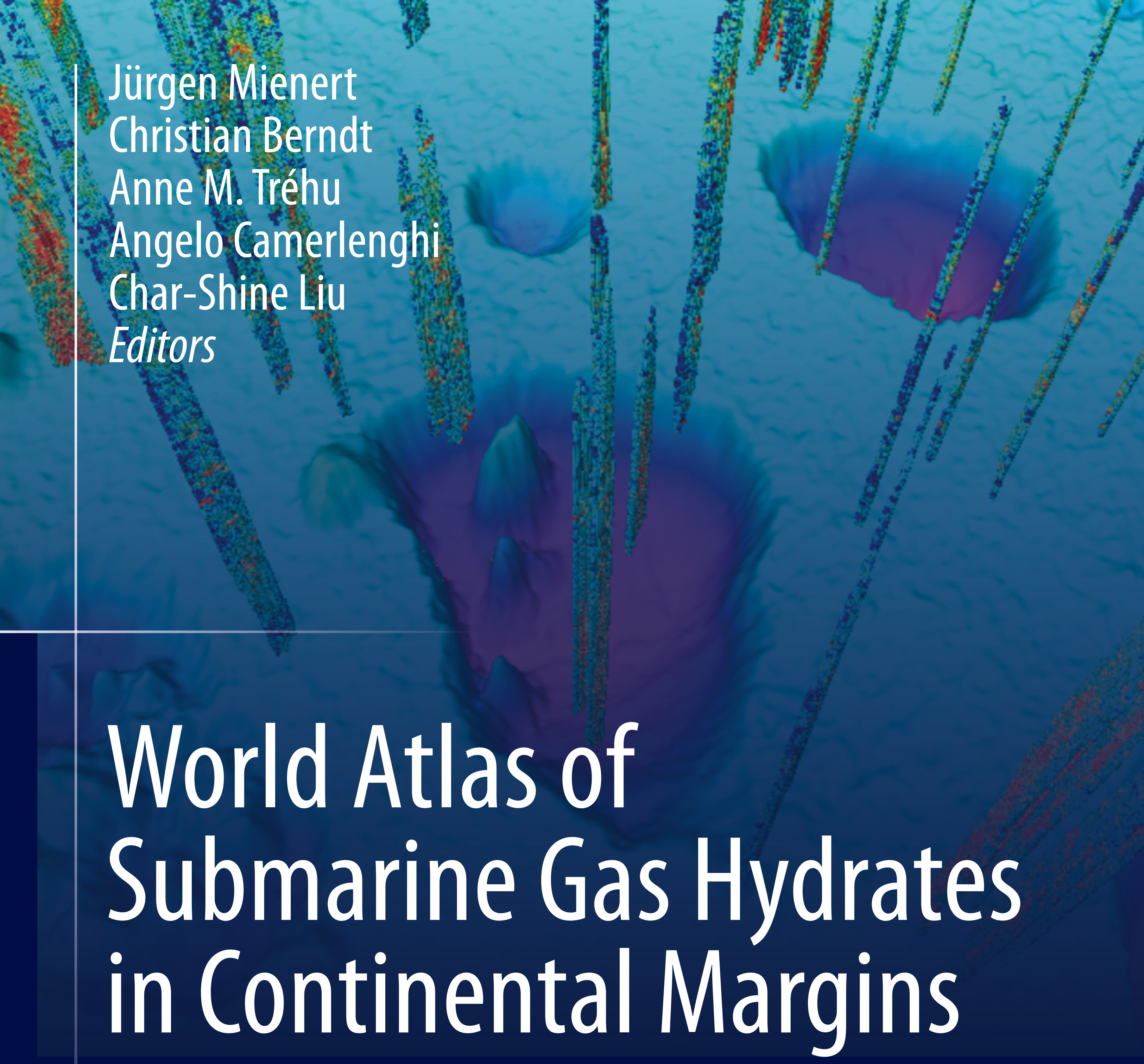

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ISBN 978-3-030-81185-3 ISBN 978-3-030-81186-0 (eBook)
https://doi.org/10.1007/978-3-030-81186-0

