploit the resources at their disposal.

Even as the commercial feasibility of gas hydrate extraction is demonstrated, technology alone will not determine the energy future. Economic, social, and environmental considerations, among others, will weigh in the decision. Recent decisions by Germany and Japan to move away from nuclear power as an energy source (see IEA 2011a) are examples. The time horizon of 2050 also provides enough time to consider alternative future pathways for the external factors that could have a major impact on how the gas hydrate option is utilized over the long term.

1.5 IMPLICATIONS OF DEVELOPING GAS HYDRATES

In considering energy for sustainable development, the following factors come into play:

- economic impacts, such as boosting productivity for sustainable economic growth;
- geopolitical considerations, such as energy security;
- environmental impacts, such as air pollution and greenhouse gas emissions; and
- societal impacts, such as improving living standards and enhancing safety and security.

The economic, geopolitical, environmental, and societal impacts of gas hydrate development are introduced briefly below.

1.5.1 ECONOMIC IMPLICATIONS

Understanding the economic impact of gas hydrates involves assessing a wide range of variables. Gas hydrates are a potentially vast source of natural gas. One of the most appealing aspects of this potential new gas source is that large deposits may be distributed widely in marine and permafrost environments around the globe, including in those regions with the greatest expected growth in energy demand. The possible direct market benefits of gas hydrate resources derive fundamentally from the sale of the produced natural gas. Additional natural gas resources could translate not only into new and expanded economic activity, employment, and tax and royalty payments, among other benefits, but also into additional energy availability, mitigation of energy prices, and decreased price volatility.

Gas hydrate research and development is also providing insight into the nature of geohazards relevant to conventional oil and gas drilling (Hadley *et al*. 2008; McConnell *et al*. 2012), with substantial economic impacts on deep-water and Arctic energy development. In addition, given the fundamental nature of much continuing gas hydrate research and development, further efforts aimed at enabling production will generate scientific knowledge about the development and physical/chemical nature of gas-hydrate-bearing sediments. The scientific and, ultimately, economic value of this knowledge could potentially be considerable. For example, gas hydrate research is attempting to evaluate the role of gas hydrates in the environment over various time scales (e.g., Reagan and Moridis, 2008; 2009; Elliott *et al*., 2011). This includes their role in the long-term global carbon cycle (Volume 1 Chapter 2) and in near-term responses and potential feedbacks to climate change (Volume 1 Chapter 3), as well as the risks and implications of various gas-hydrate-related geohazards such as sea-floor instability.

Gas hydrate research is one area where private investment may not be in accord with the potential public benefit. As a consequence, public-sector programs might be desirable in some instances. Other unconventional energy resources, such as coal bed methane and shale gas, have been developed with the aid of government-supported research. Fifteen years ago, coal bed methane was an unknown resource. With focused research, development, and production incentives, coal bed methane now contributes nearly 10 per cent of U.S. natural gas production, and global production is expected to grow from about 105 Bcm in 2011 to about 150 Bcm in 2021 (M&M 2011).

1.5.2 ENERGY SECURITY IMPLICATIONS

The uninterrupted and affordable supply of vital energy services is a high priority for every nation. Energy security involves more than just reliable and affordable energy. It also includes issues of diversification, mitigation of supply disruptions, globalization of the energy chain, and economic stability. The concept of energy security, however, is strongly context-dependent. For most industrialized countries, energy security is related to import dependency. Many emerging economies without sufficient energy resources have additional vulnerabilities, such as inadequate capacity and rapid demand growth. In many low-income countries with similar lack of sufficient energy resources, supply and demand vulnerabilities overlap, making them especially insecure.

Enhanced energy security for regions can be achieved by greater use of domestic energy sources and by increasing the diversity and resilience of energy systems. As an additional primary energy source, gas hydrate development could increase the diversity and domestic share of primary energy in many parts of the world, potentially decreasing import dependency.

Oil ranks ahead of electricity in terms of final energy consumption and remains the world's dominant form of energy supply to the broader economy, making it essential to energy security (IEA 2008; Chang and Liang Lee 2008). Supply concerns for natural gas are mostly regional, due to the limited role of natural gas in global trade. However, the trade in liquefied natural gas increasingly connects natural gas markets globally. The transition toward gas usage in electricity generation could result in greater energy security concerns because of the increased dependence on imports.

Gas hydrates appear to be widely distributed around the world and are, therefore, very attractive to countries not naturally endowed with conventional domestic energy resources. As gas hydrate resources occur in proximity to many of the world's largest and most rapidly growing economies – such as China, India, Japan, and the United States – they provide opportunities to improve energy security by reducing these countries' reliance on energy imports. Globally, this increased measure of self-sufficiency can have a mitigating effect on potential future discord resulting from competition for access to external energy sources.

1.5.3 ENVIRONMENTAL IMPACT

Methane is a powerful greenhouse gas. Natural gas extraction and gathering activities lead directly to methane emissions through leakages during drilling, completion and stimulation activities. in transportation pipelines and other infrastructure. The scale of these impacts in unconventional gas extraction is not well known, nor is it clear whether gas hydrate production will have similar effects. Monitoring and assessment of such potential emissions, therefore, have been identified as key priorities of initial gas hydrate field evaluation programs (Arata *et al.* 2011). Further, gas transmission and distribution introduce significant potential fugitive methane emissions, and these issues would be no different regardless of the whether the gas was derived from conventional or unconventional sources.

When gas-hydrate-derived methane is combusted, it produces carbon dioxide, just as any hydrocarbon would. It will, therefore, contribute to carbon emissions. However, the amount of carbon dioxide per unit of energy released that is produced during combustion of methane is as much as 40 per cent lower than that produced by coal or about 20 per cent lower than oil. Due to this efficiency, any net displacement of higher greenhouse gas emitting fuels by methane will result in a net mitigation of global greenhouse gas emissions (IEA 2011b). Natural gas gives off fewer pollutants when burned, including less particulate matter, sulphur dioxide, and nitrogen oxides. In addition, it produces no waste products that require management, such as coal ash or nuclear waste. Compared to conventional gas, gas originating from hydrates contains even fewer impurities, such as hydrogen sulphide. This means that, of all natural gas sources, gas hydrates require the least refining to produce consumable natural gas (e.g. Collett et al, 2009).

Although gas hydrate resources may prove to be vast, they are best considered as a potential option to ease the transition to future sustainable energy systems. Ideally, gas hydrate development should not displace the necessary investment in renewable energy technologies that will form the basis of those future systems. If technologies to reduce greenhouse gas emissions associated with expanded gas utilization can be proven, it would be most beneficial to pursue parallel developments in fugitive emission reduction during production and in carbon dioxide mitigation technologies.

Production research and development studies suggest that gas hydrate deposits in both marine and permafrost settings can be produced using techniques and methods already employed by the hydrocarbon industry worldwide (see Volume 2 Chapter 3). It is therefore reasonable to anticipate that the environmental considerations will also be similar. The principal issues are likely to include hazard mitigation, disruption of sensitive ecosystems, and the cumulative impacts of development. Development will likely occur both in areas with established energy production infrastructure, regulatory frameworks, and public acceptance, as well as in areas without these advantages. Careful attention to safety standards and regulation will be critical, as will efforts to minimize any negative societal and environmental impacts of development.

It is noteworthy that gas hydrates are generally located at shallower depths than most currently producing gas reservoirs. In marine setting this shallow depth and the associated lack of consolidation of the host strata mean a heightened potential for seafloor subsidence. As a result, this potential impact is being considered closely in initial field research and development programs (Rutqvist and Moridis, 2009; Arata *et al.* 2011).

Finally, while the rates and economic costs of gas hydrate production can be studied, environmental implications may be harder to estimate. Science has yet to understand fully the socio-ecological impacts of extracting gas hydrates. However, the advantages and consequences of these actions must be understood and considered before moving forward. Assessment of the net social cost or benefit of these consequences must supplement purely economic analyses of gas hydrate feasibility.

1.5.4 SOCIETAL IMPLICATIONS

As science and industry work to find new sources of energy, it is important to understand the societal implications of developing potential resources. The size of the resource, its economic viability, and its environmental impacts all play roles in determining the true value of gas hydrates to society.

The potential positive social impacts of gas hydrate exploitation include improved living standards and enhanced safety and security in both developed and developing countries. In developing countries especially, increased local natural gas exploitation has the potential to improve infrastructure for electrification and all domestic needs. The potential benefits of responsibly-managed gas hydrate operations include increased local employment, the transfer of technical and commercial skills, the development of local capacity, and a share in fiscal revenues at the local level.

1.6 CONSIDERATIONS AND CONCLUSIONS

The future energy system could develop in a number of different directions, depending upon how we prioritize various objectives, including climate change mitigation, energy security, economic development, air and water pollution, and human health. These considerations often compete with each other for the attention of policy-makers. Transforming the global energy system to achieve a sustainable future requires an integrated approach that addresses a diverse set of objectives simultaneously. The transformation is technically possible, but reaching it will require the rapid introduction of coordinated efforts to address global concerns. International technical and scientific cooperation on gas hydrate issues will help inform decision-makers and potentially lead to more effective and sustainable policies in the future.

1.6.1 GAS HYDRATES COULD SUPPORT GLOBAL ENERGY SECURITY

As the cleanest of the fossil fuel options, natural gas could be an important source of energy for any future energy scenario. Gas hydrates are believed to occur in abundance in many settings around the world. If this potential is confirmed, they will become highly valued as local energy resources, particularly for nations with limited conventional domestic energy options. A sound scientific understanding of the implications and environmental consequences of gas hydrate production needs to be developed before there is strong pressure for wide-scale production.

1.6.2 CARBON CAPTURE AND STORAGE IS A VITAL PARTNER TECHNOLOGY

As most long-term business-as-usual energy scenario projections show, the world is currently on a high greenhouse-gas-emissions pathway. Although nations are now making commitments to reduce absolute greenhouse gas emissions or greenhouse gas intensity, it seems likely that atmospheric carbon dioxide will increase to more than 450 parts per million by 2100. Beyond this level, according to the IPCC, dangerous climate change becomes likely. Expanded gas use can somewhat mitigate greenhouse gas emissions through reducing demand for less clean-burning fossil fuels. However, it is possible that, without additional investment in mitigating technologies, disincentives for nuclear and renewable energy could lead to a gas-fuelled future that does not meet greenhouse gas reduction targets.

Carbon capture and storage technology could be a possible partner for the hydrocarbon industry. Research to evaluate production techniques that sequester carbon dioxide while producing methane from gas hydrates is currently under way. Policy-makers will need to consider developments in such technologies when making investment decisions about gas hydrates.

1.6.3 REGULATORY REGIME

For many countries with a history of hydrocarbon development, regulations are well-established, with careful checks and balances to assure safety and environmental protection. For countries without a long history of hydrocarbon development and/or without a strong/efficient regulatory system, it may be desirable to provide international assistance to establish sound regulatory regimes. It is, however, noteworthy that even with well-established regimes, failures like the Exxon Valdez and Deepwater Horizon disasters occur.

In this chapter, we discussed a long-term vision for the energy system and the possible role of gas hydrates in the transition towards this vision. Recent gas hydrate assessments suggest that such transformational pathways to a sustainable future are achievable in technological and economic terms. The latter are dependent on societal choices and carefully considered government policies and industry strategies.

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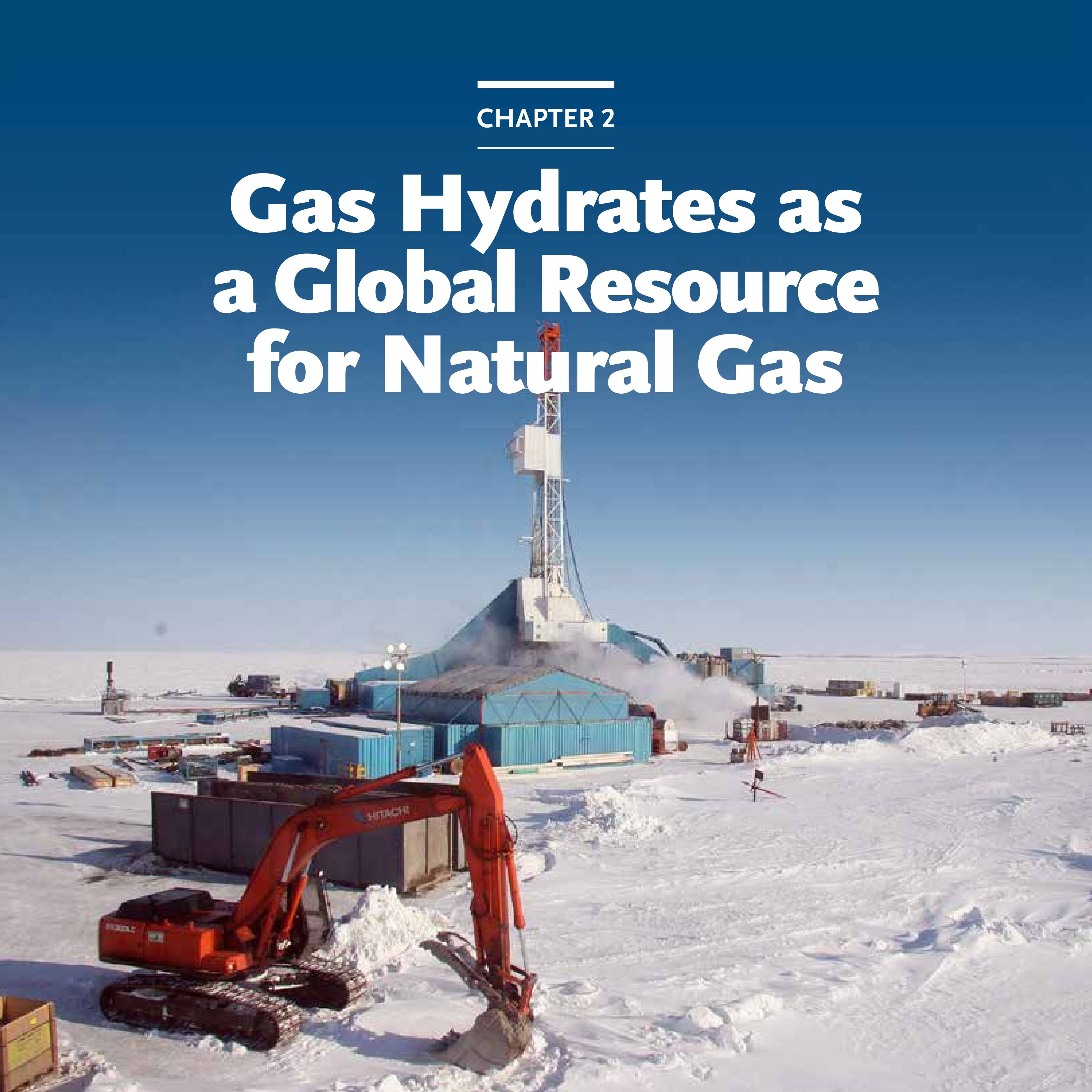
CHAPTER 2

Gas Hydrates as a Global Resource for Natural Gas



2.1 INTRODUCTION

Gas hydrates occur broadly throughout Earth's deep-water continental margins and in areas overlain by thick permafrost (see Volume 1 Chapter 1). They represent a massive natural storehouse of methane gas and hold significant potential as a future energy resource. Though no commercial-scale extraction of methane from gas hydrates has yet occurred, developing the necessary tools and techniques appears plausible given recent advances in hydrocarbon recovery capabilities. For example a number of previously inaccessible hydrocarbon resources are now being tapped – reservoirs 9 000 metres deep and in 2 500 metres of water (Cunha *et al.* 2009) and gas trapped in deep shale formations once thought to be unproduceable.

However, as with any component of the global energy resource base, gas hydrates do not occur in the same manner everywhere. Some deposits, due to the nature of their geologic settings, will be more promising targets than others. A number of highly variable and location-specific factors influence the nature and development potential of gas hydrate reservoirs. These include the local supply of methane gas, the configuration of pathways for gas to migrate and concentrate, the presence and extent of the zone in which pressure-temperature conditions allow gas hydrates to form, the nature and properties of the host sediments and their capacity to hold rich accumulations, and the regional geology that provided the time and conditions for gas hydrates to form and to persist as significant accumulations. Because these factors vary significantly, even at a local scale, gas hydrate occurrences are highly variable (Fig. 2.1). Therefore, while it is likely that Earth contains enormous volumes of methane within gas hydrates, it is also likely that only a small percentage of that gas exists in a manner that makes extraction technically and/or economically feasible, at least in the relatively near future (Text Box 2.1).

This chapter reviews some key issues in understanding the energy supply potential of gas hydrates. We discuss the best-studied sites where gas hydrates have been evaluated, ranging from the most promising sites to the most problematic. Then, in Chapter 3, we discuss the leading means by which these reservoirs might be produced.

General schematic showing typical modes of gas hydrate occurrence relative to the geologic environment

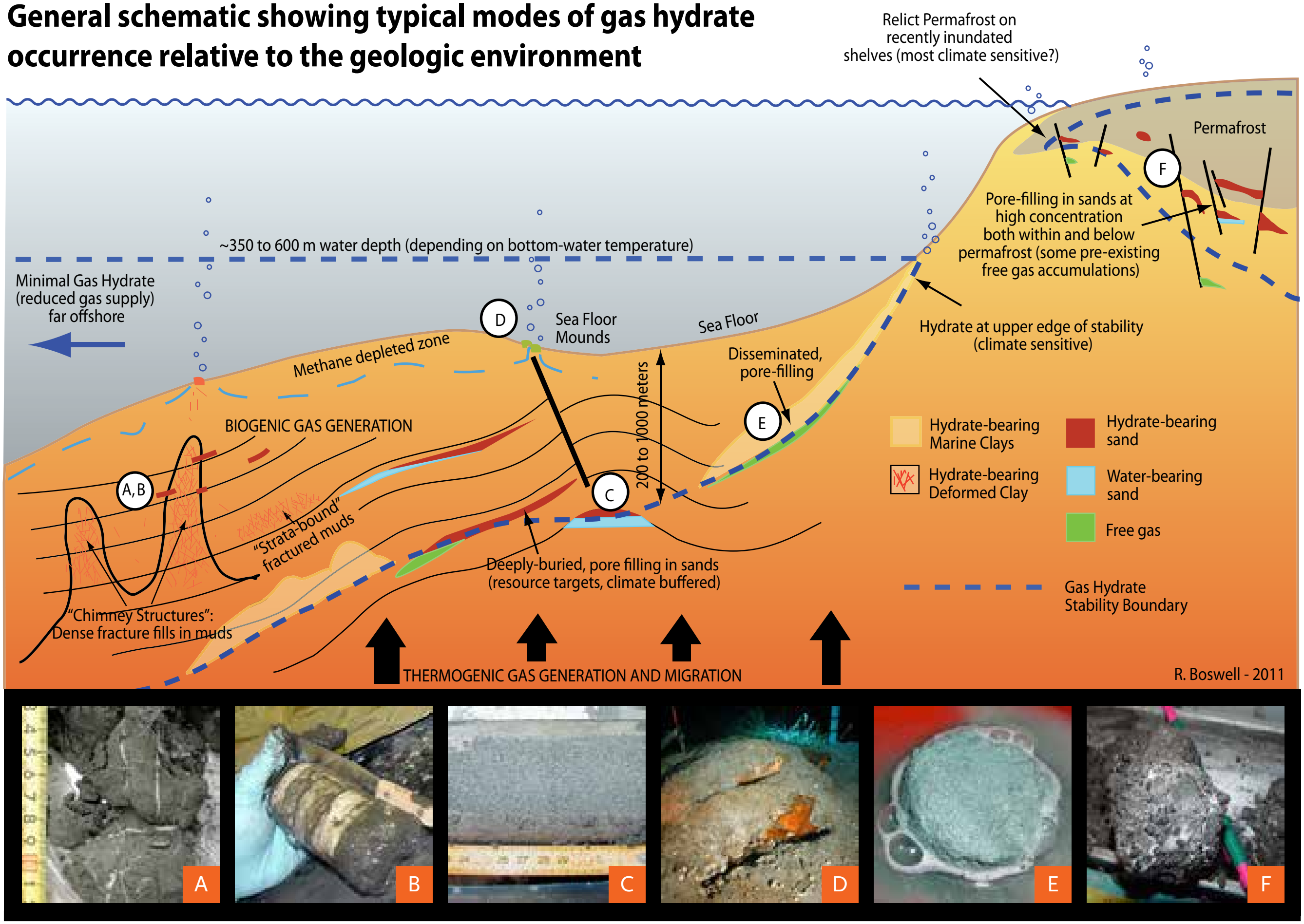


Figure 2.1: General schematic showing typical modes of gas hydrate occurrence relative to the geologic environment. Thin (A) and thickly veined (B) sediment-displacing gas hydrates (white) in fine-grained sediment (grey); (C) pore-filling gas hydrates in sand; (D) gas hydrate mounds on the sea floor (hydrate has an orange coating from oil and is draped with grey sediment); (E) disseminated gas hydrates (white specks) in fine-grained sediment (grey); (F) gas hydrates (white) in coarse sands (grey) (adapted from Boswell 2011).

Box 2.1 **The gas hydrate resource pyramid**

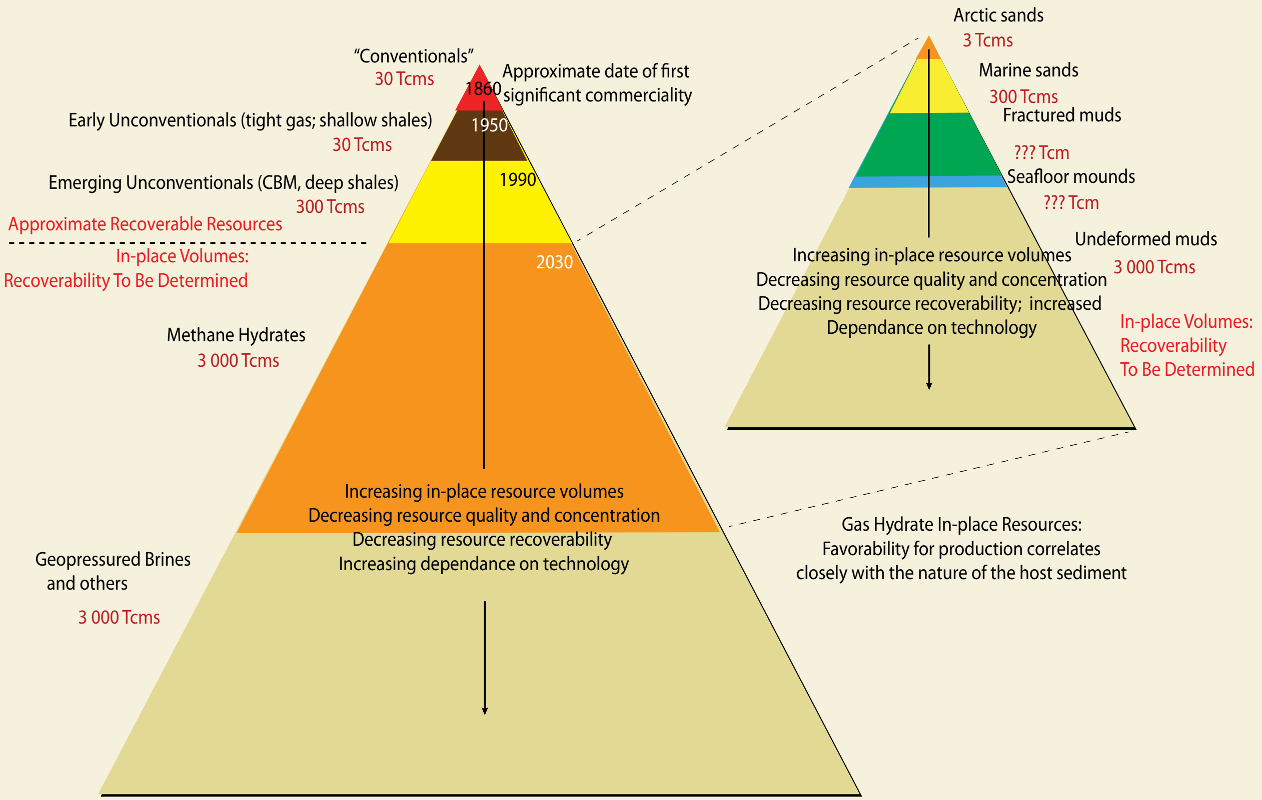
For many years, gas hydrate resources were characterized by extremely large numbers, with perhaps the most commonly-cited value being 700 000 trillion cubic feet (roughly 20 000 trillion cubic metres). While such numbers are meaningful in the context of understanding the role of gas hydrates in carbon cycling and other global processes, they tended to significantly overstate the practical resource potential of gas hydrates by lumping together all manner of gas hydrate occurrences (Boswell and Collett 2011). Earlier attempts to dissect resources of all kinds according to potential productivity revealed a characteristic pyramid shape, with the most favourable elements (at the top) occurring in relatively small volumes, while those resources that pose greater technical challenges (at the bottom) commonly occur in far greater abundance (Masters 1979: Kuuskraa and Schmoker 1998). A pyramid devised for the specific case of gas hydrates (Figure TB2.1.1; after Boswell and Collett 2006) is no different.

As with all resource pyramids, the gas hydrate pyramid only suggests the overall order in which production is expected to occur, with resources at the top of the pyramid likely to be produced before those at the bottom. At present, the global energy industry has worked its way well down the total gas resource pyramid, having focused on shallow onshore deposits at the onset and beginning only recently – after more than a century of exploration – to seriously exploit larger elements at the base, such as shale gas. A similar progression can be expected for gas hydrates. However, the time intervals could well be shorter, given increasingly strong global demand for energy and, in particular, growing use of the relatively carbon-efficient natural gas.

While gas hydrate in-place resources change – and change dramatically – over geologic time (see Volume 1 Chapter 2), it is safe to assume that the in-place gas hydrate resource is, for practical purposes, unchanging over human time scales. However, the ability to work through the resource pyramid means that resource recoverability is time-dependant, and the general nature of technological advance (which can be intermittently evolutionary and revolutionary) suggests that recoverable volumes can change dramatically and quickly. In addition, simply being recoverable does not mean a resource will be utilized. It must also be viable economically, which introduces a range of complex and locally varying economic, political, and societal factors.

Figure TB-2.1: The total in-place natural gas resources represented globally by methane hydrates are enormous, but they occur in a wide range of accumulation types. As with other petroleum resources, the accumulation types most favorable for production are the least abundant, creating a pyramidal resource distribution. A generalized resource pyramid for gas hydrates (right) is shown in relation to resource pyramid for all gas resources (left). Society continues to progress down through the global gas pyramid (left), aided by occasional technological breakthroughs that enable significant access to previously unrecoverable resources. Gas hydrates (right) may experience a similar progression with initial production most likely to occur within marine or Arctic sands. Given the vast scale of hydrate resources, however, potential volumes even at the apex of the hydrate pyramid are significant. Figure after Boswell and Collett, 2006. "The Gas Hydrates Resource Pyramid."

Resource pyramid for gas hydrates



Source: redrawn from Boswell and Collett, 2006

2.2 WHAT ARE THE MOST PROMISING ACCUMULATIONS FOR PRODUCTION?

The criteria that determine the attractiveness of a gas hydrate accumulation for production are similar to those applied in other hydrocarbon-rich basins around the world. An extensive discussion on the subject can be found in Moridis *et al.* (2009). Initial production will likely target large and richly concentrated occurrences that can be produced safely and at rates that make the venture profitable. It is not sufficient that the in-place resource simply be there. There must also be a way to extract the gas that is economically viable, safe, and environmentally responsible.

As discussed in Chapter 3, the cumulative results of work in the field, in the lab, and through application of numerical models – conducted mainly within the past decade – indicate that the richest gas hydrate occurrences discovered to date, as well as those most likely to support economically viable production of methane, are found in sand-rich sediments (Fig. 2.2). Production would proceed through specially-tailored applications of well-drilling technologies used in conventional oil and gas production. While it appears that, globally, most gas hydrates are housed in clays, assessments in the highest-studied areas (the Alaska North Slope, the Gulf of Mexico, and offshore southeastern Japan) show large potential resources in sand-rich deposits (Boswell and Collett, 2011). What makes sand reservoirs attractive is the sediment's high natural permeability, a measure of the ease with which fluid can flow. This permeability is key to enabling gas hydrates to accumulate at high concentrations. Once hydrates form, that permeability is dramatically reduced, but it is still sufficient to allow pressure (and even advection-based thermal) changes to be delivered into a reservoir from a drilled well.

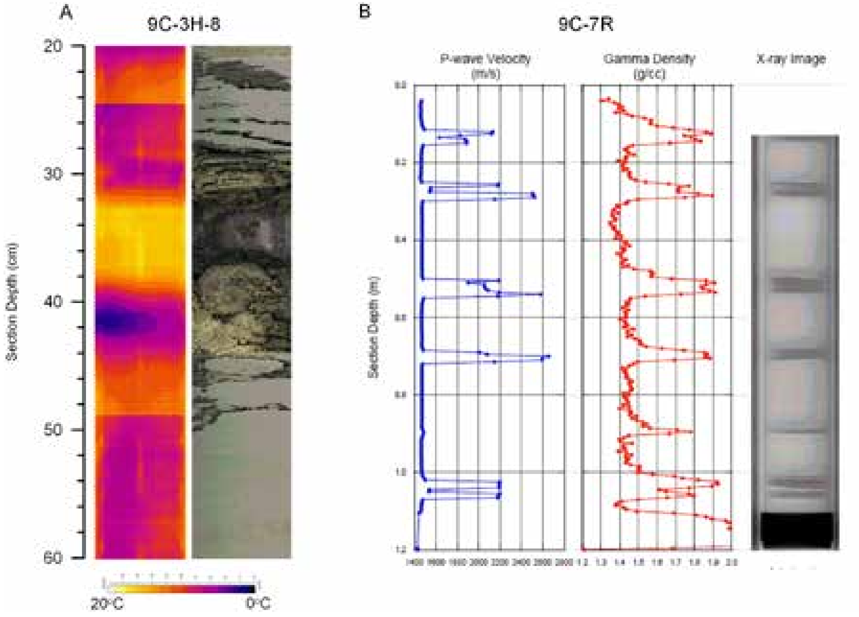
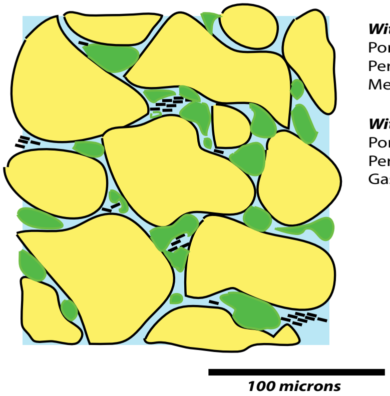


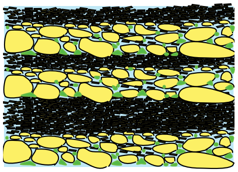
Figure 2.2: Permeability of gas-hydrate host sediments. Right: The most promising gas hydrate occurrences are distinguished primarily by the nature of the enclosing sediment (after Boswell *et al.* 2011). The high initial permeability of sand-rich units enables gas hydrates to accumulate to high saturations. After gas hydrate is emplaced measurable permeability is maintained in the sediments sufficient to enable existing well-based extraction technologies. Left: Gas hydrates limited to thin sand intervals in cores obtained from the Ulleung basin, Korea, in 2010 (from Bahk *et al.* 2011b with permission).

Silt and Sand-rich Host Sediments

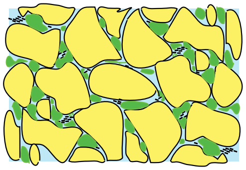


Without Gas Hydrate
Porosity: 30-45%
Permeabilitiy 500-2000 md
Mechanical Strength: Low

With Gas Hydrate
Porosity: 10-15%
Permeability; 0.1 - 0.5 md
Gas Hydrate Saturation: 50-90%



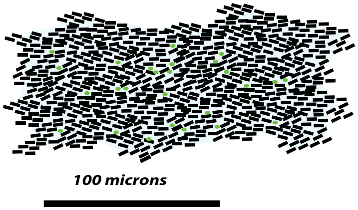
Thinly interbedded
(Nankai Trough; Gulf of Mexico GC955)



Massively-bedded
(Gulf of Mexico WR313; Mallik)

Clay-rich Host Sediments

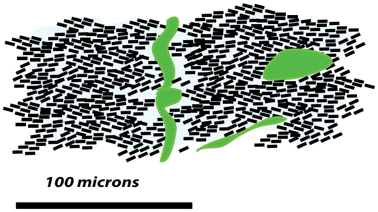
Pore-filling in undisrupted sediments
(Blake Ridge)



Without Gas Hydrate
Porosity: 50-70%
Permeability: Diminishes with Depth to very low values (0.0001 md)
Mechanical Strength: Very Low

With Gas Hydrate
Porosity: 45-60%
Permeability: Nil (0.0001 md)
Gas Hydrate Saturation: 1-10%

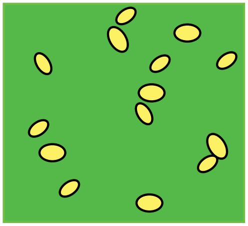
Grain-displacing in disrupted, deformed sediments
(KG Basin, Ulleung Basin)



With Gas Hydrate
Porosity: 45-60%
Permeability: Nil (0.0001 md)
Gas Hydrate Saturation: 5-40%

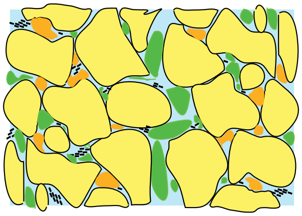
Massive Occurrences (no host sediment)

(Gulf of Mexico, Cascadia, others)



Consolidated host sediments (rock)

(Messoyahki, Barrow (AK), Qilian Mtns (Tibet))



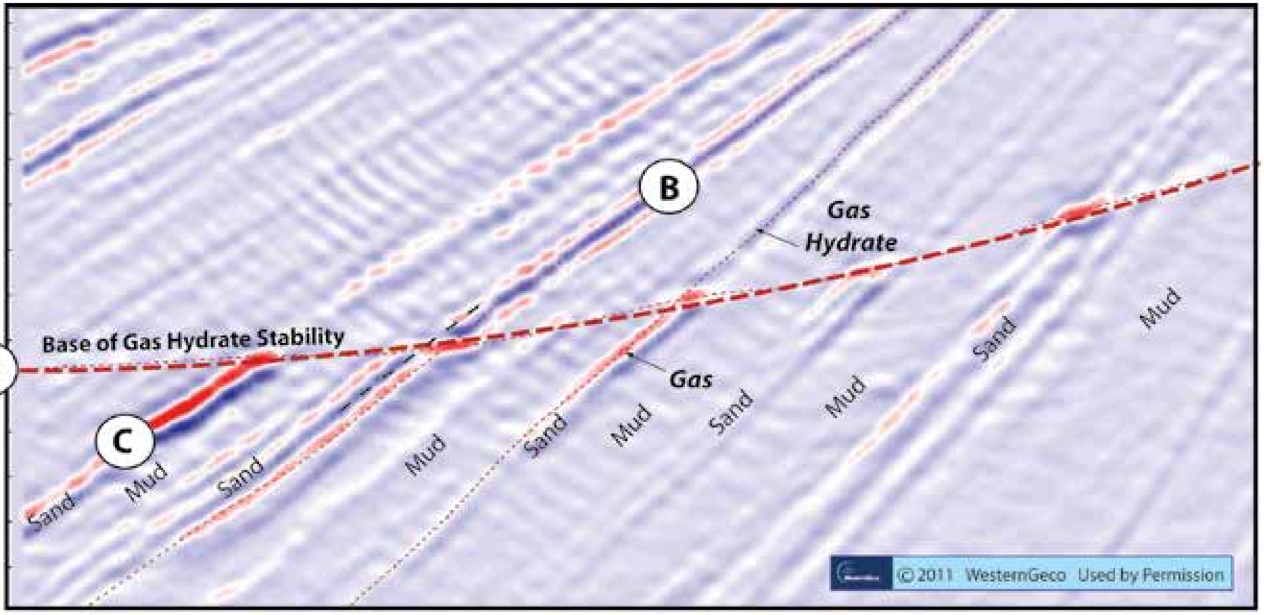
Variety of Lithologies
Porosity: Reduced due to grain compaction, cementation
Permeabilitiy: Reduced 500-2000 md
Mechanical Strength: Very high

2.3 GAS HYDRATE EXPLORATION

As with traditional oil and gas resource development, gas hydrate development will occur through two linked phases: exploration and production. In the exploration phase, various geological and geophysical tools and concepts are applied (Riedel *et al.* 2010c) to search for the most promising deposits and to evaluate the resource potential of the fields. These interpretations are then tested through exploration drilling, with extensive data collection that includes complex geophysical well logging and collection and analysis of core samples (Text Box 2.2). If initial drilling results are positive, delineation wells might be drilled to refine the extent and nature of the accumulation. Numerical reservoir simulation is then used to assess the potential recovery and the nature and potential economics of the full development plan (Moridis *et al.*, 2009; Kurihara *et al.* 2010). Only when it is deemed cost-effective to develop the resources in accordance with required environmental standards will industry move into the production phase. (Promising production technologies are discussed in Volume 2 Chapter 3 of this report.)

Although gas hydrate exploration is still in the research phase, initial results are positive. Progress toward viable exploration approaches has been confirmed in both Arctic (Lee *et al.* 2011) and deep-water (Shelander *et al.* 2010) settings, where pre-drill, geophysics-based predictions were confirmed by later drilling. This approach tailors the petroleum systems concepts that guide traditional hydrocarbon exploration to the issue of gas hydrates (Fig. 2.3; Text Box 2.2). Future gas hydrate exploration will search for locations that combine evidence from seismic surveys and other remote-sensing data with interpretations of the geologic development of the region that suggest the confluence of supplies of gas, reservoir-quality sediments, and gas hydrate stability conditions (Collett *et al.* 2009).

Figure 2.3: Gas hydrate exploration. The method shown here is a tailored variant of the "petroleum systems" approach that guides conventional oil and gas exploration. In this example, a cross-section and map view (insert) from the deep-water setting, geological and geophysical data from previous drilling and remote sensing are used to reduce the uncertainty associated with geophysically-defined prospects (B) by confirming the presence of gas hydrate stability conditions (A), the occurrence of gas sources and pathways (C), and the occurrence of potential reservoirs (D).



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Petroleum Systems Approach:

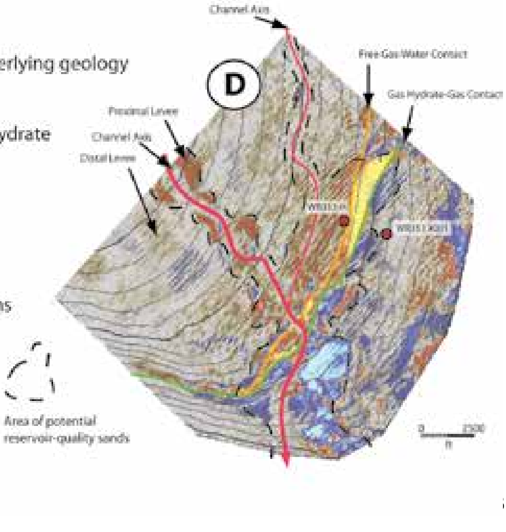
A. interpret extent of gas hydrate stability conditions (pressure-temperature)
Estimate based on water-depth and temperature, gas/water chemistry, and similar data,
Confirm via seismic data, i.e. a pressure-temperature controlled boundary overprints the underlying geology

B. prospect for direct geophysical indications of gas hydrate
These strong events (blue) are generated by anomalously "hard" units, consistent with solid hydrate

C. assess the occurrence/distribution of gas and gas migration pathways
These bright (red) events indicate the presence of gas

D. interpret the geologic history, including the distribution of sand-rich reservoirs
Maps of prospective units show features consistent with sand-rich submarine channel systems

E. estimate gas hydrate content and select drilling locations



Box 2.2 **Gas hydrate evaluation through drilling and coring**

The pace of scientific expeditions designed to investigate the occurrence of gas hydrates continues to accelerate. Such expeditions use specialized drilling vessels staffed by large teams of scientists, engineers, and technicians. The goal is to gather data from the subsurface using well-logging tools, as well as gathering sediment samples and returning them to the ship deck or to onshore labs for analysis (Figure TB2.2).

While the initial field programs focused largely on coring, a more recent strategy involves an initial, dedicated, logging-while-drilling campaign that can test many locations. Gas hydrate logging operations utilize the same tools used in traditional oil and gas evaluation to determine sediment lithology, porosity, and other parameters (Goldberg *et al.* 2010).

Based on logging data, the most intriguing sites can be revisited for more intensive continuous or spot-coring campaigns, application of specialized tools such as borehole temperature and seismic devices, and wireline logging programs (Dallimore and Collett 2004; Collett *et al.* 2011). Standard coring recovers sediment from gas-hydrate-bearing intervals, although the reduction in pressure and increase in temperature that occur as the core sample is retrieved often result in the dissociation of all but the most massive hydrates. Nonetheless, the dissociation of gas hydrates and release of nearly pure water into the original saline pore fluids results in a unique chemical signal called freshening, which can be exploited to infer the presence and concentration of gas hydrates (Kastner *et al.* 1995; Hesse 2003). The dissociation of gas hydrates also results in a cooling of the surrounding sediments due to the endothermic nature of the dissociation reaction. This phenomenon was first used systematically to infer gas hydrate presence in sediment cores during ODP Leg 164 at the Blake Ridge (Paull *et al.* 1996) and has since served as the basis for the development of a technology involving the automated infrared imaging of the recovered core immediately after it arrives on deck (Long *et al.* 2010).

The development of pressure coring – recovery of sediment in devices that maintain pressures near in situ conditions – has greatly increased our ability to characterize and image gas-hydrate-bearing formations. Pressure coring is ideally suited to the problem of gas hydrate sampling, providing the best known means to determine gas hydrate concentrations and showing remarkable detail of the morphology of gas hydrate occurrences (Holland *et al.* 2008). Technologies for acquiring samples and analyzing their physical properties prior to the onset of the substantial disruption caused by gas hydrate dissociation have improved steadily (Schultheiss *et al.* 2010; Yun *et al.* 2006), and are now an increasingly critical aspect of gas hydrate evaluation.

Wireline logging techniques, typically conducted in the same hole from which cores were recovered, are identical in principle to the logging-while-drilling approach. Better vertical resolution can usually be achieved, but deploying tools on a wireline is operationally more complex than tool deployment on the drill pipe. Steady improvement in logging-while-drilling tools continues to reduce the need for wireline operations. One data set that is currently best acquired through wireline logging and that has effective application to gas hydrate studies is the nuclear-magnetic resonance (NMR) tool (Kleinberg *et al.* 2005). At present, NMR provides the best available information on both sediment permeability and the distribution of various pore-filling constituents, including mobile liquid water, which is critical to the most promising production techniques (Volume 2 Chapter 3). Other key data sets, such as shear velocity, are also best gathered with wireline tools.

Wireline logging allows the deployment of geophones to conduct a borehole seismic experiment (vertical seismic profile, or VSP) that can be critical to the calibration of log and conventional seismic data. The simplest option is to deploy a seismic source from the drill ship. More advanced techniques, such as 3D-VSP imaging can be applied, but they require access to a second ship for the operation of the seismic sources (Pecher *et al.* 2010).

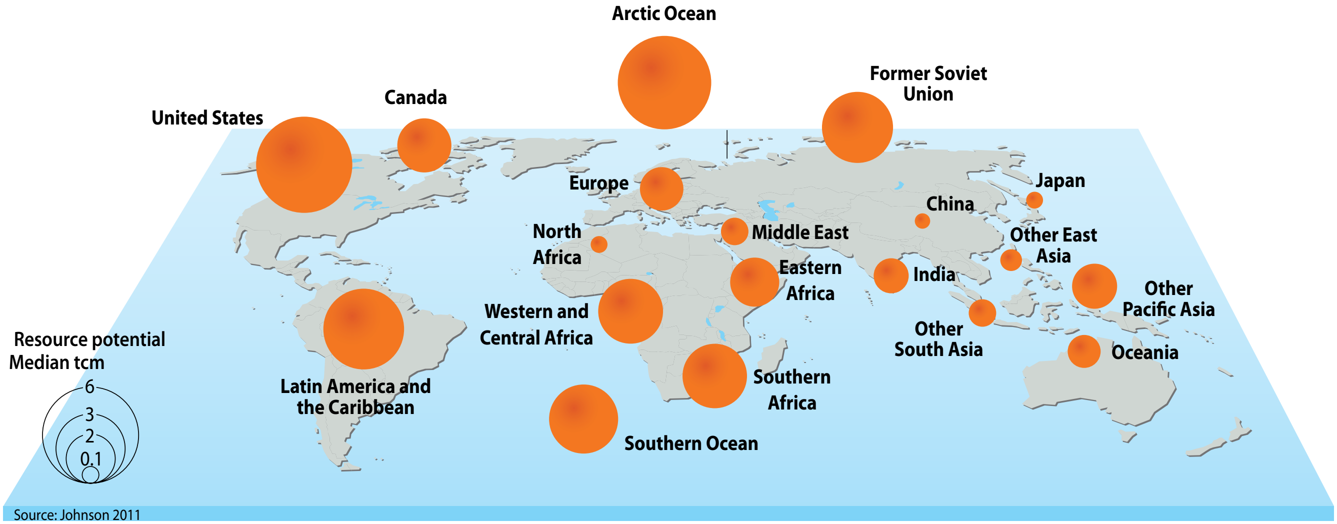
Figure TB-2.2: Gas hydrate evaluation. Left: Advanced well logging devices being deployed in the deepwater Gulf of Mexico (courtesy Gulf of Mexico gas Hydrate JIP Leg II Science Team). Right: Core samples are prepared for evaluation on the catwalk of the drill ship Joides Resolution, Bay of Bengal, India, in 2006 (courtesy NGHP Expedition-01 Science Team).

2.4 WHERE AND HOW MUCH?

At present, little is known about the details of the global occurrence of gas hydrates. The pressure and temperature conditions for gas hydrates exist broadly across the globe, and substantial amounts have been found both in areas with major conventional oil and gas accumulations and in areas without those accumulations. The preponderance of evidence suggests that gas hydrates will be found on the continental margins, as opposed to the centres of ocean basins.