Cover image: Giant blow-out craters and active gas flares from the shallow (< 350m) Barents Sea floor document massive reactions of shallow gas hydrate provinces to ice sheet thinning and retreat during the postglacial. Courtesy of Andreia Plaza Faverola, CAGE—Centre for Arctic Gas Hydrate, Environment and Climate, UiT- The Arctic University of Norway, Tromsø, NO.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The *World Atlas of Submarine Gas Hydrates in Continental Margins* is a comprehensive global compilation of geophysical evidence for the presence of natural gas hydrates in the seafloor. Gas hydrates represent a major carbon reservoir in the Earth system that traps vast amounts of methane below the seafloor. Hydrates form through the capture of gas molecules in water molecule cages when there is sufficient water and free gas and if temperature and pressure conditions are met. Favorable conditions for gas hydrate formation can usually be found beyond the shelf edge and within the top few hundred meters below the seafloor. Because the kinetics of gas hydrate formation and dissociation are fast compared to many other geologic processes, this reservoir is dynamic and sensitive to climatic and tectonic perturbations. Thus, the gradual warming of the seafloor may destabilize gas hydrates, leading to gas blowouts and possible destabilization of the seafloor. The process of mapping the distribution of gas hydrates is therefore critical for the evaluation of offshore geohazards. As methane is the main component of natural gas, the methane in gas hydrates is also considered a future energy source, especially for countries that lack conventional hydrocarbon reservoirs. In the absence of photosynthesis, bacteria that feed on methane are one base of the food chain in the deep ocean. Gas hydrate formation, dissociation, and bacterial activity are important modulators for the flux of methane to the seafloor. For all these reasons, gas hydrate research has played a prominent role in the field of marine geology and microbiology over the past three decades.

As the most striking geophysical observation linked to gas hydrates is the bottom simulating reflector (BSR), we initially considered calling this book "The Atlas of Bottom Simulating Reflectors." A gas hydrate-related BSR shows a phase reversal compared to that of the seafloor. It is caused by an abrupt change in acoustic impedance at the boundary between the gas hydrate-bearing sediments above the BSR and the sediments containing free gas below. The BSR thus represents the base of the gas hydrate stability zone (GHSZ) and can be used to infer subseafloor temperature and pressure conditions as well as the presence or absence of gas hydrates and free gas. The atlas fills a major gap in the literature of geophysical exploration through the compilation of typical shapes and seismic expressions for almost all ocean areas where gas hydrates have been reported or suspected. This covers vastly different geological settings, including volcanic and non-volcanic passive margins as well as oceanic and continental subduction zones. By summarizing the main findings for each of these areas, the book both provides an overview of the occurrence of gas hydrate-related BSRs in different geological settings and with different types of geophysical data. It also provides new insight into the processes and time scales that affect gas hydrates.

Observations of BSRs in 2D and 3D seismic reflection data, combined with detailed analysis of P- and S-wave velocity and attenuation, electrical resistivity imaging, and gas hydrate stability zone (GHSZ) modeling, aid researchers in both academia and the hydrocarbon industry in understanding the potential extent and volume of gas hydrates in a wide range of tectonic settings on continental margins. Sub-seabed imaging techniques provide insight into the controlling mechanisms for the distribution and migration of gas as it enters and moves through the gas hydrate stability zone. Repeated imaging at the same site uncovers new details regarding the dynamic behavior of these systems. Over the past few decades, drilling campaigns such as the Deep Sea Drilling Project (DSDP), the Ocean Drilling program

(ODP), and the International Ocean Drilling/Discovery program (IODP) have allowed for the direct sampling of gas hydrates. They have been instrumental in constraining the geological and physical boundary conditions necessary for the formation of natural gas hydrates in continental margins and lakes. This volume summarizes these results and discusses the geophysical observations in this context.

The *World Atlas of Submarine Gas Hydrates in Continental Margins* is aimed at students, researchers, governmental organizations, and professionals from the hydrocarbon industry. Some familiarity with seismic data and some basic understanding of geological and tectonic processes will be required to get the most out of this volume. Apart from presenting a short overview of gas hydrate science (e.g., geology, geophysics, modeling), its main aim is to provide a global perspective on the variable geophysical observations related to gas hydrates in different parts of the world. With comprehensive references to key papers covering each location, it should also provide a good starting point for those who are new to a particular gas hydrate province. It will also provide ample teaching material for classes in marine geology and geophysics.