Global resource volumes are also poorly known. To date, assessments of total in-place resources are based on scant data and provide little context to the issue of near-term gas hydrate resource potential, since they generally exclude the localized and anomalous occurrences that are the most favourable targets (Boswell and Collett 2011). Recently, however, focused and regional assessments for the Alaska North Slope (Collett *et al.* 2008), Arctic northwestern Canada (Osadetz and Chen 2010),

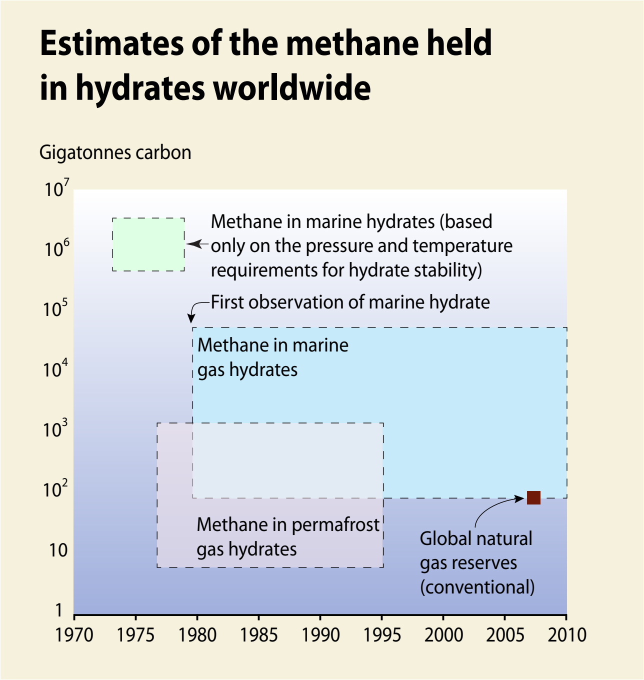
Gas hydrates resource potential by global regions



Source: Johnson 2011

Figure 2.4-a: Gas hydrates resource potential by global regions. This figure includes only that subset of global in-place gas hydrates that appear to occur at high concentrations in sand-rich reservoirs, the most likely candidates for development. Source: Johnson 2011.

the Gulf of Mexico (Frye *et al.* 2008), and the eastern Nankai Trough (Fujii *et al.* 2008) provide insight into the resources that might be available as sand-hosted gas hydrates. These studies informed a recent global review by Johnson (2011), which provides a rough first-order estimate of the share of global in-place resources of gas hydrates that could occur in sand reservoirs (Figure 2.4). The estimate suggests significant potential technically recoverable resource (TRR) of gas hydrates in every region of the globe, with a cumulative mean estimate of in-place resources within sand reservoirs of more than 1 217 trillion cubic metres of gas. That value represents roughly 5 per cent of the typical mid-range estimate for global gas hydrate in-place resources. However, these estimates are highly speculative and require significant field confirmation. The following sections review a range of the best-studied occurrences of gas hydrates in both coarse-grained and fine-grained reservoirs.



Estimates of the methane held in hydrates worldwide

Figure 2.4-b: Gas hydrates resource potential by global regions. Estimates of the methane held in hydrates worldwide. Early estimates for marine hydrates (encompassed by the green region), made before hydrate had been recovered in the marine environment, are high because they assume gas hydrates exist in essentially all the world's oceanic sediments. Subsequent estimates are lower, but remain widely scattered (encompassed by the blue region) because of continued uncertainty in the non-uniform, heterogeneous distribution of organic carbon from which the methane in hydrate is generated, as well as uncertainties in the efficiency with which that methane is produced and then captured in gas hydrate. Nonetheless, marine hydrates are expected to contain one to two orders of magnitude more methane than exists in natural gas reserves worldwide (brown square) (U.S. Energy Information Administration 2010). Continental hydrate mass estimates (encompassed by the pink region) tend to be about 1 per cent of the marine estimates (Figure modified from Boswell and Collett (2011)). Estimates are given in Gigatonnes of carbon (GtC) for comparison with other organic hydrocarbon reservoirs. At standard temperature and pressure, 1 GtC (Gigatonnes of carbon) represents 1.9 Tcm (trillion cubic meters) of methane which has an energy equivalent of approximately 74 EJ (exajoules).

2.5 CASE STUDIES OF GAS HYDRATE OCCURRENCES

2.5.1 PORE-FILLING GAS HYDRATES IN SAND RESERVOIRS

This most promising form of deposit, in terms of production potential, has been observed widely across the globe. Gas-hydrate-bearing sands have been discovered offshore Korea, where they are currently under evaluation as future production test sites (Lee, S-R. *et al.* 2011; Moridis *et al.*, 2013), and have been reported as well from the Cascadia margin (Riedel *et al.* 2006), the permafrost of Siberia (Makogon 1981), and elsewhere. The best-studied occurrences are permafrost-associated sands on the Alaska North Slope (Collett *et al.* 2008) and the Mackenzie Delta of Arctic Canada (Dallimore *et al.* 1998; Dallimore and Collett 2005), in the extensive deep-water turbidites of the Nankai Trough, and the deeply buried sands of the northern Gulf of Mexico.

The Alaska North Slope has a long history of oil and gas exploration. Gas hydrates were first inferred in 1972 during initial exploration of the Prudhoe Bay oil field. Drilling data from more than 1 000 wells in the area indicate that gas hydrates likely occur throughout the Alaska North Slope. They have been confirmed within a thick sequence of sand reservoirs below the base of permafrost throughout a broad area known as the Eileen Trend (Collett 1993). A second trend, the Tarn Trend, was discovered in the early 1990s overlying the Kuparuk River oil field (Collett 2002). In this case, gas-hydrate-bearing sands are present largely within the lowermost permafrost-bearing section. Inks *et al.* (2009) used standard industry seismic data to interpret more than a dozen specific gas hydrate prospects within the Milne Point unit at the northern end of the Eileen Trend. In February 2007, the most promising of these, the Mount Elbert Prospect, was drilled, logged, and cored (Hunter *et al.* 2011), confirming the occurrence of a sand reservoir with gas hydrate saturations ranging from 50 to nearly 80 per cent. In 2011, the Ignik Sikumi #1 research well confirmed similar occurrences of gas hydrates in four separate sand reservoirs (Schoderbek and Boswell 2011) in the western Prudhoe Bay unit.

The geology of the shallow sediments of the Alaska North Slope, and of many other Arctic regions in which gas hydrates occur, is dominated by sediments deposited in shallow-water marine, coastal, and terrestrial environments. These continental deposits generally include significantly greater proportions of sand-sized sediments than are typically found in deep-water settings. Virtually all known gas hydrate occurrences in the Arctic are associated with sands. Prudhoe Bay gas hydrates are charged primarily by the upward migration (aided by many faults) of gas leaking from the deeper Prudhoe Bay oil and gas fields. It appears likely that gaseous methane began to charge sand reservoirs prior to the evolution of gas hydrate stability conditions roughly 1.6 million years ago (Collett 1993). Conversion to gas hydrates occurred after the climate cooled dramatically during glacial times, aggrading thick occurrences of terrestrial permafrost.

Collett (1995) assessed Alaska North Slope in-place gas resources from gas hydrates at 16.7 trillion cubic metres. Subsequently, using information from the 2007 Mount Elbert well and recent advances in numerical modelling (Anderson *et al.* 2010), Collett *et al.* (2008) provided the first assessment of technically recoverable resources from gas hydrates, indicating a mean of 2.4 trillion cubic metres from Alaska North Slope sand reservoirs using existing technologies.

Compared to the data available about permafrost gas hydrates on the Alaska North Slope and the Mackenzie Delta, very little is known about gas hydrates in the vast deep-water basins of the world. Perhaps the best-characterized occurrences in sand reservoirs are those located in the eastern Nankai Trough, off the southeastern coast of Japan (Figure 2.7). The

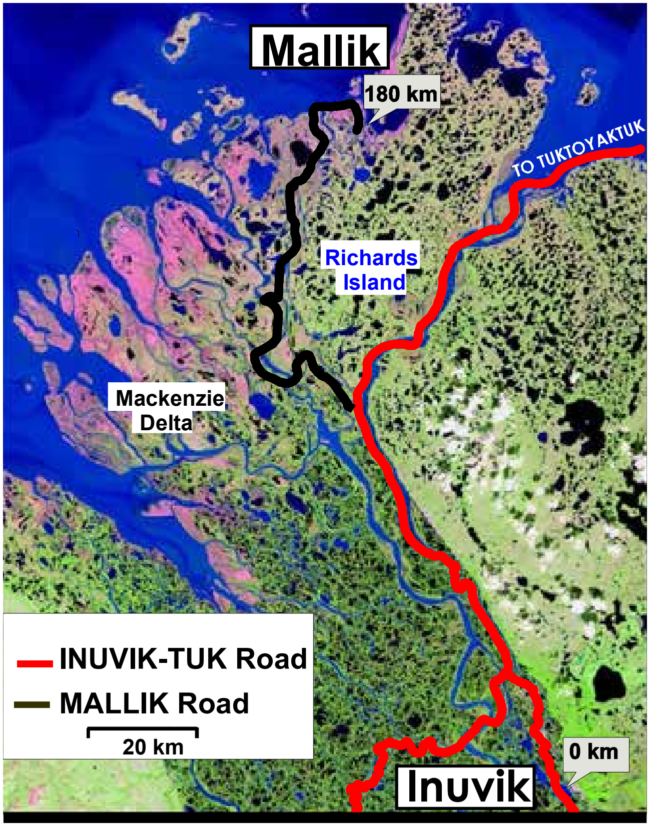
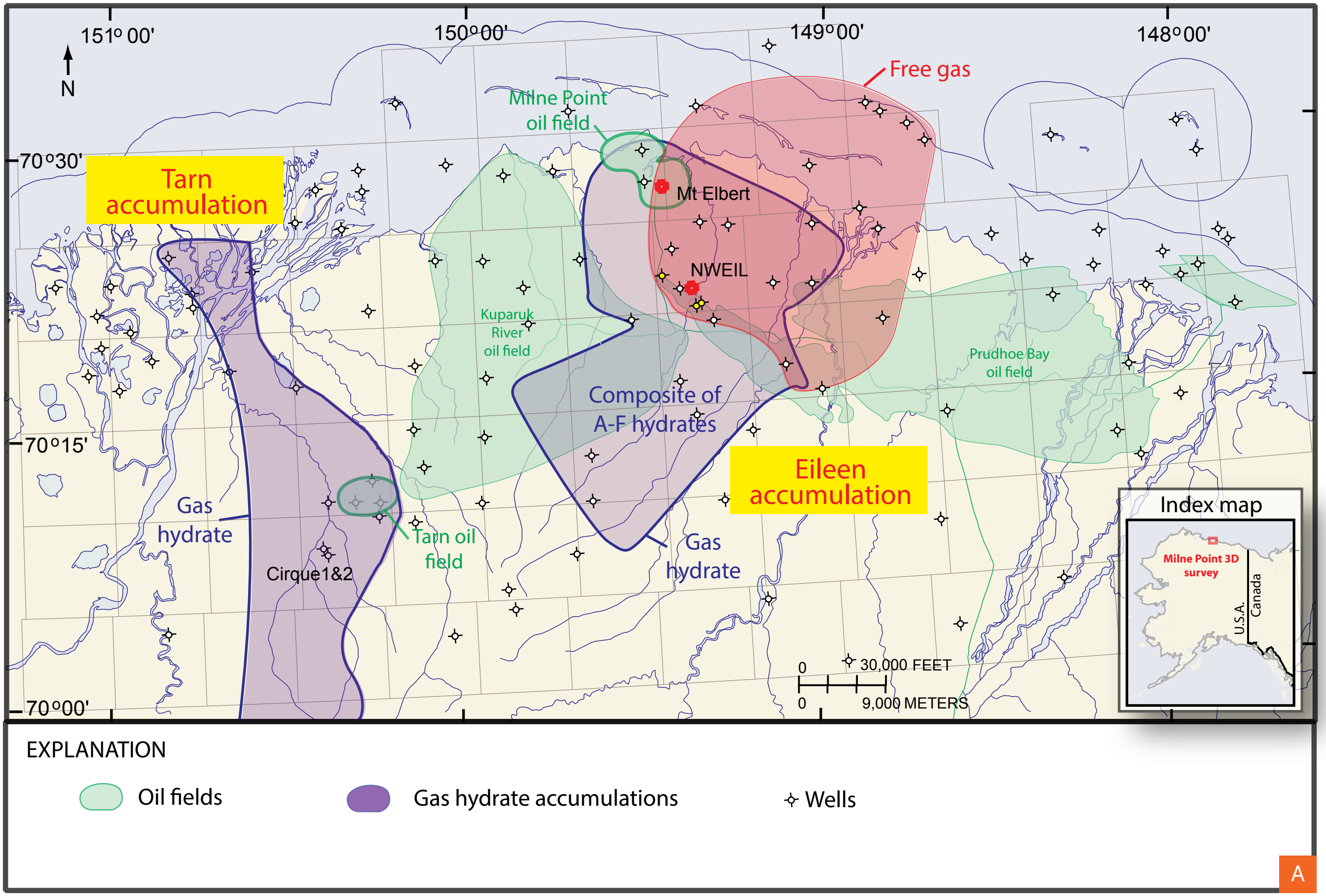


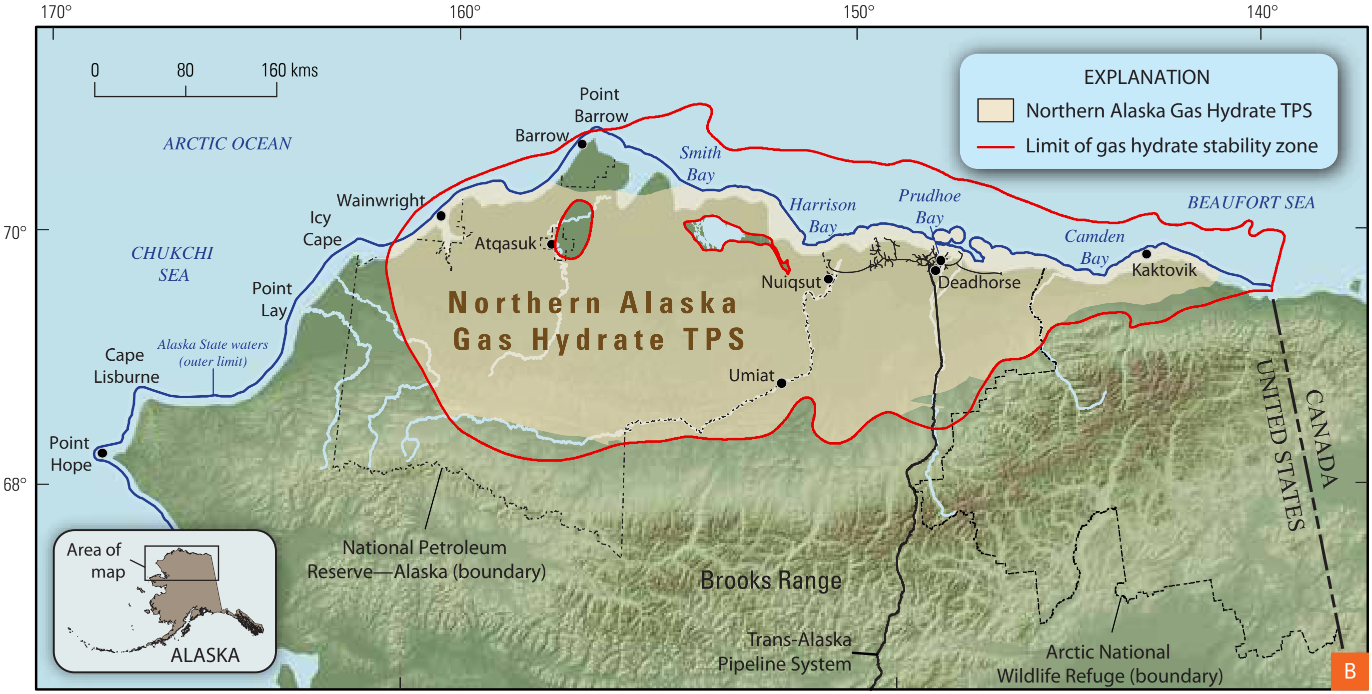
Figure 2.5: The Mallik site in Canada's Arctic. This has been the site of dedicated gas hydrate programs since 1998. The map (above) shows the route of the temporary ice road (red line) that provides access to the site near the shore of the Mackenzie delta. The photo (below) shows a sample of gas-hydrate-bearing coarse-grained sandstone recovered from the site in 1998. (Courtesy: Geological Survey of Canada.)

Nankai Trough is a subduction zone where the Philippines Sea Plate to the east is being overridden by the Eurasian Plate to the west. This deep basin has collected thick sections of sediment eroded from the Japanese Islands – including extensive turbidite channel complexes and other sand-rich strata. Exploration drilling conducted in the eastern Nankai Trough in 1999 provided the world's first confirmation of substantial gas-hydrate-bearing sand reservoirs in a deep-water setting (Tsuji *et al.* 2004). Guided by a range of advanced geophysical studies, additional drilling in 2004 permitted the delineation of more than ten separate accumulations of gas hydrates in deep-water sands (Tsuji *et al.* 2009; Fujii *et al.* 2009). The reservoirs in the Nankai Trough are characterized by thick sections of interbedded deep-water sands and muds (Takano *et al.* 2007; Noguchi *et al.* 2010) with individual gas-hydrate-bearing sand layers typically less than a metre thick (Fujii *et al.* 2008; 2009).

Analysis of data acquired during the 2004 drilling and coring programs (Takahashi and Tsuji 2005) and associated geophysical programs demonstrated that conventional oil and gas data sets and concepts could be applied to the problem of deep-water gas hydrate detection and characterization (Saeki *et al.* 2008). Fujii *et al.* (2008) conducted an assessment of gas hydrate resources in the most extensively studied area in the eastern Nankai Trough, an area estimated to represent perhaps ten per cent of the total prospective area for gas hydrates in waters around Japan. The assessment revealed a mean estimate of gas-in-place of approximately 1.1 trillion cubic metres within a region totalling 7 000 square kilometres, with 550 billion cubic metres occurring at high concentrations in sand reservoirs. Kurihara *et al.* (2010) reported numerical simulations of production potential and determined that the technically recoverable portion of this resource is likely large, constituting 50 per cent or more of in-place resources, depending on production method and location-specific geology. In 2012, Japan re-initiated drilling and sampling activities in the Nankai Trough in preparation for the first field trials (which began in 2013) of gas hydrate production from a deep-water sand reservoir (Yamamoto *et al.* 2011). The 2013 drilling program included a rigorous review of baseline environmental conditions and monitoring of environmental impacts that might be associated with gas hydrate production (Arata *et al.* 2011).

Figure 2.6: Within the greater Prudhoe Bay region, two distinct trends of gas hydrate accumulations in sand reservoirs (A; after Collett 1993). Extensive data derived largely from ongoing oil and gas development on the Alaska North Slope has enabled the delineation of the Northern Alaska Gas Hydrate Total Petroleum System (B, after Collett et al. 2008). Sub-permafrost hydrates in the Eileen Trend have been the subject of two collaborative federal-industry scientific field evaluation programs, including the BP-DOE-USGS Mt. Elbert Program in the Milne Pt. Unit (C, Mt. Elbert well site, March 2007; courtesy Mt. Elbert Science Team) and the ConocoPhillips-JOGMEC-DOE Ignik Sikumi program in the Prudhoe Bay Unit (D; Courtesy ConocoPhillips).




170°
160°
150°
140°
70°
68°
0
80
160 kms
EXPLANATION
▭ Northern Alaska Gas Hydrate TPS
— Limit of gas hydrate stability zone
ARCTIC OCEAN
CHUKCHI SEA
BEAUFORT SEA
Point Barrow
Barrow
Smith Bay
Harrison Bay
Prudhoe Bay
Camden Bay
Kaktovik
Wainwright
Icy Cape
Atqasuk
Nuiqsut
Deadhorse
Northern Alaska Gas Hydrate TPS
Point Lay
Alaska State waters (outer limit)
Cape Lisburne
Umiat
Point Hope
CANADA
UNITED STATES
Area of map
ALASKA
National Petroleum Reserve—Alaska (boundary)
Brooks Range
Trans-Alaska Pipeline System
Arctic National Wildlife Refuge (boundary)
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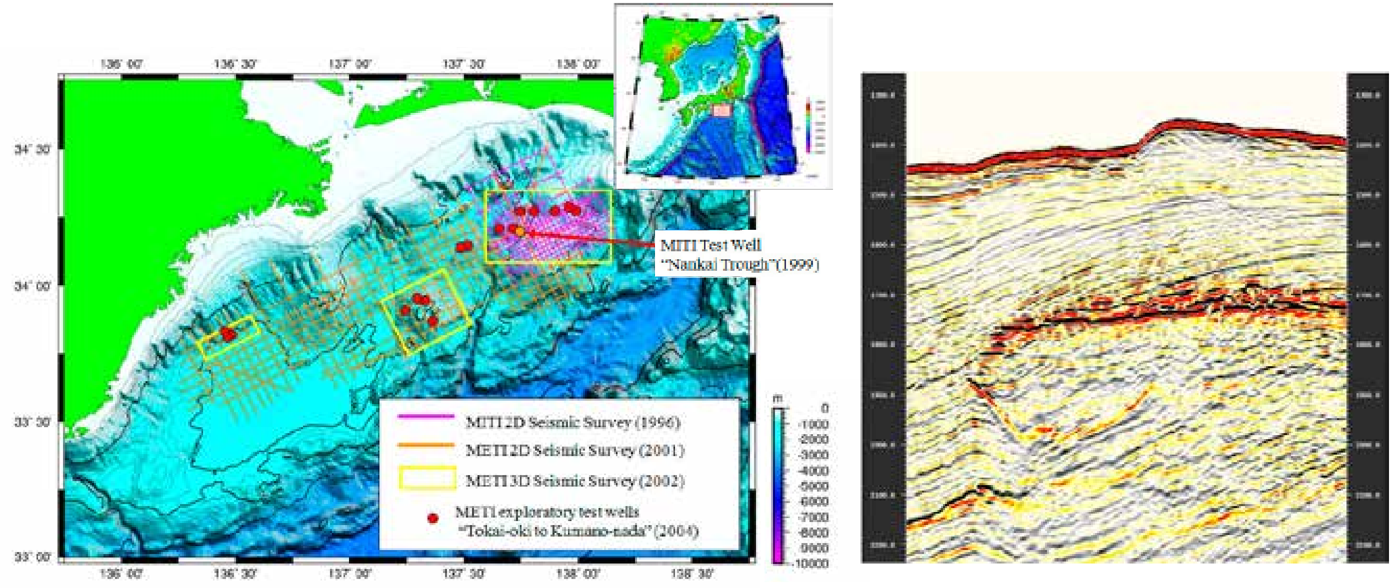

Figure 2.7: Exploratory drilling and extensive geophysical surveys in the Nankai Trough. Drilling and surveys conducted in the Nankai Trough, off the southeastern coast of Japan (left), have discovered thick sequences of gas hydrate in reservoir-quality, sand-rich sediments. The gas hydrate adds significant strength to the sediment, resulting in the strong seismic reflections where the sand-rich units extend upwards into the gas hydrate stability zone (right). Reservoirs such as these are the subject of the world's first deep-water gas hydrate production tests, which Japan began conducting in early 2013 (Images courtesy JOGMEC).

Unlike the Nankai Trough, the northern Gulf of Mexico hosts a prolific petroleum system that continues to yield large conventional oil and gas discoveries. Nonetheless, although more than 1 200 wells had been drilled through the gas hydrate stability zone in the deep-water Gulf of Mexico by the end of 2005, observations of gas hydrates in the basin had been largely limited to sea-floor features associated with cold seeps (Boswell *et al.* 2012). An early assessment (Collett 1995) of gas hydrate resources assigned more than 991 trillion cubic metres gas-in-place to the basin. As indications of sub-sea-floor gas hydrates were observed and as industry began to investigate gas-hydrate-prone deep-water areas, concern over potential drilling hazards increased. That led to the formation of an international industry research consortium to address gas hydrate issues in the Gulf of Mexico (McConnell *et al.* 2012). Information gained during a 2005 drilling expedition (Ruppel *et al.* 2008) addressed many of these questions, and attention has increasingly focused on gas hydrate resource appraisal. In 2008, vast volumes of industry well and seismic data were accessed to provide a comprehensive evaluation of the potential for gas generation, migration, and trapping in hydrate form (Frye 2008). This study determined that of 607

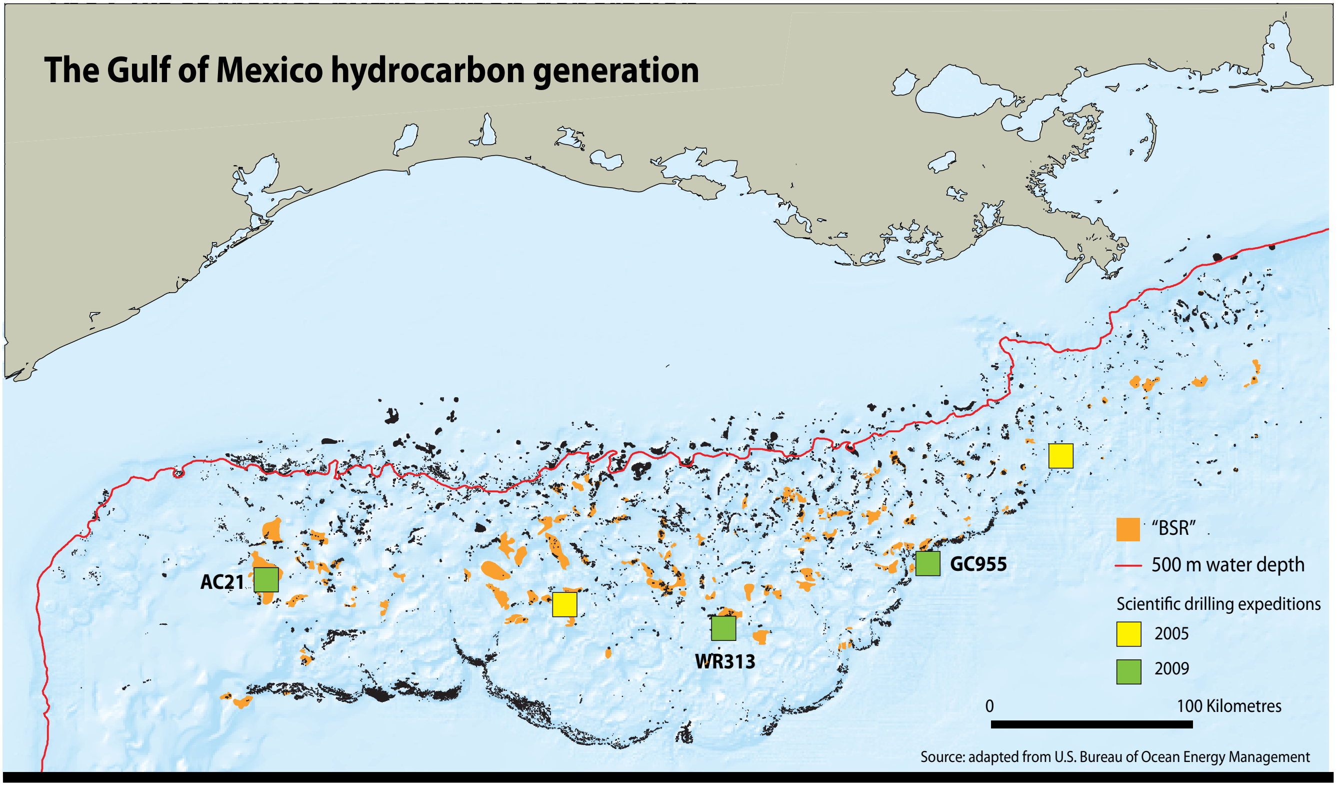

Figure 2.8: The Gulf of Mexico is a region of prolific hydrocarbon generation and flux through the shallow sediments. Areas of seafloor amplitude anomalies are shown in black, while areas with geophysical indications of gas hydrate, "BSRs" are shown in orange (see Shedd *et al.* 2012). Through integration of such geological and geophysical data, the expected distribution of 190 Tcm of methane held in gas hydrate in reservoir quality sands has been interpreted (image courtesy U.S. Bureau of Ocean Energy Management).

trillion cubic metres gas-in-place (mean statistical estimate) in gas hydrates in the northern Gulf of Mexico, 190 trillion cubic metres were likely to occur in sand reservoirs.

An initial search for specific gas-hydrate-bearing sands in the deep-water Gulf of Mexico resulted in the first pre-drill estimates of gas hydrate saturation at specific targets (Shelander *et al.* 2010). Of seven wells drilled, six discovered gas hydrates in sand reservoirs in close agreement with the pre-drill predictions. While these first discoveries are relatively small in size, they are a sampling from a large number of areas in which geophysical data indicate potential gas hydrate accumulations (Shedd *et al.* 2012). The reservoirs are as much as 800 metres below the sea floor, providing the benefits of both warmer and more competent reservoirs, in addition to more effective overlying seals with stronger mechanical properties. Confirmation of the presence of these deeply buried and well-defined reservoirs from such limited drilling is a promising indicator for basin-wide resource potential, and the high success rate of the drilling program further supports the validity of the integrated geologic systems approach to exploration.

2.5.2 GRAIN-DISPLACING, FRACTURE-DOMINATED OCCURRENCES IN MUDDY SEDIMENTS

Gas hydrates in the form of grain-displacing veins and nodules in fine-grained sediments have been reported from coring programs offshore Japan (Fujii *et al*. 2009) and Malaysia (Hadley *et al*. 2008) and are likely very common worldwide. Perhaps the best-studied sites are the particularly thick and rich occurrences discovered offshore India in 2006 (Collett *et al*. 2006) and offshore Korea in 2007 (Park *et al*. 2008).

Drilling at Site 10 in the Krishna-Godovari Basin, a part of India's 2006 NGHP Expedition 01, showed gas hydrates occurring as a pervasive network of fracture-filling veins and lenses in mud-rich sediments (Figure 2.10). The 150-metre-thick unit lay below roughly 20 metres of gas-hydrate-free mud-rich sediments and had no clear sea-floor expression. Core samples revealed the fossilized remains of an earlier sea-floor chemosynthetic community at the top of the gas hydrate deposit (Mazumdar *et al*. 2009), suggesting that a relatively recent sea-floor slump had buried a once-active cold seep, promoting the accumulation of sub-sea-floor gas hydrates at the site. The gas hydrates are not evident in standard analyses of geophysical data, but advanced techniques have delineated a 1.5-square-kilometre area inferred to represent the zone of increased gas hydrate occurrence (Riedel *et al*. 2010a, b). The site also provided an opportunity to cross-calibrate core-based and log-based analyses, enabling scientists to refine significantly the models used to estimate gas hydrate saturation from log data in fracture-dominated systems (Lee and Collett 2009; Cook *et al*. 2010). Core data confirmed that gas hydrate concentrations are about 25 per cent of the pore space, on average, throughout the gas hydrate deposit. Prior to the drilling at Site 10, it was widely believed that gas hydrates could not accumulate to values much in excess of 10 to 15 per cent in muddy sediments, and that whatever gas hydrates occurred in such settings would generally be dispersed within the sediment pore space. The surprising findings at Site 10, therefore, fundamentally changed the view of fine-grained gas hydrate systems.

Confirmation of the potential global abundance of rich gas-hydrate occurrences as fracture-fill in muddy sediments was obtained in the Ulleung Basin, offshore Korea, in 2007 (Expedition UBGH1). Among other targets, this program tested several chimney structures (Figure 2.11), anomalous vertical features of reduced seismic amplitude that are observed worldwide in areas of significant gas seepage (Riedel *et al*. 2002; Wood *et al*. 2000; Westbrook *et al*. 2008). UBGH1 provided both well-log and core data through two chimneys (Park *et al*. 2008), confirming significant fracture-filling gas-hydrate occurrence. A second expedition (UBGH2), conducted in 2010, tested several more chimney structures with similar results. Abundant chimney structures, perhaps more than 1 000, have been identified in the Ulleung Basin alone (Horozal *et al*. 2009; Kang *et al*. 2011), and it now appears likely that virtually all these structures represent significant occurrences of grain-displacing gas hydrates. Preliminary analyses of logging-while-drilling and core data show that concentrations are quite variable, but likely similar to those seen offshore India (about 25 per cent of pore space).

While fracture-filling gas hydrate deposits probably represent significant global in-place resources, no promising production strategies have yet been proposed. Challenges include the production difficulties (many of which are related to the geomechanical stability of the formation and of the wellbore assembly) and the potential environmental impact associated with extraction from such shallow, highly unconsolidated, and low-permeability sediments.

2.5.3 PORE-FILLING GAS HYDRATES IN MUDDY SEDIMENTS

Perhaps the bulk of global gas hydrate in-place resources occurs in low concentrations, dispersed within the pores and grains of clay-rich sediments. Such accumulations exist broadly across the globe, their presence commonly betrayed by conspicuous geophysical responses such as bottom-simulating reflectors (BSRs) and blanking zones (Tucholke *et al*. 1977; Text Box 2.3). The investigation of such features and their potential links to gas hydrates turned the attention of the first dedicated gas-hydrate scientific field program (IODP Leg 164) to the Blake Ridge, offshore eastern North America, in 1995 (Paull *et al*. 1996).

At the Blake Ridge, drilling confirmed the widespread occurrence of gas hydrates throughout a thick (approximately 200 metres) and very fine-grained sediment section. The concen-

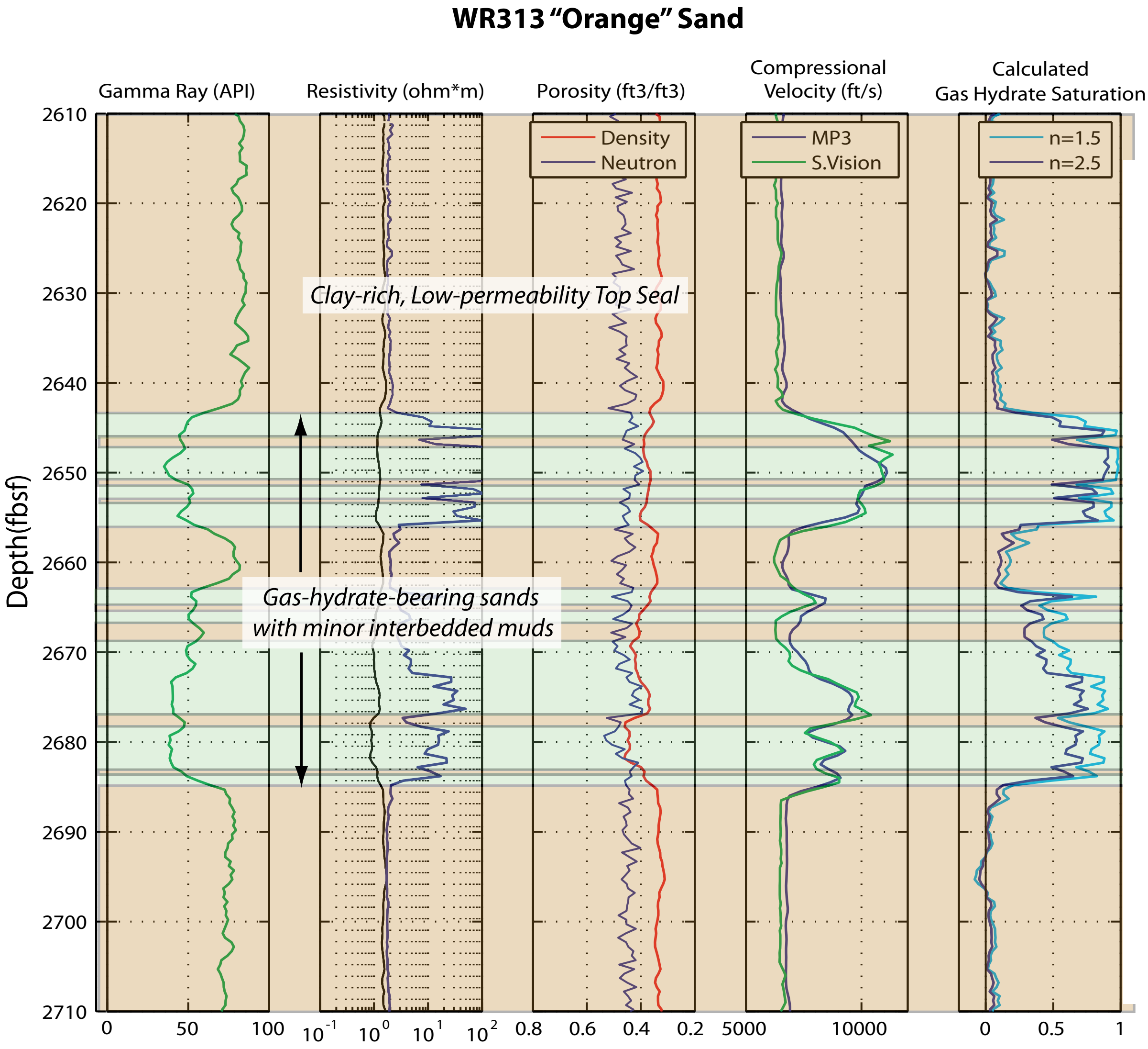

Figure 2.9: Well data from a gas hydrate exploration well drilled in the northern Gulf of Mexico in 2009. These data obtained from the Walker Ridge 313 "H" well show two sand-rich reservoirs enclosed in clay-rich sediments that are fully saturated with gas hydrate (right panel). (From Boswell *et al.*, 2012).

Box 2.3 **Changing approaches to gas hydrate exploration**

Geophysical methods hold great promise for the remote detection and quantification of gas hydrate deposits because of the strong changes in the physical properties that are induced by the presence of gas hydrates. Replacing water or gas in the sediment pore space with solid gas hydrates results in marked increases in the both the electrical resistivity and the acoustic wave velocity of the sediment. These physical changes can be detected with electromagnetic and conventional reflection seismic technologies deployed from ships and used to evaluate large regions. The data, when integrated with models that correlate physical properties to gas hydrate occurrence, make it possible to make general estimates of the location, extent, and concentration of gas hydrate deposits prior to drilling (Shelander *et al.* 2010).

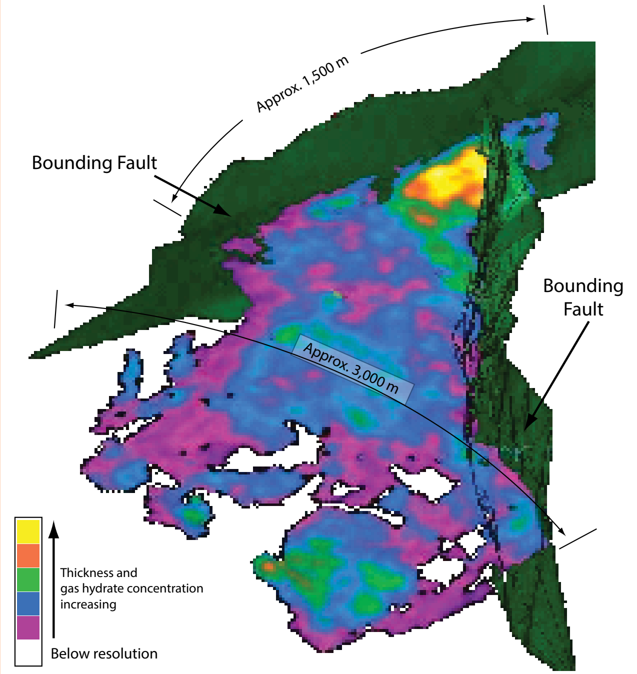

Figure TB-2.3: A gas hydrate prospect delineated on the Alaska North Slope. The image shows geophysically-inferred gas hydrate trapped within a sand layer at the intersection of two fault planes (green). (Courtesy US Geological Survey).

Direct detection of gas hydrate deposits, particularly those that are widespread and highly concentrated, is a relatively new development in gas hydrate science. Previously, the presence of gas hydrates in marine sediments had been deduced seismically from the presence of a bottom-simulating reflector (BSR; Shipley *et al.* 1979), which commonly marks the base of the gas hydrate stability zone (GHSZ). Physically, the BSR is the transition from gas-hydrate-bearing sediments to gas-charged (or at least gas-hydrate-free) sediments below. While early research focused on how to exploit the seismic character of a BSR and infer gas hydrate concentrations above and free gas concentrations below the reflection (Hyndman and Spence 1992; Yuan *et al.* 1996), more recent analyses show that the seismic characteristics of BSRs cannot easily be related to the concentration of the pore-filling material (Chapman *et al.* 2002), a conclusion confirmed by drilling results (Tsuji *et al.* 2009).

A complementary technique, controlled-source electromagnetic imaging (CSEM; Edwards 1997), attempts to exploit the increased electrical resistivity of gas-hydrate-bearing sediments. However, the physical nature of electromagnetic wave propagation through marine sediments results in a reduced lateral and vertical resolution, compared to seismic imaging. As a result, CSEM may be more suitable for imaging chimney structures and other fracture-dominated systems (Schwalenberg *et al.* 2005).

Much prior gas hydrate exploration used sea-floor phenomena, such as seabed hydrate mounds, pock marks, mud volcanoes, and depth of sulphate penetration, as general indicators of the nature of historical or current gas seepage. However, while these are interesting physical features for understanding natural systems, they have not yet been shown to be useful in prospecting for deeper reservoirs.

Recently, approaches to exploring for gas hydrate deposits have shifted towards a more integrated evaluation of the full petroleum system (Collett *et al.* 2009). This approach incorporates geologic information (such as the availability of gas sources, fluid migration pathways, and suitable reservoirs) with direct geophysical indicators (such as anomalous strong reflectors or high calculated velocities) in a way regularly applied in the oil and gas industry (Saeki *et al.* 2008 Boswell and Saeki 2010). The approach acknowledges that all exploration has great uncertainty, and that no single tool or piece of evidence will be definitive and reliable. Instead, exploration uncertainty is best managed by a comprehensive evaluation of all relevant data to provide confidence in the occurrence of each necessary part of the system.

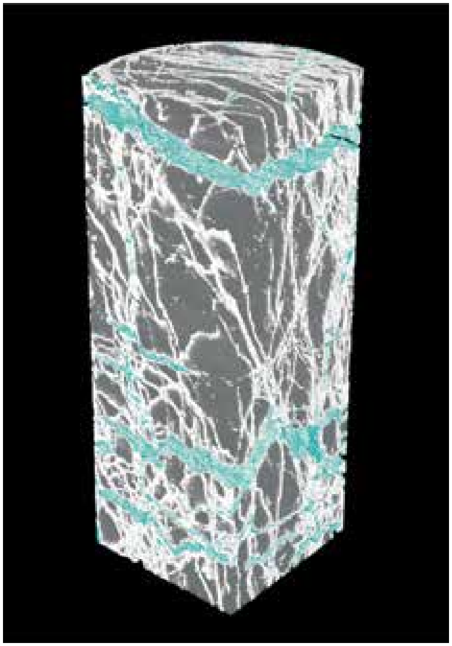

Figure 2.10: Gas hydrates in clay-rich sediments. Gas hydrates have been discovered in rich deposits characterized by dense arrays of nodules and hydrate-filled fractures in clay-rich sediments. Left: CT image of a core samples collected offshore India in 2006. The hydrate-filled veins appear as white (from a paper by Rees *et al.* 2011, published by JMPG, permission would be needed). Above pictures, gas hydrate samples (courtesy NGHP Expedition-01 science party).

tration of gas hydrates was generally low – typically 5 per cent or less of pore space, with local increases up to 10 per cent or more correlated with fine, vertical-scale increases in sediment grain size (Ginsburg *et al.* 2000). Although the resource concentration is low, the large area and significant thickness of the gas hydrate occurrence at the Blake Ridge results in very large cumulative in-place resources of gas (Dickens *et al.* 1997), potentially exceeding 28 trillion cubic metres.

A recent gas hydrate drilling expedition within the Shenhu region of the South China Sea (Expedition GMGS-1) provided additional insight into gas hydrate occurrences in mud-rich systems (Yang *et al.* 2008; Figure 2.11). Analysis of log data suggested potential gas hydrates at the base of the gas hydrate stability zone (GHSZ) at five of eight sites drilled. Cores acquired at these five locations confirmed significant gas hydrates near the base of the GHSZ at three locations. At each well, degassing of pressurized core samples confirmed gas hydrate at saturations routinely of 20 per cent, with local increases to more than 40 per cent in thin zones (Wu *et al.* 2010). Notably, analysis of X-ray radiographs from Shenhu showed the gas hydrates were primarily in disseminated, pore-filling mode. Only minor macroscopic lenses, nodules, or fracture-fills typically seen in rich, fine-grained occurrences were observed. Such high saturations are unique, so far, for fine-grained gas-hydrate systems lacking macro-scale fractures and may reflect locally high concentrations of silt-sized particles, in particular biologic fragments (foraminifera tests) that might enhance permeability above normally expected levels in predominantly fine-grained sediments (Wu *et al.* 2010).

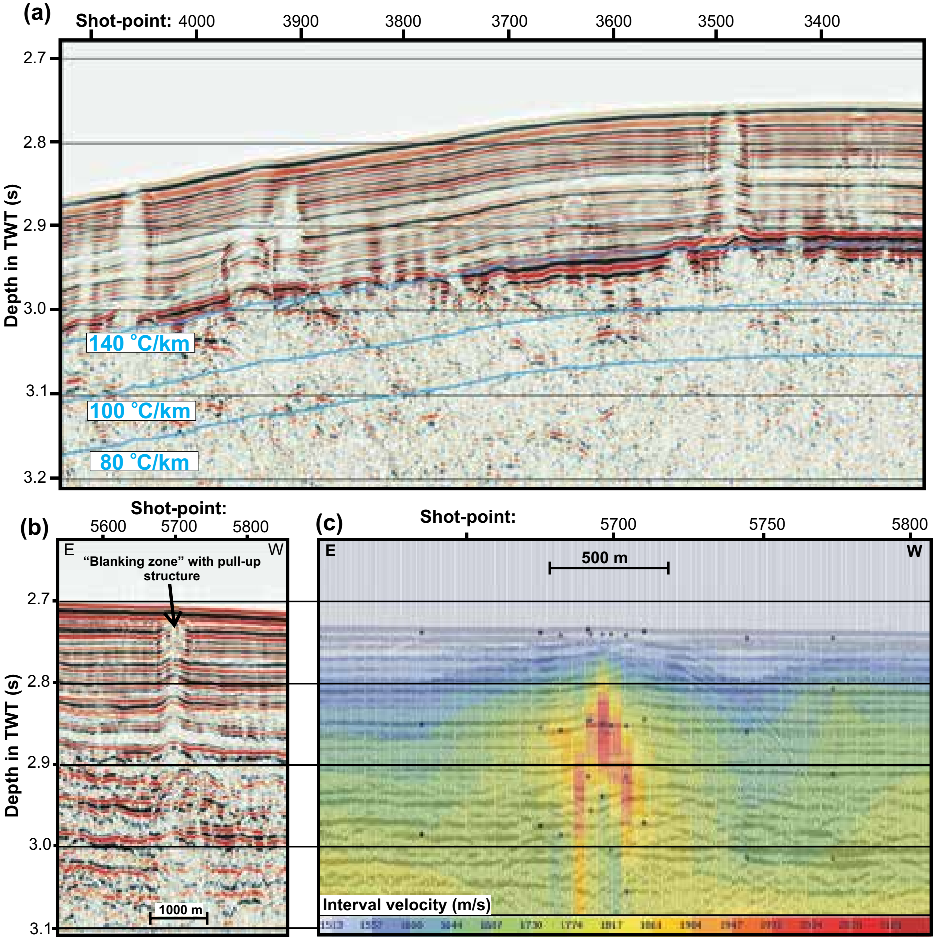

Figure 2.11: Drilling expeditions and results, Ulleung Basin. Scientific drilling expeditions evaluated gas hydrates in the Ulleung basin off the eastern coast of South Korea in 2007 and in 2010. The drilling confirmed that the basin contains a wide array of gas hydrate occurrence types, including a multitude of gas-hydrate-bearing “gas chimneys”. Above: Location of Ulleung basin Right: Geophysical data showing typical Ulleung basin gas chimneys (vertical features with anomalous physical properties) (with permission from Ryu *et al.*, 2009). Drilling has confirmed high concentrations of gas hydrates in the centres of these chimneys.