The atlas consists of fourteen parts containing a total of 43 peer-reviewed articles written by esteemed researchers from universities and government agencies around the world. The articles provide both new data and reviews of previously published data. Geophysical interpretations are discussed in the context of drilling and coring results when possible to ground truth the geophysical findings. The majority of contributions describe and discuss geophysical data from gas hydrate systems worldwide. These contributions are organized by geographic area (see map) and may serve as a reference for documenting future changes. Future researchers may use this comprehensive compilation of gas hydrate stability zone data to further investigate questions such as: What is the gas hydrate inventory for active and passive margins? Where are the most climatically sensitive gas hydrate reservoirs on Earth and how fast can they respond to geological and oceanographic perturbations? Which gas hydrate occurrences should be considered geological hazards? How do the geophysical characteristics of BSRs differ in various geological settings?

Each of the 14 parts of the atlas cover topics of international interest in documenting gas hydrates:

I A History of Gas Hydrate Research (Chaps. 1–3)
II Gas Hydrate Fundamentals (Chaps. 4–6)
III Gas Hydrate Drilling for Research and National Resources (Chaps. 7–16)
IV Arctic (Chaps. 17–21)
V Greenland and Norwegian Sea (Chaps. 22–23)
VI North Atlantic (Chaps. 24–27)
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XIII Antarctic (Chap. 40–42)
XIV Where Gas Hydrate Dissociates Seafloor Microhabitats Flourish (Chap. 43)

We are grateful to all our colleagues who contributed to this atlas documenting the characteristics of gas hydrate systems on continental margins.

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Acknowledgements

The World Atlas of Submarine Gas Hydrates in Continental Margins documents the high level of international research efforts necessary to understand the global occurrences of natural gas hydrates. Substantial knowledge increases about where gas hydrates lay in different geological environments have been made possible through decades of funding and a culmination of several years of dedicated geophysical exploration and gas hydrate sampling.

We are grateful to all our colleagues who contributed to this atlas documenting the characteristics of gas hydrate systems on continental margins. We thank those from the United States Geological Survey for encouraging us to compile this book, and we thank the Norwegian Research Council for providing financial support for this effort through funding the Centre of Excellence for Arctic Gas Hydrate, Climate and Environment (CAGE) at UiT—The Arctic University of Norway (grant 223259). We thank Jessica Green, a science writer at UiT funded by CAGE, for her help with language cleansing and styling guidelines. We also wish to acknowledge and thank the numerous national and multinational funding sources that enabled the geophysical expeditions that were necessary to acquire the data presented in this book.

Jürgen Mienert

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About the Editors

Jürgen Mienert is a Professor Emeritus for Applied Geophysics and Arctic Marine Geology at UiT—The Arctic University of Norway, Tromsø, Norway. He chaired the Department of Geology from 2008 to 2012, before he received an award for a Centre of Excellence by the Norwegian Research Council in 2012. He was Founding Director of this Centre for Arctic Gas Hydrate, Environment and Climate—CAGE—from 2013 to 2017. His research focuses on understanding the rate at which rising ocean temperatures can destabilize shallow, Arctic methane hydrate reservoirs leading to geohazards and methane release to the ocean and atmosphere. Jürgen received his Ph.D. in marine geoscience from the Christian-Albrechts University (CAU) at Kiel, Germany (1985). He was awarded a DAAD fellowship for studying at LDGO—Lamont-Doherty Observatory of Columbia University, New York (1981–1982) and was awarded a post-doctoral position at WHOI—Woods Hole Oceanographic Institution, Woods Hole, USA (1985–1988). He returned to Kiel in 1988 to join the newly established Centre for Marine Geosciences—GEOMAR—at the CAU, Kiel, before he moved to the Arctic University of Norway in Tromsø (1998). His collaboration with teams from Russia, USA, Canada, and Europe on polar shelf and slope environments facilitated active cooperation among hydrocarbon companies, technology providers, and Arctic research groups. His many sea expeditions included contributions to the Norwegian deepwater gas field "Ormen Lange" investigation, dives with Russian submersibles MIR from RV Keldysh (1998) to the deep ocean floor at the giant submarine "Storegga slide" on the Mid-Norwegian Margin and to natural gas release sites along the Barents-Svalbard Margins, which provided an indispensable guide for methane hydrate studies. His international research encompassed stays at Scripps Institution of Oceanography, USA (2002–2003), IFREMER—L'Institut Français de Recherche pour l'Exploitation de la Mer, FR (2007–2008), MBARI—Monterey Bay Aquarium Research Institute, USA (2017–2018), and OGS- Istituto Nazionale di Oceanografica e di Geofisica Sperimentale, IT (2018–2019). Jürgen has authored and co-authored more than 200 papers in scientific journals and special volumes.

Christian Berndt is Professor of Marine Geophysics at GEOMAR Helmholtz Centre for Ocean Research Kiel. He has a background in active source seismology. He has been working for the past 20 years on various aspects of fluid migration in sediment basins. These include the role of gas hydrates in the Earth system, hydrothermal systems caused by magmatic intrusions, and the links between pore fluids and slope stability. He held academic positions in the U.S.A., Norway, and the United Kingdom and has led or participated in more than 30 research expeditions all over the world.

Anne Tréhu is a Professor of Geophysics in the College of Earth Ocean and Atmospheric Sciences at Oregon State University. She obtained her Ph.D. from the MIT/WHOI Joint Program in 1982, where she specialized in ocean bottom seismometry and its application to seismicity and structure of plate boundaries. She has been interested in gas hydrates since she was introduced to them by Bill Dillon when she worked at the United States Geological Survey in Woods Hole, Massachusetts (1982–1987). She has been at Oregon State University since 1987, where her work on hydrates dovetails with her parallel interest in structures associated with subduction zone earthquakes since accretionary wedges provide a mechanism for methane to generate seafloor cold seeps and rich hydrate deposits. In 2004, she was Co-Chief Scientist of IODP Leg 204, which was dedicated to understanding the distribution and dynamics of gas hydrates associated with a structure named Hydrate Ridge on the continental margin offshore Oregon. She has published ~150 articles, with approximately one-third focused on gas hydrates, and participated in over 40 field expeditions, including one dive in Alvin and five expeditions using ROVs to explore and sample cold seeps and hydrates.

Angelo Camerlenghi is Director of the “Geophysics” Research Section of the National Institute of Oceanography and Applied Geophysics (OGS) and Associate Professor of Marine Geology at the University of Trieste. He holds a Master of Science in Geological Oceanography from Texas A&M University, College Station TX (1988) and a Ph.D. in Earth Sciences from the University of Milano (1991). From 2004 to 2011, he was ICREA Research Professor at the University of Barcelona. His research is on ocean margins geology and geophysics, with focus on polar margins, submarine geohazards, and manifestations of formation fluids circulation in marine sediments. His research is tightly related to scientific ocean drilling. He has studied the geophysical evidence of marine gas hydrates on the South Shetland Margin, Cascadia Slope, West Svalbard, and the mud volcano belt of the Eastern Mediterranean. His research is currently on the Mediterranean salt giant.

Char-Shine Liu is a Senior Researcher and CEO of the Ocean Center, National Taiwan University, Taipei, Taiwan. He was the Director of this Center from 2016 to January 2018 when he retired from faculty position at the Institute of Oceanography, National Taiwan University, where he was a Professor since 1994. During his Professor tenure, he also served as Director of the National Center for Ocean Research from 2003 to 2006 and Chairman of the Taiwan SCOR Committee from 2004 to 2009, among many other roles in his career. Char-Shine received his Ph.D. in Earth Science from the Scripps Institution of Oceanography, University of California, San Diego, USA in 1983. He did a 2-year (1983–1985) postdoc work at the Cornell University, New York, USA, followed by a 3-year stint as a geophysicist at then Standard Oil Company (now BP) in Dallas, Texas, USA, before returning to Taiwan in 1988 and took an Associate Professor position at the Institute of Oceanography, National Taiwan University. He has broad research interests from active tectonics of the Taiwan arc-continent collision to marine seismic exploration, seafloor surveying, and gas hydrate investigation. Char-Shine has collaborated with colleagues from USA, France, Germany, and Japan on various research topics from tectonics of Taiwan to gas hydrate study. He has led geophysical investigation of the gas hydrate field offshore southwestern Taiwan since 2004, and has authored and co-authored more than 140 papers in scientific journals and special volumes.

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Part I

A History of Gas Hydrate Research

1 Gas Hydrate Research: From the Laboratory to the Pipeline

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Abstract

Gas hydrates have been the subject of intensive research over the past several decades. Complications created by hydrate formation and the plugging of gas and oil flowlines has been the main driver in the development of predictive models based on experimental observations. The multiscale approach discussed in this article is based on many years of systematic investigations; phenomena related to gas hydrate formation are considered at the microscale to the macroscale. The processes surrounding hydrate nucleation, growth and agglomeration are critical to designing strategies for hydrate plug avoidance and management. An overview of the main key experimental techniques used in hydrate research will be presented, with special emphasis on how those techniques may provide valuable input in improving integrated hydrate models in different flow assurance scenarios.