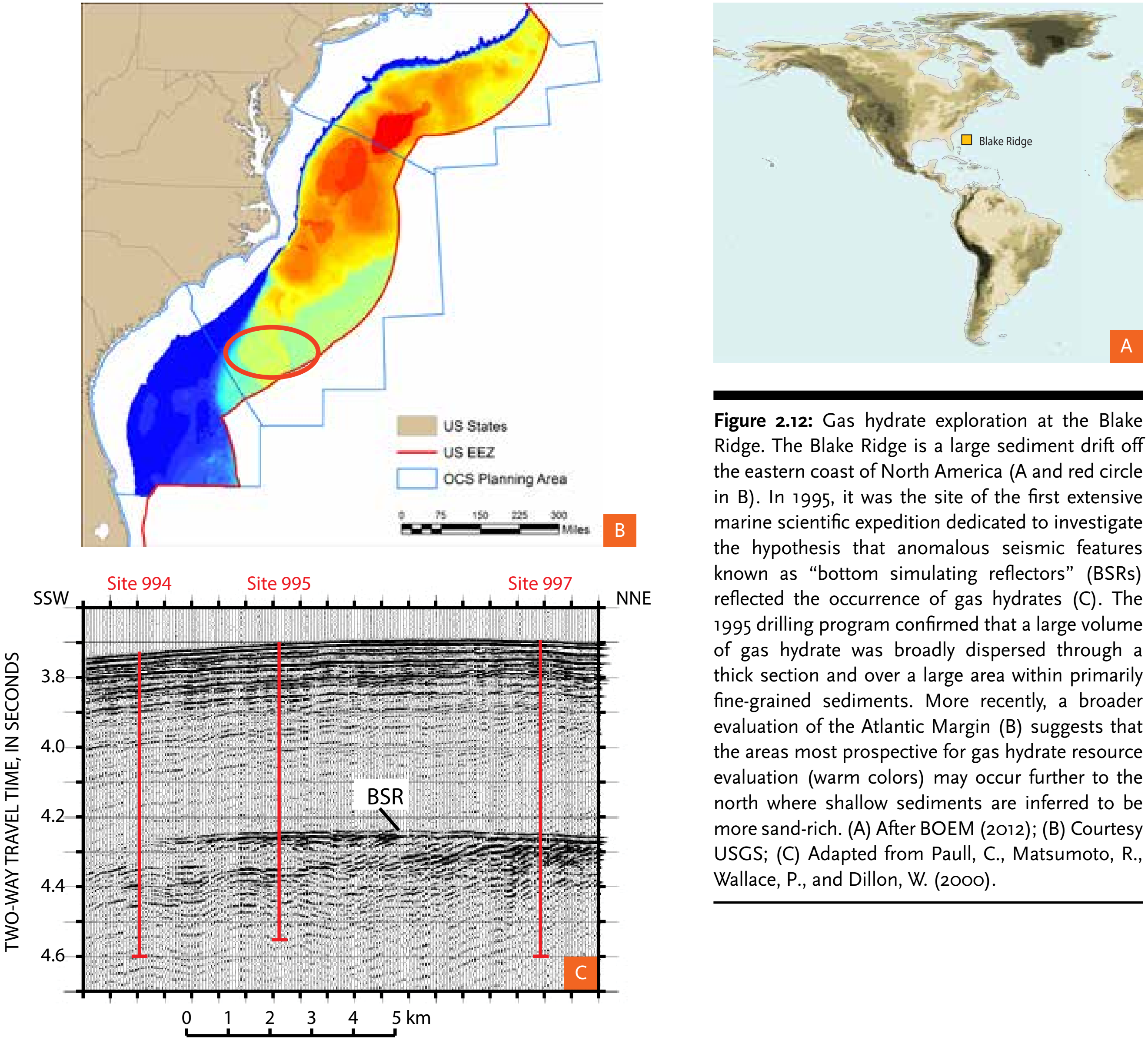

Figure 2.12: Gas hydrate exploration at the Blake Ridge. The Blake Ridge is a large sediment drift off the eastern coast of North America (A and red circle in B). In 1995, it was the site of the first extensive marine scientific expedition dedicated to investigate the hypothesis that anomalous seismic features known as “bottom simulating reflectors” (BSRs) reflected the occurrence of gas hydrates (C). The 1995 drilling program confirmed that a large volume of gas hydrate was broadly dispersed through a thick section and over a large area within primarily fine-grained sediments. More recently, a broader evaluation of the Atlantic Margin (B) suggests that the areas most prospective for gas hydrate resource evaluation (warm colors) may occur further to the north where shallow sediments are inferred to be more sand-rich. (A) After BOEM (2012); (B) Courtesy USGS; (C) Adapted from Paull, C., Matsumoto, R., Wallace, P., and Dillon, W. (2000).

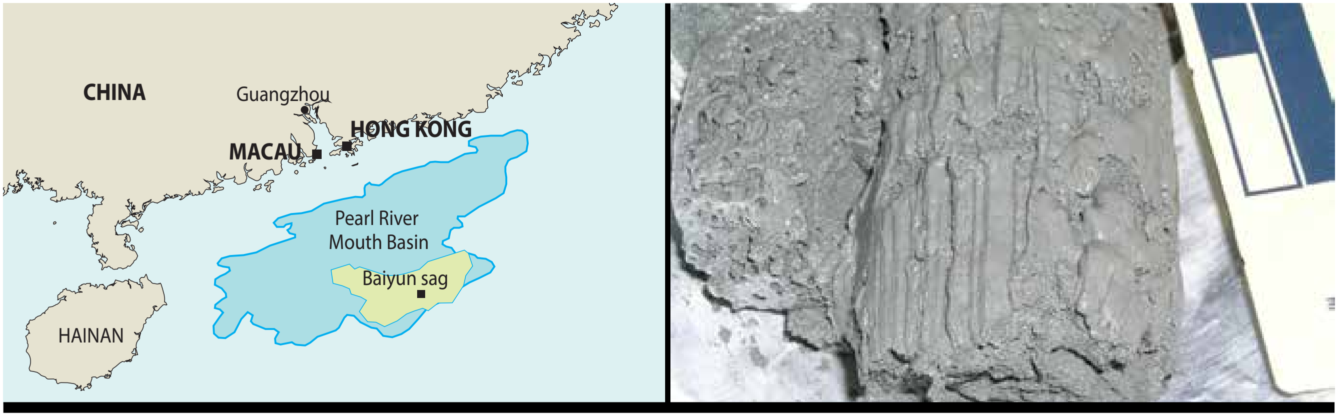

Figure 2.13: Gas hydrates in the South China Sea. The photograph shows a mud-rich sediment sample acquired from the Shenhu region, South China Sea, in 2007. The sediment shows the frothy texture that results from the dissociation of gas hydrates and the release of gas during sampling and recovery (courtesy, GMGS-01 Science Party).

Given the large resource volumes in settings such as the Blake Ridge and the Shenhu area, pore-filling, fine-grained systems are being rigorously evaluated for their energy resource potential. At present, the consensus is that production of such deposits is not feasible with existing technologies (Moridis and Sloan 2007; Li *et al.* 2010). The primary reasons are low hydrate saturation, low sediment mechanical strength, lack of confining low-permeability boundaries, and access to abundant free water, which makes depressurization difficult to achieve and limits potential production rates to extremely low values.

2.6 SUMMARY

Nearly two decades of drilling and coring programs have confirmed that gas hydrates occur in substantial volumes in nature. However, the form in which these resources occur varies widely, largely influenced by the nature of the enclosing sediment. Because of these variations – which include gas hydrate concentration, burial depth, and many other factors – only a subset of the global in-place resource is potentially technically recoverable through the application of known technologies. This subset consists primarily of gas hydrates housed in sand-rich sediments. Total resource volume in sand reservoirs remains as poorly constrained as the global in-place estimates, but may be on the order of 285 to more than 1 400 trillion cubic metres of gas (Boswell and Collett, 2011). Large volumes are also likely present in muddy systems, particularly in association with chimney structures, but the lack of any feasible production approach for such deposits means that these resources cannot currently be considered part of the recoverable resource base.

Given the limited amount of exploration conducted to date, even within the best-studied locations, it should not be assumed that any of the specific cases referred to in this chapter typify the nature of gas hydrate resources in the regions where they were found. For example, both the Gulf of Mexico and Nankai Trough, discussed above with reference to sand reservoirs, contain large resource volumes within thick accumulations at low concentrations in mud-rich sediments. The Ulleung Basin, presented as an example for chimney structures, has confirmed pore-filling gas hydrates in discrete turbidite sands (Bahk *et al.* 2011a), which are currently under evaluation as future production test sites (Moridis *et al.*, 2013). Similarly, the large, diffuse deposit on the Blake Ridge – once thought to be typical of all marine gas hydrates – may not even be representative of gas hydrate occurrence along the eastern coast of North America. Recent work by Frye *et al.* (2011) shows great potential for sand-rich sediment in the shallow section of the hydrate stability zone just north of the Blake Ridge.

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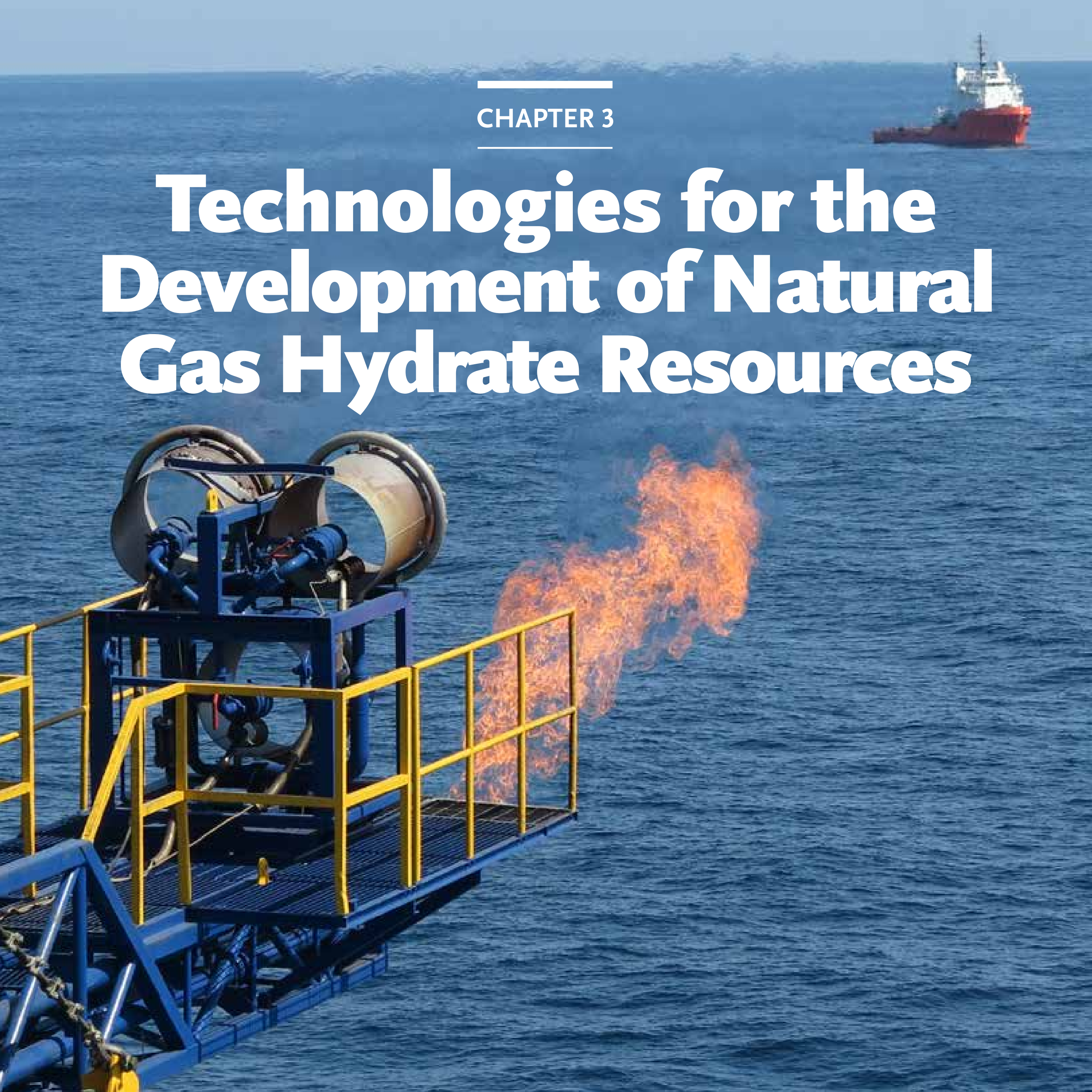
CHAPTER 3

Technologies for the Development of Natural Gas Hydrate Resources



3.1 INTRODUCTION

If economic and environmentally responsible production of gas hydrate resources proves achievable, the global consequences are potentially far-reaching. Natural gas emits substantially less greenhouse gas than many other fossil fuels – up to 40 per cent less than coal or oil (EIA 2013). It has, therefore, been identified by many countries as a preferred energy source over other hydrocarbons for the near future. Gas hydrates are thought to occur in relative abundance (in terms of the size of the resource) in select locations around the world. They occur in both marine and permafrost settings where methane gas and water co-exist at pressures and temperatures suitable for hydrate formation and stability (Figure 3.1).

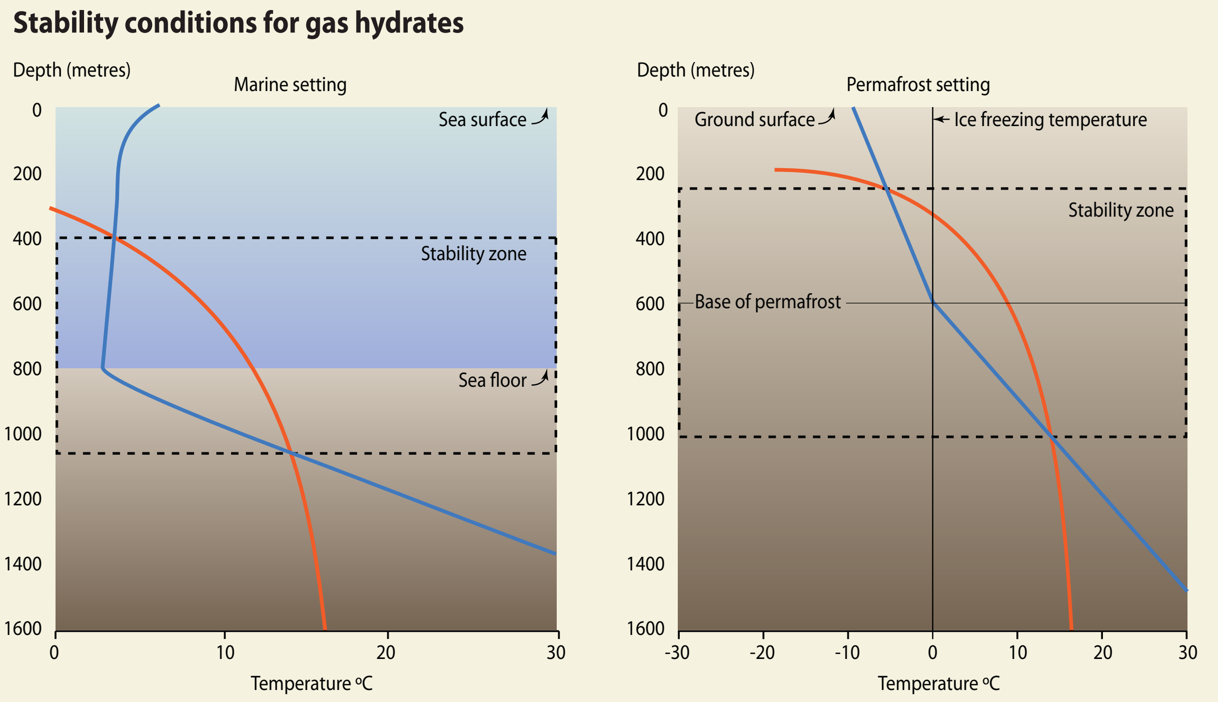


Figure 3.1: Phase diagrams illustrating where methane hydrate is stable in marine (left frame) and permafrost settings (right frame). Hydrate can exist at depths where the temperature (blue curve) is less than the maximum stability temperature for gas hydrate (given by the hydrate stability curve in orange). Pressure and temperature both increase with depth in the Earth, and though hydrates can exist at warmer temperatures when the pressure is high (orange curve), the temperature in the Earth (blue curve) gets too hot for hydrate to be stable, limiting hydrate stability to the upper ~1km or less of sediment.

While gas hydrates have considerable potential as an energy resource, the challenges to realizing their commercial production are not trivial. This is largely due to the fact that gas hydrates occur in a solid form, with the gas molecules (usually methane) trapped within a crystalline lattice of water molecules. Many early concepts for producing methane from gas hydrates were based on mining technologies, in which solid masses of gas hydrate or gas hydrate-bearing sediment would be physically removed from the sea floor. However, major international gas hydrate research programs now tend to dismiss mining approaches on the grounds of significant detrimental environmental consequences and of economic and technical impracticality.

However, recent field studies worldwide have confirmed that concentrated deposits of gas hydrates can occur in reservoir settings that are consistent with potential extraction using existing hydrocarbon exploration, drilling, and production technologies (Collett *et al.* 2009). These settings are where gas hydrates reside within the pore spaces of discrete, permeable to highly permeable, laterally continuous units rich in sand and or coarse-grained silts. (Moridis *et al.* 2009). This would involve accessing the reservoir via drilled wells, manipulating local pressure-temperature conditions to force the solid hydrate crystal to dissociate into its water and gas components, and then producing the released gas to the surface.

The advantage of using conventional hydrocarbon production technologies is that there is a great deal of worldwide experience on the subject, covering the spectrum from exploratory drilling to production. Based on this experience, it appears likely that gas hydrate production in marine or permafrost environments will involve the following existing hydrocarbon production approaches that are designed to enable production while minimizing environmental impact:

- Establishment of safe foundation conditions for the well infrastructure through detailed pre-production study of the well-site geology in order to recognize and avoid potential hazards and provide a full understanding of the potential impact of production on the ground supporting the well infrastructure;
- Installation and cementing of casing strings to maintain well stability while drilling into the target gas hydrate production interval;
- Installation of production casing and downhole completion equipment to enable testing and production of hydrocarbon-bearing intervals;
- Effective well control and zonal isolation during production;
- Minimization of the impact of gas extraction on the surface and subsurface environment; and
- Monitoring of the response of the gas hydrate field to production.

This chapter describes some of the most recent suggested approaches to meeting these requirements for gas hydrate production.

3.2 ESTABLISHING SAFE SITE CONDITIONS

Over the past several decades, industry and regulators have established procedures for evaluating site safety with regard to locating conventional oil and gas exploration and production facilities. Once a promising location has been confirmed, surveys and evaluations are conducted to determine the geology, geohazards, drilling hazards, and environmental conditions (Graber 2002; Kvalstad 2007; NGI 2005). Surficial surveys (primarily shallow geophysics and coring) are used to characterize the geology of shallow sediments and to determine their geotechnical properties. A geohazard assessment is undertaken to document active geologic processes (seabed erosion, deposition, slope instability, and unique ecological habitats), to quantify the seismic risk, and to consider the potential occurrence of shallow gas, shallow water flows, or other anomalous subsurface conditions. In deepwater marine settings (at water depths greater than 250 metres), the possible occurrence of shallow gas hydrates or seafloor outcrops of gas hydrates should be routinely evaluated, as they can become unstable when disturbed (Hovland and Gudmestad 2001; Peters *et al.* 2008; McConnell *et al.*, 2012) or might be associated with unique biological habitats (MacDonald *et al.* 1994).

Normal practice has been to avoid locating wells where shallow gas hydrate outcrops occur and to drill and case any shallow hydrate intervals as quickly as possible. The challenge in establishing production from a gas hydrate field is that the gas hydrate interval itself cannot be avoided, as it is the target. Quantifying the geomechanical response of the gas hydrate-bearing strata during methane production will be an important consideration in establishing safe site conditions for gas hydrate production facilities (Kleinberg and Jones 2004; Yamamoto 2008; Rutqvist and Moridis 2009).