1.1 General Aspects

Gas hydrates are solid inclusion compounds in which a hydrogen-bounded water network (the host) encapsulates small gas molecules (the guests). Common varieties of hydrate guests, also known as 'formers', include small hydrocarbons (e.g. methane, ethane), noble gases (e.g. xenon), diatomic gases (e.g. nitrogen), and fluorinated compounds (e.g. CH_2FCF_3) (Sloan and Koh 2007).

Although formation conditions are specific to a particular guest, hydrates are always stable at high pressure and low temperature (Sloan and Koh 2007). On a microscopic level, hydrates can form three different crystalline structures; these are known as Structure I (sI), Structure II (sII) and Structure H (sH). Structures sI and sII are of special interest as they can trap the small gas molecules found in both natural and industrial systems. In all three of the crystal configurations, the hydrogen-bounded water molecules form molecular cages, as shown in Fig. 1.1. The 5^{12} cage is considered a basic building block of these structures (Giavarini and Hester 2011; Jeffrey 1984; Koh et al. 2011; Warrier et al. 2016).

It is the size of the guest that determines which of the three structures will be created. Thus, gases smaller than 6 Å (e.g. methane, ethane, and carbon dioxide) induce the formation of Structure I, molecules between 6–7 Å (e.g. propane and isobutane) form Structure II, and molecules larger than 7 Å (e.g. iso-pentane, combined with a small guest such as methane) promote the formation of Structure H (Sloan and Koh 2007).

The increasing interest in gas hydrates is largely due to their potential as an energy resource. They are a non-conventional fossil fuel able to store up to 164 m^3 of methane gas for each cubic meter of hydrate, which is a high value of energy density compared to conventional fuel sources (Demirbas 2010). Another advantage of hydrates as a prospective fuel source is their abundance in nature, representing over half of the total reserves of organic carbon on Earth (Mahajan et al. 2007). Further research on natural methane hydrates motivated by implications for climate change, submarine geohazards, and geo-microbiological processes at the seafloor exist but are outside the scope of this article.

Gas hydrates have potential application in several technological areas, as shown in Table 1.1. In some cases, gas hydrate occurrence is not only desirable but critical in accomplishing a process goal (e.g. gas separation, desalination). On the other hand, the plugging of flowlines by gas hydrates in conventional offshore oil/gas operations represents a flow assurance problem, which can reduce or even stop the hydrocarbon flow. A similar problem can also occur in the extraction of gas from naturally occurring hydrate sources. Thus, significant effort and expense have been put

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J. Mienert et al. (eds.), *World Atlas of Submarine Gas Hydrates in Continental Margins*,
https://doi.org/10.1007/978-3-030-81186-0_1