3.3 DRILLING A GAS HYDRATE PRODUCTION WELL

Drilling through gas-hydrate-bearing strata involves a variety of potential technical and environmental challenges. For example, some early exploration wells in the Arctic experienced shallow gas flows and borehole stability problems, including abnormal hole erosion and/or tight hole conditions (Collett and Dallimore 2002). The problems were linked mainly to the accepted drilling practices in the 1970s and 1980s, which could cause significant thermal and/or mechanical disturbance of the gas-hydrate-bearing strata. This could potentially result in the release of free gas and a significant reduction in sediment strength (Figure 3.2). Similar problems have been encountered in other settings (Borowski and Paull 1997; Nimblett *et al.* 2005). Industry has

Gas hydrate drilling and production problems

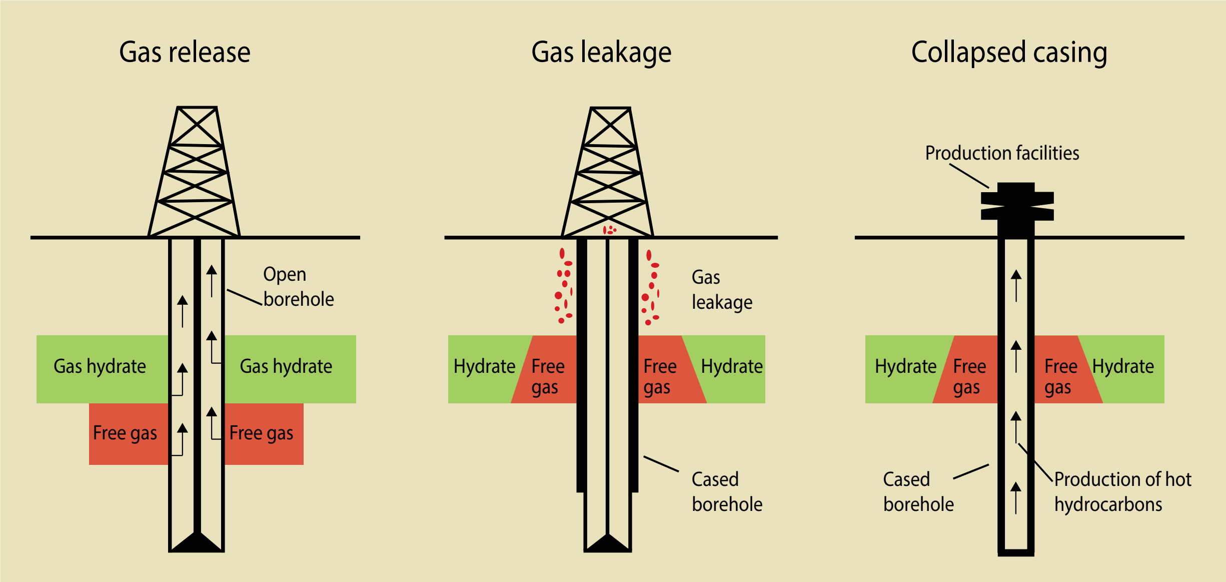


Figure 3.2: Potential drilling and production problems: The figure shows typical gas-hydrate-related drilling and production problems encountered during drilling programs in the Arctic (from Collett and Dallimore 2002). Gas release scenario (left): over-pressured free gas is encountered unexpectedly beneath a gas hydrate layer. Gas leakage scenario (centre): possible disturbance of gas hydrate by drilling that has dissociated gas hydrate and caused free gas migration outside of the drill casing. Collapsed casing scenario (right): possible disturbance of gas hydrate caused by conventional production of warm hydrocarbon at depth.

largely overcome these problems by introducing modifications to the drilling procedures and equipment, including:

- Chilling the drill mud to reduce thermal disturbance of the formation;
- Managing the weight of the drill mud to achieve sufficient downhole pressure to stabilize the in situ gas hydrates, while remaining below the pressures that might fracture downhole formations;
- Using chemical additives (or avoiding dissociation-inducing inhibitors such as salts and alcohols) in the drill mud to maintain gas hydrate stability in the formation and prevent gas hydrate dissociation in the drill cuttings;

Box 3.1 **Gas hydrate coring and drilling studies**

The major advances in understanding the drilling behaviour of in situ gas hydrates have come through field programs dedicated specifically to the study of gas hydrates. Substantial resources have been devoted to gas hydrate research and development over the past several decades (Collett *et al.* 2009), with more than 100 dedicated gas hydrate wells successfully drilled to date. Several Integrated Ocean Drilling Program (IODP) expeditions have investigated gas hydrate occurrences along active and passive continental margins. Multi-well exploration campaigns have been undertaken by national gas hydrate research programs in Canada, China, India, Japan, Korea, and the United States. In addition, dedicated research and development programs conducted offshore Japan and in permafrost settings in Canada and Alaska have tested the effectiveness of gas hydrate drilling, coring, and cementing technologies. The Japanese program included a short horizontal well in gas-hydrate-bearing strata 350 metres below the sea floor (Takahashi and Tsuji 2005). At the Mallik site in the Canadian Arctic, a full-scale thermal production test was completed in 2002 (Dallimore and Collett 2005). Gas hydrate production by depressurization of the reservoir was tested there during successive winter programs in 2007 and 2008 (Dallimore *et al.* 2012). In Alaska in 2012, an advanced production test program involving carbon dioxide injection and pressure drawdown was completed (Schoderbek *et al.* 2012).

Figure TB-3.1: Notable gas hydrate field programs. This is a general representation of notable hydrate field programs that have been or are taking place around the world. The compilation is indicative and does not necessarily depict all hydrate field programs.

- Controlling drilling rates to penetrate and case the hydrate-bearing strata quickly in order to stabilize the gas hydrate interval, while allowing sufficient time to remove the gas hydrate or the free gas contained in mud returns; and
- Using cements with low heat of hydration for casings in order to establish a good bond between the casing and the surrounding formation, while minimizing thermal heating and local gas hydrate dissociation.

Over the past decade, many dedicated gas hydrate field investigations have been conducted worldwide (Text Box 3.1). These have demonstrated that gas hydrates can occur in a variety of reservoir settings with different overburden/underburden sediments and physical properties of the host strata (e.g., gas hydrate form, thickness, sediment porosity, permeability, thermal properties, pressure, and temperature regimes). Such reservoirs also vary widely in the degree of heterogeneity in important parameters such as gas hydrate saturation, permeability, and enclosing sediment characteristics. As with conventional hydrocarbon fields, the specific drilling technologies and methods employed to exploit gas hydrates depend on the local geology and environmental setting.

A summary of drilling considerations for various gas hydrate deposits is provided in Table 3.1. Well designs may include high-angle, horizontal, and multi-lateral wells (Hancock *et al.* 2010). In marine settings, drilling will be carried out from floating drilling structures or drill ships, employing technologies routinely used by industry for activities in water depths of 500 to 2 000 metres (Anderson *et al.* 2011; Figure 3.3). Drilling hazards and associated environmental risks are likely to be similar to those faced when drilling deep conventional wells, where the risks of shallow groundwater flow, overpressure, and shallow free gas must be assessed (Aubeny *et al.* 2001; Kvalstad *et al.* 2001).

Additional environmental risks relate to the challenge of drilling and well completion in the relatively shallow depth of many marine gas hydrate production targets, some of which are at depths of less than 300 metres below the seabed. Where soft sediments occur near the seabed, special care will be required in the design of shallow surface casings to carry the load of the well infrastructure. Similarly, the intermediate casings between the production interval and the surface casing must be designed to ensure zonal isolation and to prevent vertical migration of produced gas through the wellbore annulus towards the seabed. Considerable efforts are in progress to improve well-bore simulation models for gas hydrates in order to allow detailed risk assessment and identification/ consideration of optimal drilling practice (Birchwood *et al.* 2005; Rutqvist and Moridis 2008; Rutqvist *et al.* 2008; Yamamoto 2008).

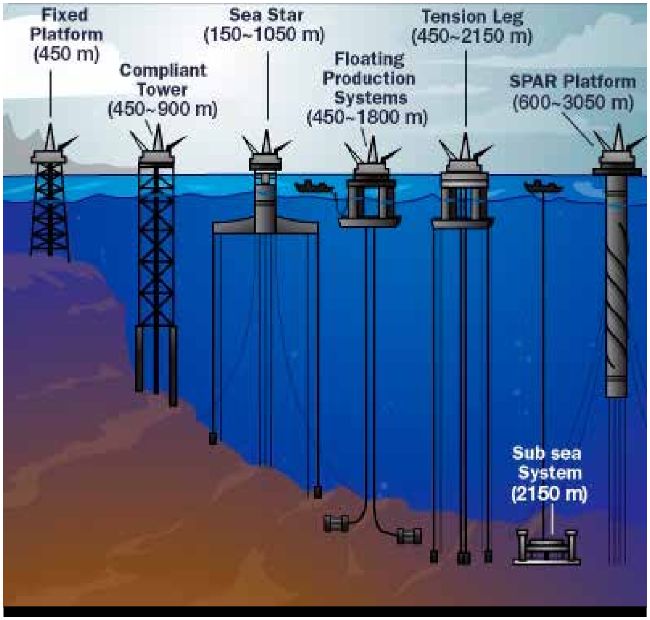


Figure 3.3: Marine drilling platforms. These platform designs are currently used in various deepwater settings around the world. The tension-leg system is founded on the bottom, whereas the other systems are floating structures (Figure from Lamb, Robert. "How Offshore Drilling Works" 10 September 2008. HowStuffWorks.com).

In onshore areas where the gas hydrate production interval is beneath ice-bonded permafrost, drilling technologies are likely to be similar to those employed on the North Slope of Alaska (Hancock *et al.* 2010). A typical well design will include a shallow surface casing and an intermediate casing that spans the permafrost interval. As with marine gas hydrates, Arctic gas hydrate wells will require an assessment of the risk of overpressure and free-gas migration while drilling through the permafrost interval.

Table 3.1-a: Production challenges and associated environmental considerations for permafrost gas hydrate deposits

Reservoir type	Reservoir setting	Production maturity[1]	Site survey & foundation considerations	Drilling, completion & production	Environmental response
Onshore – Sand-host sediment	Beneath permafrost – Pore-space occurrence – Temp. 0 to ~12 °C – Sites: Alaska North Slope (USA), Mackenzie-Beaufort/ Arctic Islands(Canada) and Siberia (Russia)	– Discovered technically recoverable resources (Alaska North Slope and Arctic Canada) – With completion of demonstration projects at Mallik site in Mackenzie Delta, currently existing production technologies have been verified. However, market and infrastructure not presently in place.	– Several well described sites have been identified in North America – Environmental and geo-hazard issues related to near surface infrastructure expected to be similar to conventional	– Conventional drilling practice & sand control/flow assurance measures – Dissociation primarily through pressure draw-down (down-hole pump) – Challenges associated with low reservoir temperatures & retaining formation integrity when hydrates are dissociating – Subsurface water-disposal strategy will be required – Flow assurance measures will be necessary to reduce risk of secondary gas hydrate formation in gas production stream – Horizontal wells may be required	– Negligible ground surface interactions are expected as the most prospective gas hydrate accumulations are buried many hundreds of metres below the ground level, beneath a competent permafrost interval – Control on reaction provided by ability to control pressure in the well bore. – Seal integrity expected to be sufficient as the accumulations are likely to be converted, pre-existing, free gas traps.
	Within permafrost – Pore-space occurrence – Temp. < 0 °C – Sites: as above	– No technically recoverable resources identified (Seismic evaluation complex due to hydrate-ice similarities) – Development hindered by low reservoir temperatures	Not considered	Not considered	Not considered
Onshore – Other host sediment environments	Within and beneath permafrost – pore and fracture fill modes in fine grained strata, lithified sediments with low permeability etc. – Sites: Qilian Mtns, China; also likely in other permafrost settings but presently not documented	– No technically recoverable resources identified – Gas hydrate saturation and reservoir extent unclear, additional work needed	Not considered	Not considered	Not considered
Offshore – Variable host sediment environments	Thick offshore permafrost occurrences are suspected beneath the Arctic shelves (Beaufort Sea, Siberia) where terrestrially formed deposits have been submerged by transgression. Gas hydrate can be expected within and beneath permafrost in settings similar to those described above	– No technically recoverable resources identified – Gas hydrate saturation and reservoir extent unclear, additional work needed	Not considered	Not considered	Not considered

1. Likely commerciality time-line (i.e., produceable/non-produceable in the near future)

Table 3.1-b: Production setting and associated environmental considerations for marine gas hydrate deposits

Reservoir type	Reservoir setting	Production maturity[1]	Site survey & foundation considerations	Drilling, completion & production	Environmental response
Marine – “shallow” Sand- host sediment	Shallow – < 250 m below sea floor – > 500 m WD[2] – Pore-space occurrence	– Discovered technically recoverable resources (Gulf of Mexico & Japan) – First offshore production test in 2013 (Nankai Trough) – First production may occur in Asia from c. 2020	– Conventional approach to hazard delineation and engineering design – Shallow settings may present increased risk of sea floor instability and disruption of shallow ecosystems – Unique challenges may be encountered related to geologic settings such as active tectonic continental margins where there is increased seismic activity and pervasive sediment deformation	– Conventional drilling practice & sand control/flow assurance measures – Horizontal drilling may be difficult due to shallow reservoir and weak formation-strength – Unconventional surface conductor and casing design due to weak formations – Dissociation primarily through pressure draw-down (down-hole pump) – Operational challenges owing to cold reservoir temperatures and formation mobility when gas hydrate is dissociated – A water-disposal strategy is likely to be required – Seal integrity may be an issue due to lack of sediment strength and consolidation	– Shallow reservoir depths and weak sediment strengths above producing interval pose unique challenges to field development – Conventional experience worldwide is limited in similar settings, however engineering design methods are well developed
Marine – “deep” Sand-host sediment	Deep – > 250 m below sea floor – > 1000 m WD – Pore-space occurrence – Sites: AC 818, WR 313, GC 955 (GoM), Beta (Nankai Trough), UBGH2-2_2, UBGH2-6 (Ulleung Basin)	As above	– Conventional approach to hazard delineation and engineering design, ease of application of existing approaches increases with increasing reservoir depth	– Conventional drilling practice & sand control/flow assurance measures – Horizontal drilling may be difficult due to shallow reservoir and weak formation-strength – Dissociation primarily through pressure draw-down (down-hole pump) – A water-disposal strategy is likely to be required	– Conventional experience worldwide is limited in similar settings, however engineering design methods are well developed
Marine – Mud host sediment	Disseminated – Widespread occurrences – High volume but low resource density – Sites: Blake Ridge (USA)	– Conventional practice in industry would be to avoid these occurrences due to low resource density – Modeling to date shows no clear viable production mechanism	– Conventional experience worldwide is limited in similar settings, however engineering design methods are well established – Not considered for fracture fill	– A number of scientific and exploratory research wells have successfully penetrated these deposits using conventional drilling methods – It is unlikely that these deposits will be developed using conventional industry completion/production methods	– Not Considered
	Fracture-fill – Widespread occurrences – High volume but low resource density – Sites: KG Basin (India): Ulleung Basin (Korea); Gulf of Mexico (USA)	– Conventional practice in industry would be to avoid these occurrences despite moderate to high gas hydrate saturations, due to geo-mechanical instability and restriction of fluid flow			
Marine – Solid hydrate	Sea floor: – Massive (mounds) – Sites: GoM, Baltic Sea, Black Sea, Bering Sea, Barkley Canyon (Canada) NGS/BS[3] Vents: – Massive, disseminated & fracture-filling (?) – Sites: Bering Sea, NGS	– Conventional practice in industry would be to avoid these occurrences due to their unusual geotechnical properties and association with unique biological communities	– Not Considered	– Not Considered	– Non traditional extraction methods may be destructive to sea floor biological communities and cause sea floor settlement

1. Likely commerciality time-line (i.e., produceable/non-produceable in the near future)
2. Water Depth
3. NGS/BS: Norwegian Greenland Sea and Barents Sea

3.4 GAS HYDRATE PRODUCTION

Three primary gas hydrate production concepts have been proposed to date, all based on the concept of in situ dissociation of gas hydrates to release free gas that can then be delivered to the surface (Figure 3.4). The depressurization technique dissociates gas hydrates by reducing local formation pressures, the heating technique raises the formation temperature, and the chemical stimulation technique changes the chemical equilibrium conditions (Makogon 1997).

While no commercial gas hydrate production has yet been attempted, several scientific field tests have been carried out in the Arctic. A full-scale thermal stimulation test was undertaken by a five-country consortium in 2002 at the Mallik gas hydrate field in the Mackenzie Delta (Dallimore and Collett 2005). At the same site, depressurization testing was undertaken by a Canada-Japan research program in 2007 (Dallimore *et al.* 2008a, b; 2011; Numasawa *et al.* 2008) and 2008 (Yamamoto and Dallimore 2008). Additional data useful for evaluating gas hydrate production potential are available from short-term drill-stem tests conducted by industry in the 1970s (Bily and Dick 1974) and from small-scale formation tests conducted as part of the 2002 Mallik program

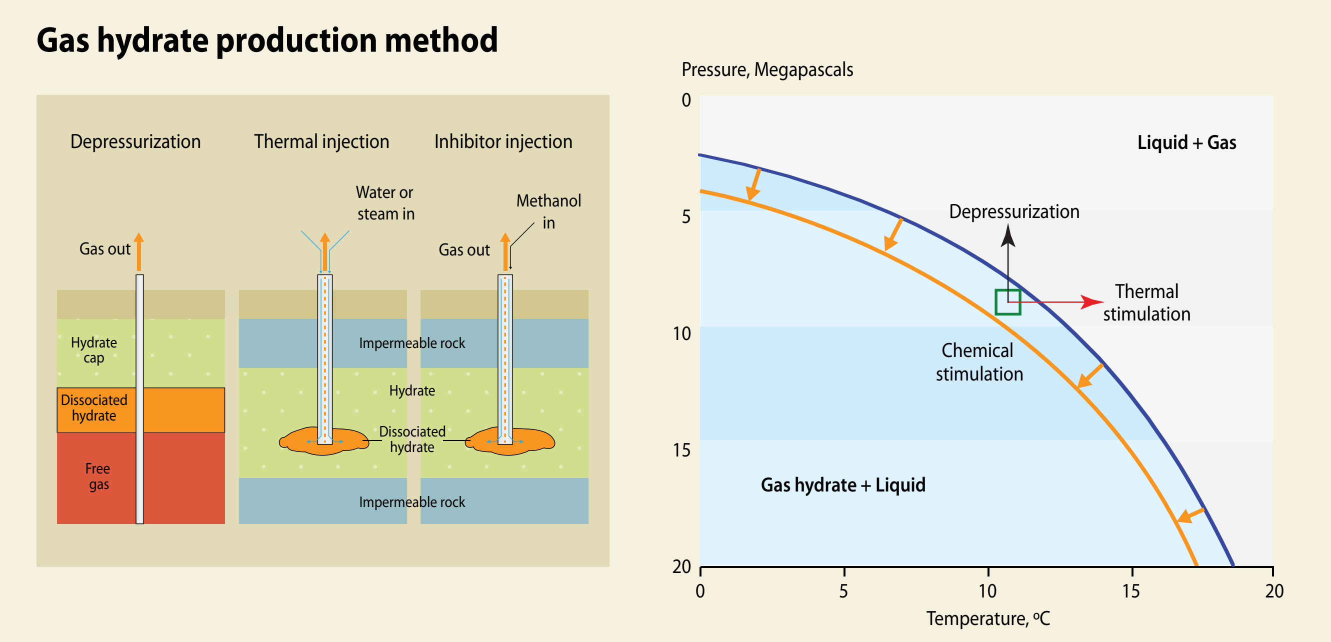


Figure 3.4: Production methods and impacts on gas hydrate stability. For each of the three proposed gas hydrate production methods (left frame), conditions within initially stable hydrate-bearing sediment are shifted such that hydrate at that location is no longer stable, and will begin dissociating. Right frame: Depressurization: achieved by reducing the formation pressure below equilibrium limits. Thermal stimulation: achieved by increasing the formation pressure beyond equilibrium conditions. Chemical stimulation: changes in gas hydrate equilibrium conditions are induced by inhibitor injection.

Box 3.2 **Studies assessing the depressurization production technique**

The first quantitative studies of the response of a gas hydrate reservoir to pressure drawdown were carried out as part of the 2002 Mallik research and development program in Canada's Mackenzie Delta. Using Schlumberger's Modular Formation Dynamics Tester (MDT) wireline tool, small-scale pressure drawdown tests within 0.5-metre-thick perforated intervals were undertaken in a variety of reservoir settings (Dallimore and Collett 2005). Complementary core data and well logs supported the detailed assessment of formation porosity and permeability and gas hydrate saturation.

These studies confirmed that the gas hydrates occurred within the pore space of fine- to coarse-grained sands with low but measurable permeability. The pressure response and observed gas and water flows confirmed that, in spite of the low reservoir permeability, it was possible to transmit a pressure drop into the formation and induce in situ gas hydrate dissociation. Fine- and coarse-scale heterogeneity was also documented, as well as the occurrence of natural fractures within the gas hydrate reservoir.

The MDT tool was also used in 2007 as part of a drilling program on the Alaska North Slope (Hunter *et al.* 2011). In this case, MDT testing was undertaken in an open-hole condition, rather than in the cased hole condition at Mallik, providing even more reliable measurements. The interpretations indicate measurable permeability in four discrete zones with differing reservoir properties..

Full-scale depressurization production testing was carried out at the Mallik site in the winters of 2007 and 2008 (Dallimore *et al.* 2008b; Yamamoto *et al.* 2008). A 13-metre zone near the base of the gas hydrate stability field was chosen for production testing, based on reservoir simulations that suggested this would be the most productive interval. A short production test during the first winter used a downhole electrical submersible pump positioned below the perforation interval. The pump was configured to allow downhole separation of gas and water, with the produced gas flowing to the surface and the residual water re-injected into a deeper perforated zone within the same well.

The 2007 test results revealed the mobility of the sand-gas-water mix created when the gas hydrate, which bonds and strengthens the sandy reservoir sediments, is dissociated. While the inflow of sand into the well limited the duration of the 2007 pressure drawdown test, a significant production response was observed during approximately 18 hours of testing. Gas flow rates during the latter part of the test exceeded 5 000 cubic metres a day. Operational problems encountered in 2007 were overcome in 2008 with the use of sand screens and deployment of a redesigned pump positioned above the perforations.

Both gas and water flowed to the surface in the 2008 test. The produced gas was metered at the surface and then flared to the atmosphere. The produced water was re-injected into a lower sedimentary formation via a separate water injection well. A downhole heater was used to prevent gas hydrate formation within the wellbore and production tubing. Sustained gas flows ranging from 2 000 to 4 000 cubic metres a day were maintained throughout the 6.75-day test, and operations proceeded smoothly at three successive drawdown pressures. Water production rates were below 20 cubic metres a day during the testing period.

The 2007/08 production test at Mallik can be considered as a proof of concept for gas hydrate production by depressurization of a sand-dominated clastic gas hydrate reservoir. The program successfully used conventional oilfield drilling and well-completion technologies adapted for the unique physical and thermodynamic properties of gas hydrates, and the rates of gas production were promising. Further confirmation of the sustained gas-production rates achievable through depressurization will require production tests of much longer duration. Such tests are currently being planned in both Alaska and offshore Japan.

Figure TB-3.2: The Mallik Gas Hydrate Production Research Well, Mackenzie Delta, Northwest Territories, Canada. (Photo courtesy of the Geological Survey of Canada).

(Dallimore and Collett 2005), a Japanese study in the Nankai Trough (Takahashi and Tsuji 2005), a 2007 drilling program in northern Alaska (Hunter *et al.* 2011), and a 2012 testing program conducted also in Alaska (Schoderbek, 2012).

Makogon (1981) has suggested that gas production from the Messoyakha gas field in Siberia was enhanced by significant long-term dissociation of an overlying gas hydrate deposit in contact with the conventional free-gas reservoir below. While there is evidence to suggest that some of this gas was indeed produced from the hydrate deposit by depressurization, as extraction of free gas from the underlying conventional reservoir decreased local formation pressures (Grover *et al.* 2008), there is continuing debate about this interpretation (Collett and Ginsburg 1998). Unfortunately, the lack of field data to confirm the initial conditions at Messoyakha or to quantify the production response greatly limits any modern engineering evaluation.

3.4.1 DEPRESSURIZATION OF THE RESERVOIR

Currently, the depressurization technique is considered the most cost-effective and practical way to dissociate gas hydrates (Moridis *et al.*, 2009). The primary method involves reducing reservoir pressure by mechanical means. This can be done by directly reducing the reservoir pressure or by reducing the pressure in the overlying or underlying sediments in contact with the gas hydrate reservoir and allowing this pressure change to transfer to the reservoir naturally.. Originally, it was assumed that the formation of gas hydrates consumed all free water in the sediment pores, creating a relatively contiguous solid hydrate phase that effectively prevented the transmission of a pressure change into the formation. However, field programs (Kleinberg *et al.* 2005) and laboratory studies (Kvamme 2007; Jaiswal *et al.* 2009; Minagawa 2009) have found that even the richest gas hydrate accumulations retain small but measurable volumes of mobile liquid water, sufficient to support the propagation of a pressure field into the formation.

Using conventional oilfield technology, depressurization can be accomplished by perforating the production well casing at the target interval and reducing the weight of the fluid within the well. Normally, a well is filled with fluid from top to bottom. The weight of the fluid is balanced against the pressure of the reservoir in order to prevent the contents of the reservoir (oil, gas, and/or water) from flowing up the well uncontrolled. By pumping a portion of the fluid out of the well casing, the pressure exerted on the bottom of the well (and thus on the reservoir in contact with the well bore through the perforations) can be reduced in a controlled manner. In the case of a gas hydrate reservoir, once the pressure is reduced below the gas hydrate stability condition, dissociation of gas hydrates will occur in the vicinity of the perforations, releasing gas and water that will then flow to the well. The efficiency of this technique is influenced by the abundance and inter-connectivity of pores containing liquid water, which enable the transmission of the pressure change into the formation.

For some reservoir settings, particularly those near the base of the gas hydrate stability zone, a free-gas interval may directly underlie the gas hydrate deposit (Makogon 1981; Moridis *et al.* 2007; 2011). In these cases, the well could be perforated in the free-gas zone, enabling production of the free gas. As envisaged by Makogon (1981) and shown by Grover *et al.* (2008) for the Messoyakha gas field, the resulting pressure reduction within the free-gas interval can be transmitted to the overlying gas-hydrate-bearing sediments, inducing dissociation of their gas hydrate content. In theory, such settings should yield promising productivity, although no significant deposits of this type have been verified to date.

One practical consideration of the depressurization technique is that gas hydrate dissociation is an endothermic (heat absorbing) process that induces cooling of the local formation. If the magnitude of the temperature reduction is sufficiently large, gas hydrate dissociation can be impeded. If the dissociation-inducing depressurization leads to pressures below that at the quadruple point of the hydrate (that is, the point where free gas, liquid water, ice, and hydrate coexist), the liquid pore water can actually freeze. Preliminary reservoir simulation modelling suggests that this process depends on the initial reservoir conditions and the production rate (or the constant bottomhole pressure at which the well may be operated), with transfer of heat resulting from pore-water movement being particularly important.

A similar consideration, commonly encountered with conventional gas wells, is the temperature regime of the free gas as it flows to the well and up the production tubing. In this case, the

Box 3.3 **Testing production in offshore Japan setting: The Nankai Trough**

To prove applicability of the depressurization technique as a feasible production method in methane hydrates in deepwater sediments, Japan Oil, Gas and Metals National Corporation (JOGMEC) conducted the first offshore production test off the coasts of Honshu island. A drilling vessel "Chikyu" was employed for the field program that was started in early 2012 with drilling of production and monitoring boreholes and intensive data acquisitions, and the flow test (Yamamoto *et al.*, 2014). On March 12, 2013, JOGMEC confirmed production of methane gas estimated from methane hydrate layers after lowering the bottom hole pressure of the production hole. The pressure was reduced from the original pressure of 13.5MPa to 4.5MPa, and approximately 120,000Sm^3 of methane gas was produced until sand production forced to terminate the flow on March 18. Data from this program is still being analyzed by JOGMEC, in partnership with the National Institute of Advanced Industrial Science and Technology (AIST).

concern is that the free gas cooled by the endothermy of gas hydrate dissociation and by effects associated with the pressure reduction and the high gas velocities in the vicinity of the well (the Joule-Thompson effect) can potentially lead to the reformation of gas hydrate in the well bore or production tubing, causing serious operational problems. Examples of unwanted hydrate formation plugging pipelines or processing streams are well known in the oil and gas industry and have caused costly shutdowns, sometimes for months. Technologies routinely employed to reduce this problem are referred to as flow assurance. They include injection of low dose gas hydrate inhibitors, adding heat to the system, or generating a gas hydrate slurry that can be flushed out.

3.4.2 HEATING THE RESERVOIR

The objective of the reservoir-heating technique is to increase the temperature within the reservoir beyond the localized pressure-temperature threshold for gas hydrate stability. The only full-scale field production test using this technique was conducted at the Mallik site as part of the 2002 gas hydrate production-testing program (Dallimore and Collett 2005). The test lasted approximately five days. Hot brine (70°C at surface / 50°C at formation depth) was circulated across a 13-metre perforated test interval. Bottomhole flowing pressure was maintained slightly above formation pressure. Thus the test permitted assessment of the efficiency of heat conduction into the formation (that is, with no direct heat transfer by formation fluids). With only 500 cubic metres of gas produced over the entire testing period, the 2002 Mallik test was not particularly productive. However, the objective of the test was to demonstrate the feasibility of producing gas that originated indisputably from hydrate deposits, rather than the maximization of such production. It suggested that thermal heating alone is likely to be a comparatively inefficient and expensive way to produce gas hydrates over the long term. Moridis and Reagan (2007a) and Moridis *et al.* (2009) demonstrated through numerical simulation studies that thermal stimulation is thousands of times less effective than depressurization as a dissociation-inducing method for gas production from hydrates.

Research continues into developing downhole-heating techniques that require lower direct-energy input and provide more effective heating of the formation (Schicks *et al.* 2011). Downhole heating may be beneficial, in some reservoir settings, to overcome endothermic cooling of the formation caused by gas hydrate dissociation and/or to manage the temperature regime of the gas stream to prevent re-formation of gas hydrates in the vicinity of the wellbore and inside the tubing. For certain reservoir conditions, a combination of reservoir depressurization and supplementary in situ heating might be optimal for sustaining gas hydrate production over the longer term (Moridis and Reagan 2007b; Moridis *et al.* 2009).

3.4.3 CHEMICAL STIMULATION

Gas hydrate production by chemical stimulation involves the manipulation of gas hydrate phase-equilibrium conditions by injecting dissociation-inducing chemicals, such as salts and alcohols, into the reservoir. These chemicals alter the energy potential of water in contact with the solid gas hydrate phase, causing dissociation. This approach has been used for decades to maintain flow assurance in gas wells and

Box 3.4 **The Ignik Sikumi Gas Hydrate Field Trial**

The Ignik Sikumi #1 Well was designed for a short-duration field trial of a potential gas hydrate production technology (Farrell *et al.* 2010; Schoderbek *et al.* 2012). The approach involves injecting carbon dioxide into gas-hydrate-bearing sandstone reservoirs to produce a chemical exchange reaction that releases methane gas and, at the same time, traps carbon dioxide in a solid carbon dioxide hydrate. Operations were conducted from temporary ice pads in the Prudhoe Bay area of Alaska's North Slope in the winters of 2011 and 2012.

Initially, ConocoPhillips undertook the project in collaboration with the US Department of Energy (USDOE). Drilling began on April 5, 2011, and in less than two weeks, the well had reached a depth of 781 metres. Wireline well logs confirmed four gas-hydrate-bearing sand horizons. The primary test target, 675 metres below the rig floor, was 13.4 metres thick. The well was completed and a range of scientific monitoring devices and chemical injection and gas-lift equipment was installed before the well was temporarily suspended and the rig moved off location on April 28, 2011.

Early in 2012, ConocoPhillips and the USDOE returned to the site, along with a new project partner, the Japan Oil, Gas and Metals National Corporation (JOGMEC). Their goal was to conduct the first field trial of carbon dioxide-methane exchange in naturally occurring methane hydrate reservoirs (Schoderbek *et al.* 2012). The field trial consisted of an initial phase of chemical injection, followed by controlled, step-wise pressure reduction. Over a 12-day period in late February and early March, 5 950 cubic metres of blended carbon dioxide (23 per cent) and nitrogen (77 per cent), along with small volumes of chemical tracers, were injected into the formation. Mixed gas was used, rather than pure carbon dioxide, to enhance opportunities for the carbon dioxide to interact with the native methane hydrate.

Beginning on March 4, 2012, the well was operated by pumping fluids from the wellbore. That lowered pressure enough to draw fluids from the formation, while remaining above the pressure that would destabilize the native methane hydrate. Following an initial period of erratic production and operational challenges, the well flowed continuously for the final 19 days of the test, which ended on April 11, 2012. During this final period, flowing reservoir pressures were smoothly lowered and production rates steadily increased from 560 cubic metres a day to 1 280 cubic metres a day. The recovered gas was progressively dominated by methane. Overall, the well produced for 30 days during the 38-day flow-back period, with cumulative gas production approaching 28 317 cubic metres.

The project team is currently working with the field data, which have been made public. Analysis will focus on understanding the nature of the processes active in the reservoir (Anderson *et al.*, 2014).

to prevent blockages in pipelines due to the unwanted formation of gas hydrates. While chemical injection remains an option for dealing with flow assurance issues, its utility for field-scale production of gas hydrates appears limited. Operational considerations and the costs associated with injecting large volumes of chemicals into the reservoir are major considerations, as are the rapidly declining effectiveness of the inhibitors (because of continuing dilution by the large amounts of water released during the dissociation process) and potentially overriding environmental concerns.

A new concept based on chemical processes at the molecular level has been the subject of laboratory and modelling studies (McGrail *et al.* 2007; Graue *et al.* 2006; Stevens *et al.* 2008). The goal is to release methane by introducing another gas, such as carbon dioxide, which would change the chemical conditions in the reservoir and replace the native methane hydrate with carbon dioxide or other mixed gas hydrates. This process could resolve some of the potential geomechanical issues associated with other production methods and allow for synergistic storage of carbon dioxide. However, many technical challenges exist (see Farrell *et al.* 2009), most notably the ability to inject carbon dioxide into water-bearing, low-permeability formations. A field trial of this concept, undertaken in Alaska in 2012, successfully employed a mixture of nitrogen and carbon dioxide gas to enable injection (Schoderbek *et al.* 2012). For a summary of the field trial and results to date, see Text Box 3.4.

3.4.4 WELL COMPLETION

Well completion is the final step in well construction prior to production. Well completion includes design and installation of the production casing, measures to access the formation and to control near-wellbore interactions, placement of downhole production equipment (production tubing, downhole pumps, etc.), and installation of equipment to allow intervention during production should unexpected operational issues arise or should it be desirable to further stimulate production from the reservoir. Advances in completion technologies have substantially improved the efficiency of oil and gas recovery and enabled cost-effective production in reservoirs that would not have been considered economic even a few decades ago.

The major elements of a typical well completion for a production well using the pressure drawdown technique are shown in Figure 3.5. Completion considerations for gas hydrate production will likely include:

- Measures, such as sand screens or gravel packs, to control sand inflow to the wellbore due to loss of sediment strength upon dissociation of in situ gas hydrates in unconsolidated media;
- Custom-designed downhole pumps and/or downhole heaters and/or chemical flow lines, depending on the gas hydrate production method utilized;
- Equipment to lift or pump produced gas and water to the surface;
- Completions that enable concurrent production of multiple gas hydrate layers from the same well; and
- Provisions for smart completions that allow real-time monitoring of the formation response and manipulation of downhole pressure and temperature to optimize gas hydrate production.

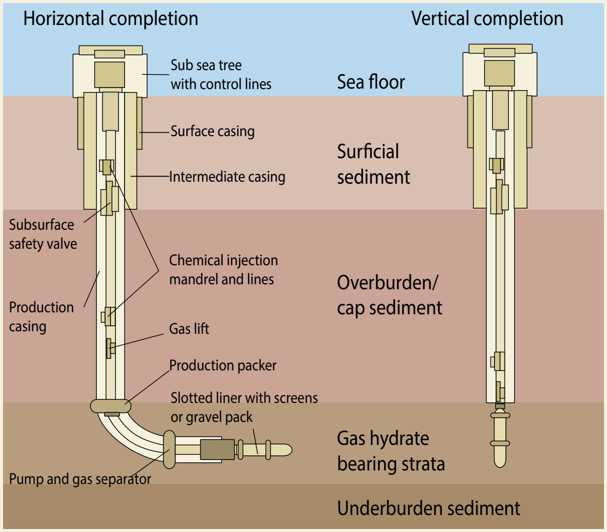


Figure 3.5: Well completion for gas hydrate production. Well schematics show possible horizontal and vertical well completions for a gas hydrate production well employing the depressurization technique. Modified after Hancock *et al.* (2010).

3.4.5 MANAGING AND MONITORING A PRODUCING GAS HYDRATE FIELD

Production operations for a typical gas hydrate field would likely extend over a decade or more. Experience to date suggests that the technologies used for sand-dominated reservoirs will be based on production equipment and procedures already employed in conventional oil and gas fields. However, as commercial production of gas hydrate is still hypothetical, it is challenging to establish a reliable basis for the prediction of the long-term production response of a gas hydrate reservoir. For a conventional gas field, such predictions are normally accomplished through sophisticated numerical reservoir simulations that enable the estimation of flow responses and evolving changes in critical reservoir properties over the anticipated production life of the field.

Given the importance of reliable field predictions, considerable effort is underway, worldwide, to develop and/or improve reservoir simulators to accommodate the unique properties and behaviours of gas hydrates. However, the task is complex. While some progress has been made in verifying the models through short-term formation pressure tests (Anderson *et al.* 2010; Wilder *et al.* 2008) and the Mallik 2008 full-scale test (Kurihara *et al.* 2012; Udden *et al.* 2012; Wright 2011), results remain speculative. Rutqvist *et al.* (2009), Moridis

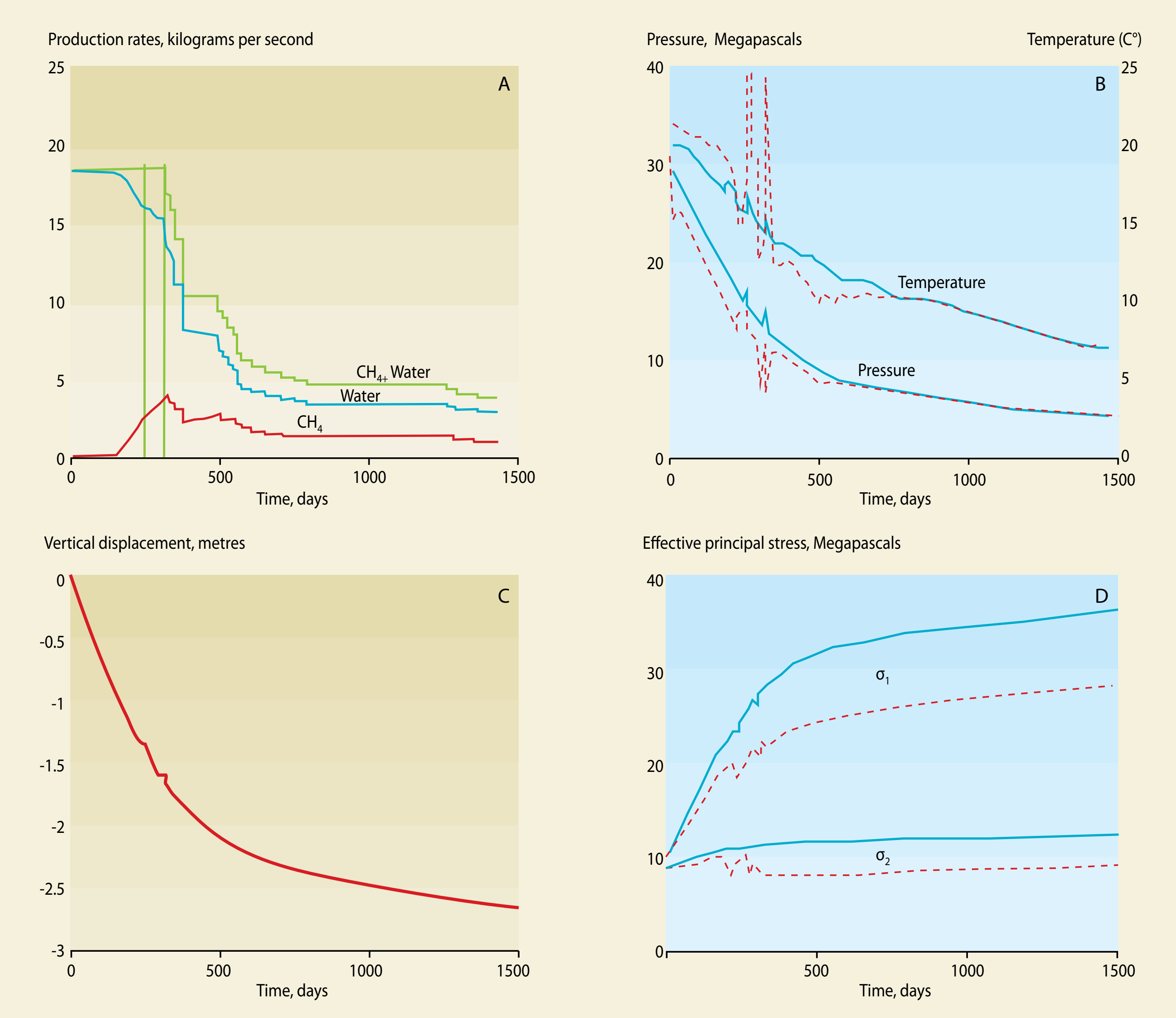


Figure 3.6: This figure shows first order reservoir simulation modeling to assess the response of a gas hydrate reservoir to depressurization-based production (Moridis et al., 2011). Frame A shows gas and water production rates, frame B shows reservoir pressure and temperature evolution, frame C shows ground surface settlement and frame D shows changes in the stress regime of the reservoir.

et al. (2011) and Rutqvist and Moridis (2012) have reviewed first-order assessment of the first four years of production and the associated geomechanical response for hypothetical marine and permafrost gas hydrate deposits. As shown in Figure 3.6, these simulations suggest substantive changes in water and gas production over time, as well as significant surface displacement.

A critical element in the field production testing phase is the detailed evaluation and monitoring of associated environmental impacts. This evaluation will require study of baseline conditions within the environment prior to the test, as well as monitoring of any changes in these conditions during and after the test (Fujii *et al*. 2012; Nagakubo *et al*. 2011). Parameters that will be monitored include the impact of subsidence or other geomechanical instability and possible release of methane or other substances into the ocean or atmosphere. An important environmental issue is the impact of the release of colder, anoxic, and low-salinity water (originating from the dissociation of marine hydrates) near the ocean floor, with potentially significant consequences for chemosynthetic communities there (Moridis and Reagan 2007a, b).

3.4.6 POTENTIAL FOR EXTENDING PRODUCTION BEYOND SAND-DOMINATED GAS HYDRATE RESERVOIRS

At this time, only gas hydrate deposits in which the hydrate occurs as a pore-fill within clay-poor sediments of high permeability are seen as well suited to sustained production with currently available technologies employed for production from conventional oil and gas resources. However, gas hydrates in such reservoirs are likely to represent only a small fraction of the global gas hydrate inventory. The bulk of global gas hydrate occurrences probably consists of dispersed, low-concentration gas hydrate accumulations (perhaps occupying five per cent or less of sediment pore space) in fine-grained marine sediments. These are unlikely to be candidates for commercial production due to low resource density, limited permeability, and low sediment strength (Moridis and Sloan 2007).

Recent drilling investigations carried out in offshore India (Collett *et al*. 2008) and Korea (Park 2008), however, have identified thick sedimentary sections containing a variety of macroscopic gas hydrate forms, including fracture fillings and nodules. Gas hydrate concentrations in these marine settings can be in the range of 20 to 40 per cent of bulk sediment pore space, making them plausible production candidates if significant geomechanical challenges can be overcome (Moridis *et al*. 2013). In addition, highly concentrated gas hydrate occurrences associated with cold vent features have been observed within 100 metres of the seabed in several offshore locations, including offshore Korea (Bahk *et al*. 2009), the Cascadia margin (Riedel *et al*. 2006a, b), and the Gulf of Mexico (Sassen *et al*. 2001). While such deposits may hold potential as future production targets, they are not suited to conventional oil and gas production methods. Thus, it is likely that new technologies and approaches will be required to achieve economic production of gas hydrates in fine-grained, unconsolidated marine sediments.

3.5 TIME FRAME FOR GAS HYDRATE DEVELOPMENT

Commercial production of gas from gas hydrates has not yet occurred. Several production research and development studies have, however, been carried out, most notably at the Mallik site in Canada (see summary in Dallimore *et al*. 2012) and in the Nankai Trough (Yamamoto *et al*., 2014). While this research has clearly identified depressurization as

Box 3.5 **Environmental Impacts of Gas Hydrate Production: Comparison to Existing Conventional and Unconventional Gas Development**

Hydrocarbon resources are commonly described as either "conventional" or "unconventional". Conventional resources are those that exist in the subsurface as liquids or gases under high pressure and within permeable reservoirs such that commercially-viable production (extraction) rates can be achieved simply by drilling into the reservoir. In fact, a primary concern with conventional reservoirs is in controlling and limiting the production rate, particularly in the early phases. Failure to maintain this well control can result in well blow-outs and uncontrolled hydrocarbon release to the environment. In contrast, reservoir quality in unconventional reservoirs is typically very low, and as a result, additional engineering means are required to improve reservoir quality around well bores to achieve desired flow rates. Gas hydrates, which require some combination of reservoir depressurization, heating, and/or chemical injection to be productive, are therefore unconventional reservoirs.

While the vast majority of hydrocarbons produced for energy continue to come from conventional reservoirs, production from unconventional resources, most notably shale gas in the United States, is growing rapidly. It cannot be assumed, however, that all unconventional resources will be associated with the same environmental risks. The following discusses general types of environmental risks with respect to the issue of gas hydrate production.

Loss of well control/spills: This risk, which is significant in conventional resource development, can also occur in unconventional development, particularly where resources are deeply buried and under high pressure. Gas hydrates, which are by definition shallow (and thus relatively low-pressure) resources, are therefore very unlikely to support uncontrollable flow rates. In fact, a primary challenge in gas hydrate production is not only establishing flow, but sustaining it. Because gas hydrate reservoirs only produce recoverable methane when artificially (and temporarily) removed from their natural pressure condition (a condition that is imposed by the simple presence of the overlying sediment for onshore gas hydrates, and by the water column for offshore gas hydrates), any cessation in the energy input used to achieve pressure reduction will immediately re-establish gas hydrate stability conditions and halt the methane release (see Nagakubo *et al*., 2011; Moridis *et al*., 2014). Lastly, liquid hydrocarbons are not known to pool at the shallow sediment depths at which gas hydrates occur, so the risk of inducing oil spills while recovering methane from gas hydrate is minimal.

Water Consumption: Unconventional production, such as shale gas, shale oil, oil shale, and tar sands are characterized by large water demands during extraction. Gas hydrate drilling and production, as now envisioned, would require minimal water useage as the primary stimulation method will be the imposition of reduced pressure through simple partial evacuation of the wellbore, as opposed to water-intensive thermal stimulation or permeability-creation through artificial fracturing.

Water Quality Impacts: All hydrocarbon production results in the co-production of reservoir brines along with the oil and the most promising technique, the testing has thus far been of limited duration and does not provide a basis for consideration of the long-term production response of the reservoir.

The next milestone in this field will likely be a series of extended-duration production tests, in which the long-term production behaviour of the reservoir and the associated physical impacts can be assessed more fully. These projects would be complex, expensive, and technically challenging. However, the data acquired during long-duration production testing are critical for the refinement and calibration of numerical reservoir simulators and for addressing persistent uncertainties in the prediction of long-term, field-scale reservoir responses and potential environmental impacts. The lessons from such tests could ultimately contribute to the design of specific production strategies tailored to particular geological settings around the world.

For the immediate future, gas hydrate production research will likely continue to be facilitated primarily by government

gas. In unconventional production, this “produced water” also includes substantial volumes of injected water that has returned to the surface. The handling, transmission, reuse and ultimate disposal of produced water are prone to incidents of water release that can impact surface water and groundwater quality. In addition, the transmission of deeper formation fluids (water and hydrocarbons) into aquifers (via loss of “wellbore integrity” commonly associated with faulty or degraded cement seals) is a poorly constrained risk in all hydrocarbon development. Gas hydrate can also be expected to result in potentially-significant volumes of produced water which will need to be disposed of. As mentioned above, however, gas hydrates tend to exist too close to the sea floor or ground surface to coexist with liquid hydrocarbons, limiting the hydrocarbon contamination danger during production. Moreover, given that the water released during hydrate dissociation is highly purified (the combination of hydrate formation and dissociation has even been researched as a means of purifying water), the produced water will be a blend of fresh and in-situ water. The issues associated with gas hydrate produced water management will therefore be unique. For example, in the marine setting, it may be necessary to add salt to the water before returning it the environment.