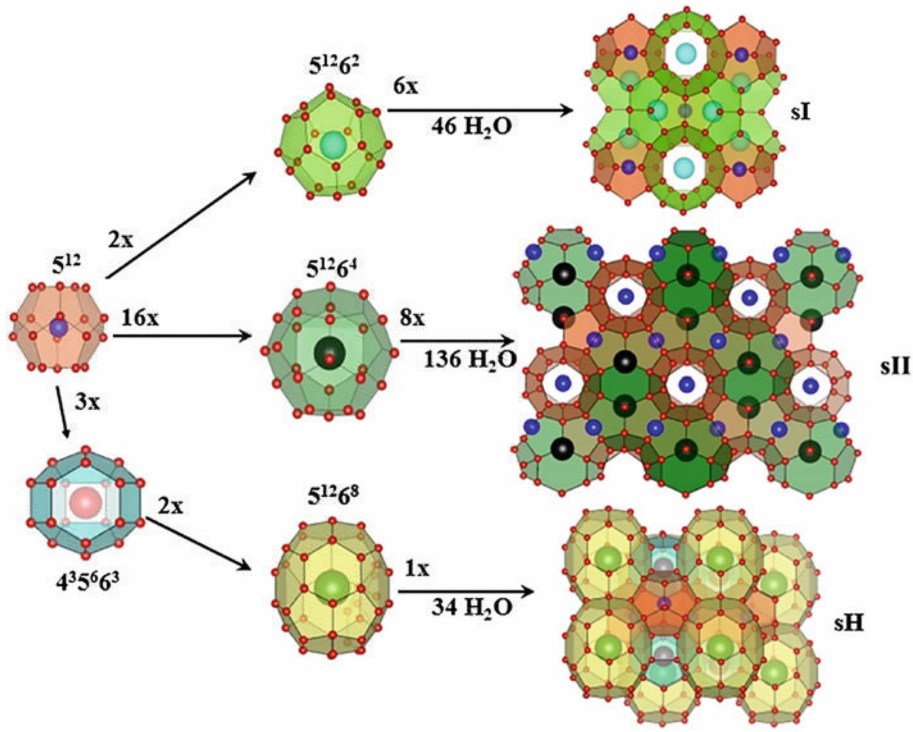

Fig. 1.1 Main gas hydrate structures. Number of cages and water molecules per unit is indicated (reproduced with license granted by AIP Publishing from Warrier et al. 2016)

Table 1.1 Summary of hydrate applications

Hydrate application	Guest/structure type	Focus areas	References
Hydrates in nature	Methane/sI (biogenic); natural gas mixtures (thermogenic	Resource exploration and assessment; gas production; geomechanics; Environmental impacts	Boswell et al. (2020) Collett (2019) Moridis et al. (2018) Ruppel and Kessler (2017)
Flow assurance	Typically sII, natural gas mixtures	Thermodynamics; LDHI-KHIs & AAs; Non-plugging oils; reaction limitations; multiphase flow	Sloan and Koh (2007) Kelland (2016) Sjöblom et al. (2010) Turner and Grasso (2017) Wang et al. (2018)
Energy storage	sI (methane); sII (hydrogen and natural gas)	Stability/capacity—NG Stability—H_2 Rapid formation	Stern et al. (2003) Florusse et al. (2004) Veluswamy et al. (2016)
Gas separation	sI, sII	Gas selectivity	Warrier et al. (2018)
Desalination	sI, sII	Salt exclusion; crystal morphology	Khan et al. (2019)

into effect to develop practical strategies for hydrate avoidance and management in production systems (Creek 2012; Sloan and Bloys 2000).

Beginning in 1810 with the discovery of gas hydrates by Sir Humphrey Davy (1811), the evolution of its research has been guided by several critical events, including detection of the formations in pipelines (1934) and later in natural environments (1965). The complications that gas hydrates create in the flow assurance of pipelines has been a driving force in the study of phenomena related to hydrate behavior. In this sense, a cross-disciplinary approach based on microscopic and macroscopic observations has been used alongside the development and implementation of predictive tools, giving rise to major advances in hydrate science. Many of these advances can be applied both within pipelines and in the natural environment (Sloan 2004).

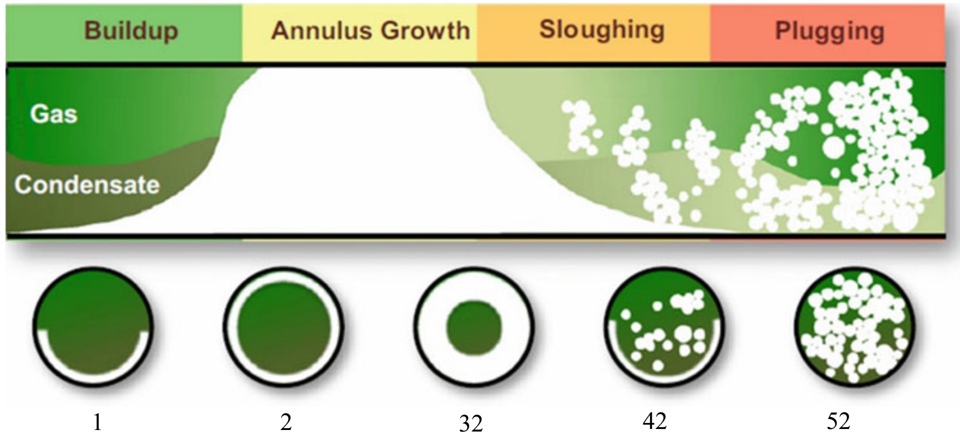

Fig. 1.2 Conceptual picture of hydrate formation and plugging in gas-dominated systems. The green color represents the gas and the white color represents the hydrates (modified from Lingelem et al. 1994 and reproduced with license granted by Elsevier from Zerpa et al. 2012)

One of the most important factors contributing to the formation of hydrates in flowlines is the relative amount of each phase present (e.g. gas, oil, or water). Thus, the mechanism for hydrate formation in oil-dominated systems is different from that of gas-dominated systems, even if some phenomena are common in both systems. Most research on the effect of gas hydrates on flow assurance in pipelines use large-scale observations as a starting point (Sloan 2004). There is a necessity to perform experimental work on a smaller scale using equipment and experimental techniques in the laboratory to obtain more detailed information on specific phenomena (e.g. viscosity, adhesion etc.) related to gas hydrates.