Air Quality Impacts: Air quality impacts can occur in a variety of ways. Fugitive emissions associated with releases during drilling and losses at pipelines and associated compressor stations are poorly constrained at present and are the subject of substantial research related to both emission detection and mitigation. Gas hydrate production, like any conventional gas production, will add to the total volume of gas being handled, and as such, could generate additional emissions. Similarly, potential impacts associated with utilization (combustion and release of CO_2) will also be the same for any gas, regardless of the reservoir from which it is produced. However, as discussed in Volume 2 Chapter 1 and Volume 2 Chapter 4, potential positive implications of additional gas hydrate utilization could occur if that gas displaces fuels that burn less cleanly. In this regard, the relative purity of hydrate-derived gas (commonly 99% methane with limited impurities, which strongly distinquishes it from other unconventional gas sources) should give it the smallest air-quality impact of any fossil fuel resource. Moreover, as suggested in Text Box 3.4, it may be possible to protect the air quality by injecting waste CO_2 gas into the hydrate-bearing formation rather than allowing the CO_2 produced while burning methane to enter the atmosphere.

Methane Gas “Burps”: Gas hydrate may have been an active participant in past episodes of global climate change, resulting in substantial additions of methane gas to the atmosphere (see Volume 1 Chapters 2 and 3 for a full discussion). Such releases are inferred to have occurred over long time frames in response to global changes in water-bottom temperature and sea-level. The potential for similar releases in response to ongoing climate change is uncertain, but whatever that risk may be, there is no connection to the issue of gas production from gas hydrate because climate-sensitive hydrates (those with the potential to respond to environmental change) and reservoir-quality hydrates exist as physically distinct and separate sub-sets of the global gas hydrate distribution. There is no meaningful opportunity to either mitigate future climate-driven releases of methane from gas hydrate, nor exacerbate them, through production (see Boswell and Collett, 2011).

funding, with industry participation. The desire to conduct tests of extended duration requires facilities and infrastructure that are accessible year-round. The most cost-effective of such locations are in the Arctic, close to areas of existing industry activity (see Text Boxes 3.2), and ultimately, learning derived in the Arctic will be tested in offshore settings. Besides the inherent complexities associated with offshore operations, a particular challenge in this setting is the shallow sub-sea-floor depth and structural complexity of the candidate reservoirs (Konno *et al*. 2010; Nagakubo *et al*. 2011).

Given the current status of gas hydrate production research and the challenges and complexities of proposed future research and development efforts, it is unlikely that meaningful production of gas from gas hydrates will occur within the next decade.

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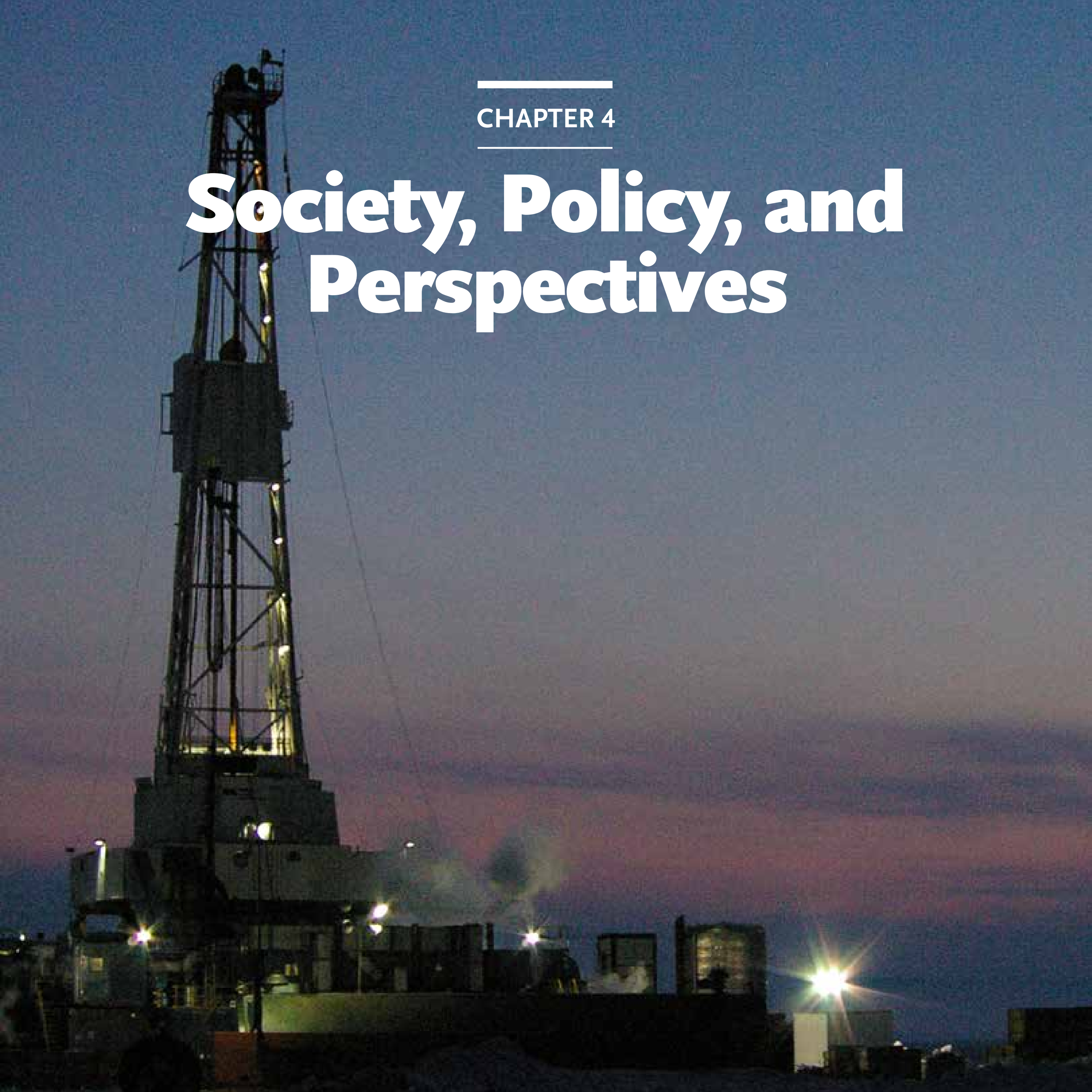

CHAPTER 4

Society, Policy, and Perspectives

4.1 INTRODUCTION

4.1.1 THE DRIVERS

For most of modern history, access to inexpensive and reliable energy has been central to economic development and social progress. However, the world is increasingly characterized by unsustainable economic growth, resource scarcity, and climate change that is driven by fossil fuel use. In these circumstances, many policy-makers have recognized the need to develop strategies to adapt the global energy mix to meet long-term social and ecological sustainability goals – part of what is called a green economy.

UNEP defines a green economy as one that results in "improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities" (UNEP 2010a). In its simplest expression, a green economy relies on low- to no-carbon energy sources and is resource-efficient and socially inclusive. In such an economy, growth in both income and employment is driven by public and private investments that reduce or eliminate undesirable carbon emissions and pollution, enhance energy and resource efficiency, and prevent the loss of biodiversity and ecosystem services.

Currently, most of our economic activity and growth relies heavily on carbon-intense energy sources and does not take into account their negative side effects on environmental quality. While fossil fuels will remain part of the world's energy system for some time, changing the balance of fuels within the mix could reduce pressure on the global climate system and the world's ecosystems. Since natural gas, of all conventional fossil fuels,

Photo: Lawrence Hislop, GRID-Arendal

emits the least amount of carbon per energy unit produced (EIA 2013), increasing the use of natural gas, while reducing the consumption of other fossil fuels, might be considered as a step towards a green economy. Many international assessments have identified natural gas as a logical bridging fuel in the shift to a carbon-free energy future (WEC 1998; IEA 2011).

Gas hydrates offer a potentially huge non-traditional source of natural gas. As described in Volume 2 Chapter 2 of this report, there is evidence that gas hydrates are widespread, both in terrestrial deposits in the Arctic and in marine deposits along the continental margins (depths below 300m) of the world's oceans. The amount of energy locked in the crystalline lattices of gas hydrates has most recently been estimated to range from 0.1 to 1.1 million exajoules (Boswell and Collett 2011), or the equivalent of 3 000 to 30 000 trillion cubic metres of methane. As a point of comparison, annual global energy consumption is approximately 500 exajoules (IEA 2011).

These numbers do not necessarily represent the volume of gas hydrates that could actually be extracted for energy use. The amount that might actually be available for commercial development is a much smaller subset of this resource (Johnson 2011; Saeki *et al.* 2008; Collett *et al.* 2008). While this subset is still very substantial, questions remain about whether and how soon natural gas could be extracted at a commercial scale – and, indeed, whether extraction of methane from gas hydrates would be desirable from a societal perspective. Extraction could be technically and economically feasible, yet undesirable from the perspective of greenhouse gas reduction and climate change mitigation.

4.1.2 REALIZING GAS HYDRATE PRODUCTION: THE CHALLENGES

Technological

The technologies used to recover hydrocarbon resources have advanced significantly in the last decade. Exploration wells are being undertaken to evaluate production from deposits more than 9 000 metres deep and in 2 500 metres of water (Cunha *et al.* 2009), and natural gas and oil have been produced from shale formations, with significant impacts on regional energy supplies. It is realistic to expect that advances in technology and infrastructure will eventually also make gas hydrates economically accessible. At that point, developing the resource would become a societal decision rather than a technological or economic decision.

The current consensus among researchers is that natural gas could be recovered from gas hydrates with conventional hydrocarbon recovery techniques, by changing the gas hydrate from solid to gaseous form in the ground and transporting the free gas to the surface (see Volume 2 Chapter 3). The most cost-effective option would likely be the depressurization technique, which produces gas from gas hydrate by lowering the formation pressure. While some exploration and production research programs have been carried out successfully in recent years, more research would be required before full-scale production could be undertaken. A thorough analysis of the current state-of-the-art of all aspects of gas production from hydrates, with an extensive discussion of technologies, challenges, and uncertainties, can be found in the review studies of Moridis *et al.* (2009; 2011).

Another approach to extraction would involve injecting carbon dioxide into gas hydrate reservoirs (McGrail *et al.* 2007; Graue *et al.* 2006; Stevens *et al.* 2008). In this technique, the injected carbon dioxide would displace individual methane molecules from the hydrate lattice structure without melting the lattice. The released methane would then be brought to the surface, leaving behind a stable carbon dioxide hydrate. To its advocates, the appeal of this approach is that it would sequester carbon as well as releasing methane, in principle reducing the greenhouse gas footprint associated with energy production from gas hydrates. In theory, it would also maintain the geomechanical integrity of the gas hydrate and limit co-production of formation water. A recent field trial of this technique is currently being evaluated (Schoderbeck 2012).

Photo: Geological Survey of Canada

Environmental

Methane is a fossil fuel that contributes to greenhouse gases when burned. In addition, methane is, itself, a greenhouse gas. The presence of methane in the atmosphere was an important factor in creating – over geologic timescales – the global atmospheric and temperature conditions that have allowed humans to flourish. In recent times, however, the scientific consensus is that both anthropogenic methane and natural methane released as a result of human activities have helped induce global warming (IPCC, 2007) and are a concern as the world struggles to mitigate and adapt to climate change. Although less common than carbon dioxide in the atmosphere (Blasing 2011), methane is a particularly potent greenhouse gas (Lacies *et al.* 1981; Hansen *et al.* 1988), and relatively small fluctuations in atmospheric methane concentrations can have a large greenhouse impact.

Methane release from naturally dissociating gas hydrates is a topic of interest to those studying global climate change (Reagan and Moridis 2008, 2009). Although research on the subject has already been reported (Elliott *et al.* 2011; Bhattacharyya *et al.* 2012), it is currently included in only a few climate predictions, partly because the magnitude and timing of geologic emissions are poorly understood and therefore difficult to build into regional-scale models. Nevertheless, dissociation of gas hydrate deposits could, in the future, amplify warming, increase ocean acidification, and exacerbate oxygen loss (Zachos *et al.* 2005; Biastoch *et al.* 2011). From a global perspective, understanding the triggers and implications of methane release from destabilized gas hydrates is a critical knowledge gap that needs to be addressed.

While environmental considerations related to gas hydrates in nature remain an understudied topic, the environmental issues related to gas hydrate production would, in many ways, be quite different. Perhaps the primary difference relates to issues of scale. For example, when considering gas hydrates in nature, first-level issues relate to the vast amounts of gas hydrate distributed widely around Earth, but in relatively low concentrations. In comparison, commercial exploitation of gas hydrates would be limited to localized, concentrated deposits. The surface area of a typical field development would be less than 10 square kilometres and production would likely last less than 25 years. However, the issue of how local-scale exploitation of gas hydrates might interact with naturally occurring processes would have to be addressed.

A unique environmental challenge facing gas production from oceanic hydrates would be the disposal of the dissociation-originating water (Moridis and Reagan 2007a, b). This water, which would be anoxic, relatively low in salinity, and possibly quite cold, could have a considerable adverse effect on chemosynthetic communities on the ocean floor if not released higher in the water column. Another important challenge relates to the burial depth of many marine gas hydrate deposits. Geohazards like slope de-stabilization could by induced by extraction activities.

Policy

The policies that shape the future global energy system will depend on how human societies and decision-makers prioritize a range of objectives, including climate change mitigation, energy security, air and water quality, and human health. The issues that will have to be addressed extend beyond national borders and beyond short-term time scales. They include, but are not limited to, the following:

- Environmental issues and safeguards;
- Socio-economic issues and opportunities; and
- Policy development at the national, multinational, and international levels.

One argument that is advanced in support of developing natural gas hydrates as an energy source is that they are relatively widely distributed in marine settings, where 99 per cent of the global inventory of hydrates is located, with the remaining 1 per cent being in the permafrost (Sloan and Koh 2008). Supporters of development point out that gas hydrates could provide a reliable, secure energy source for many countries without substantial conventional domestic energy resources.

If increased natural gas consumption were to displace the use of other fossil fuels with higher greenhouse gas emissions, gas hydrates could be a transition fuel towards a more climate-friendly future. However, many policy challenges would have to be overcome. Efficient as it is, natural gas is still a fossil fuel that emits greenhouse gases. The time required for technology development and verification is expected to be several decades. Finally, substantial infrastructure investment would be required to realize significant worldwide gas hydrate production.


Photo: Yannick Beaudoin, GRID-Arendal

Box 4.1 **Natural Systems and Environmental Assessment Tools**

A number of internationally recognized tools are available to assess and monitor potential environmental issues related to resource extraction. These tools could be applied to production from gas hydrates – possibly with some modification.
Currently available tools include the following:

Environmental Impact Assessment (EIA) – The International Association for Impact Assessment (IAIA) defines an Environmental Impact Assessment as "the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made" (IAIA 1996). An EIA also involves an evaluation of the existing environment before development occurs.

Strategic Environmental Assessment (SEA) – The strategic environmental assessment is a relatively new tool designed to encourage dialogue among stakeholders at all levels. It aims to ensure that the policies and national plans related to resource extraction take other users of land, sea, air, water, and other shared environmental assets into account. An SEA is designed to be a transparent process involving all stakeholders – governmental, civil society, and private sector (DEAT 2007).

Ecosystem Approach to Management (EAM) – There is increasing recognition of the importance of an ecosystem approach to management (e.g., UNEP 2011). The 1992 United Nations Convention on Biological Diversity defines the ecosystem approach as: "Ecosystem and natural habitats management … to meet human requirements to use natural resources, whilst maintaining the biological richness and ecological processes necessary to sustain the composition, structure and function of the habitats or ecosystems concerned" (CBD 1992). The approach requires integration of information from a wide range of disciplines, across different levels of ecological and socio-economic organization, and on a range of temporal and spatial scales (CBD 2012).

Marine Spatial Planning (MSP) – This approach is designed to manage multiple uses of marine areas. MSP maps which activities can be undertaken where, manages conflicts between competing marine activities, and reduces environmental impacts by analyzing current and anticipated uses of the ocean. It is a practical way to balance demands for development with conservation goals. The principal output of MSP is a comprehensive spatial management plan for a marine area or ecosystem (Ehler and Douvere 2009).

4.2 GAS HYDRATES AND SOCIETY

4.2.1 SOCIO-ECONOMIC CHALLENGES

The contribution of gas hydrates to social and development goals would depend on a region's, a nation's, and/or a community's state of development, its gas hydrate endowment, and other living, non-living, and human capital endowments. The key for each geographic region would be to determine where and whether gas hydrates might fit in a larger development framework and whether the extraction, processing, and marketing of natural gas from gas hydrates would provide a net advance in achieving its goals.

Another consideration for countries and communities would be the degree to which they can meet their goals without exploiting gas hydrates. Many developing countries are tapping emerging markets that generate income directly from ecosystems. These income streams come from fisheries, tourism, and direct payments to protect marine biodiversity and the carbon held in coastal habitats (UNEP *et al.* 2012; Solgaard *et al.* 2012). Nations around the world are also finding new opportunities in service and technology sectors, as well as trade and finance. Still, for many countries, non-extractive resources and human capital might be insufficient to meet social and development targets. For these countries, gas hydrates could offer one approach to achieving higher levels of socio-economic well-being, while preserving the quality of the natural environment.

4.2.2 SOCIO-ECONOMIC OPPORTUNITIES

A report on gas hydrate research and development in Canada (CCA 2008) concluded that questions will and should be asked about the societal impacts of gas hydrate development in areas where the scale and extent of the development exceeds what has been experienced to date. In industrialized and diversified economies, the report noted, the potential social impacts of resource development tend to be focused in the area experiencing the development. Those having limited experience with development will seek to have specific social and/or economic goals met and to ensure clear benefits for their communities, while those with more experience will seek to improve upon previous goals and/or identify other goals (CCA 2008).

These basic social drivers are equally applicable to communities in developing states, where gas hydrates might someday represent a new way to meet development goals. If this happens, nations or communities will need a portfolio of options for meeting development needs equitably and sustainably, and for considering how new opportunities, such as those possibly provided by gas hydrates, might affect other options. A green economy approach provides a strategic and integrated framework for considering how a variety of development options can be balanced and managed, and how economic capital or financial returns can be reinvested to build the natural and social capital upon which a sustainable and resilient economy depends (UNEP 2010b). In the case of a proposed gas hydrate development, a green approach would try to ensure that the development:

- Would improve the social and economic well-being of society through equitable capture and distribution of rents and economic opportunities associated with the utilization of non-renewable resources;
- Would not threaten environmental and ecological resilience or productivity;
- Would not raise the cost of living faster than the standard of living;
- Would guarantee the sustainability of human well-being and the ecological health that people depend upon; and
- Would keep options open for future generations.

A full cost-benefit analysis would yield benefits when evaluating potential gas hydrate development in regions with limited experience with such development, especially in developing countries. The cost-benefit analysis would include both the likely monetary and non-monetary costs and benefits (Hanley and Barbier 2009). It would also provide a clear accounting of how these costs and benefits would be distributed across society, with special attention to costs and benefits that accrue to the host country/region/community and to components of society within the host country/region/community (Munda *et al.* 1995; Spangenberg and Settele 2010).

Benefits from gas hydrate development would depend on a range of factors. States might charge fees, taxes, and royalties that could be reinvested locally. Gas hydrate development might provide direct employment opportunities, depending on the degree to which the administration, transport, and technical operations were based locally. Employment could be created directly in industries such as shipping, aviation, warehousing, maintenance, construction, regulation, and monitoring. Indirect employment – for example, in hospitality, lodging, and provisioning industries – might result if operations sourced goods and services locally. Operations might also require the development of new infrastructure (roads, ports, power plants), which could support needed infrastructure development in the host countries.

Companies might also provide direct philanthropic and community-support services, such as health and education services and, possibly, infrastructure to ensure local access and use of the resource. A number of companies currently engaged in oil and gas development are establishing skills-building programs that provide vocational training to local geologists, geophysicists, and environmental scientists, and also support selected students pursuing post-secondary studies in related fields. Industry philanthropy, however, would be case-specific, and the longevity of such activity is unclear.

Photo: Yannick Beaudoin, GRID-Arendal

4.3 POLICY ISSUES AND OPTIONS

4.3.1 REGULATION FOR SUSTAINABILITY IN A CONVENTIONAL ECONOMIC MODEL

Some of the policy issues surrounding gas hydrate development are related to regulation. Particularly as a consequence of the 2010 Deepwater Horizon blowout in the Gulf of Mexico, regulatory considerations related to frontier oil and gas exploration and development have come under increased scrutiny worldwide (Anderson *et al.* 2011). At present, there are no regulations specific to gas hydrate production. It is likely that gas hydrate production would be regulated as one of several unconventional gas resources, such as coal bed methane or shale gas.

If current practice is followed, the onus would be on industry to establish the concentration and geographic extent


Photo: Lawrence Hislop, GRID-Arendal

of the deposit, identify production technology, and quantify the reservoir productivity expected during the life of the producing field. Environmental assessments would also be required in order to consider surface and subsurface issues over both short and long terms. Potential subsurface issues to be considered might include possible leakage and migration of produced gas, strategies for subsurface disposal of wastewater, and disruption of subsurface resources, such as groundwater aquifers or conventional oil and gas deposits. Possible surface issues might include ground surface subsidence, a potentially significant challenge in oceanic accumulations (Moridis and Reagan 2007a, b; Rutqvist and Moridis 2012), as well as ecosystem impact and the cumulative effects of development.

In an offshore setting, jurisdictional issues could arise, leading to a need for special policy considerations. Although no potentially accessible gas hydrate occurrences have been found to date in areas beyond national jurisdiction, our ever-expanding knowledge of the oceans could lead to such discoveries. In these situations, global instruments like the United Nations Convention on the Law of the Sea could serve as mechanisms to address trans-boundary issues that might range from regulation and environmental management to the overall protection and equitable use of the global commons.

Other policy issues could go well beyond regulation. In a market economy, the primary drivers influencing gas hydrate research and development would vary from nation to nation and from company to company according to conventional economic factors, including national endowments of conventional hydrocarbon resources (supply), internal demand, and market forces (profitability). In those nations with abundant or secure energy resources, development of gas hydrate resources might occur more slowly or not at all, depending on the relative economics of gas hydrates versus conventional resource development and other factors. In nations with fewer and less secure conventional energy options but with significant gas hydrate prospects, a full and aggressive evaluation of gas hydrate resource potential might be more likely.

4.3.2 NATIONAL POLICY AND INTERNATIONAL ACTION ON CLIMATE CHANGE

Decisions associated with potential gas hydrate development would be influenced by more than economics and technology. Political forces and indirect economic considerations are likely to play an important role. For example, international aid, diplomatic concerns, or other socio-political factors could ultimately sway the decision as to whether a country should choose to proceed with development.

The choice to exploit or not to exploit might not, in fact, be a matter of national determination at all. The causes and impacts of climate change are global and require broad-based international action. The United Nations Framework Convention on Climate Change (UNFCC), now ratified by 195 countries, is the tool through which the nations of the world are attempting to prevent dangerous human interference with the climate system. Any development of new sources of carbon-based energy supplies might well fall under future international agreements reached through the UNFCC.

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