As mentioned, gas hydrates are commonly known to form within both gas- and oil-dominated systems, creating blockages that lead to flow problems. The conceptual model for hydrate formation and plugging in gas-dominated systems is shown in Fig. 1.2. It can be summarize as follows: (1) hydrates start to nucleate at the pipe surface, (2) after nucleation, hydrates grow rapidly and cover the circumference of the pipe, (3) the effective diameter of the line is reduced because of hydrate growth, (4) part of the deposit can detach from the wall (sloughing) due to fluid shear, and (5) hydrate particles can accumulate in other parts of the line (e.g. flow restriction) and lead the system to jam (Lingelem et al. 1994; Sloan et al. 2010; Sum et al. 2012; Zerpa et al. 2012).

Figure 1.3 depicts the conceptual model of hydrate plugging in an oil-dominated system (Majid et al. 2018). The relatively high proportion of oil and water typically makes the entrainment and emulsification of water into the oil phase a determinant step for hydrate formation. In this case, a hydrate film grows quickly around the water droplets, creating hydrate shells (5–30 μm thick) with a water core; finally, the hydrate-coated particles agglomerate to plug the flowline (Sloan et al. 2009, 2010).

Figure 1.3 shows that phenomena such as viscosification, film growth, deposition, bedding, and jamming can occur simultaneously. In contrast to gas-dominated systems (shown in Fig. 1.2), the oil chemistry of oil-dominated systems is a primary factor that can assist or restrict hydrate agglomeration and plugging (Costa Salmin et al. 2019; Fadnes 1996; Leporcher et al. 1998; Sjöblom et al. 2010; Zerpa et al. 2011).

To build and quantify conceptual models like those in Figs. 1.2 and 1.3, many observations and measurements are required in different experimental setups and at different

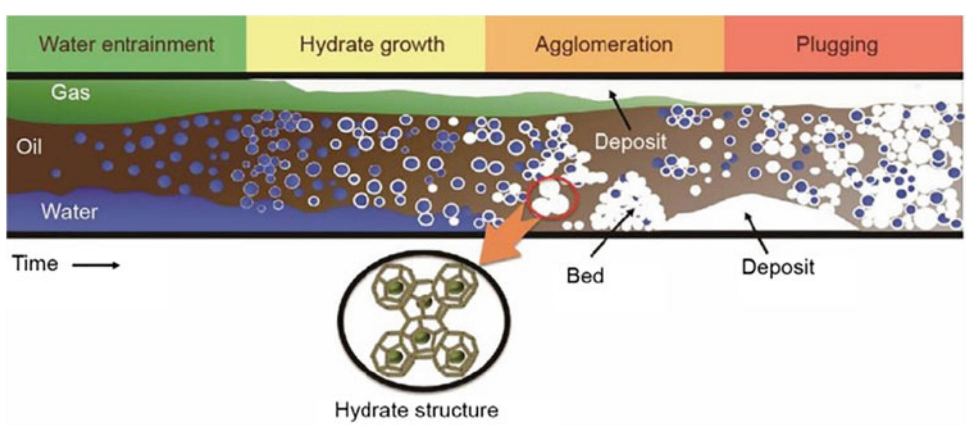

Fig. 1.3 Conceptual picture of hydrate formation and plugging in an oil-dominated system (reproduced with license granted by Elsevier from Majid et al. 2018)

scales; furthermore, phenomena such as hydrate nucleation, growth, inter-particle adhesion, wettability and jamming must also be considered. Once the microscopic phenomenology is developed, the next step consists of performing experiments at a pilot scale to obtain information on the system behavior in more realistic conditions before advancing towards field applications. It is important to keep in mind that an increase in the experimental scale also generates an increase in the volume of fluids required, while the control of experimental conditions diminishes. The final goal of gas hydrate research in flow assurance is to build a comprehensive model capable of predicting hydrate formation and plugging in certain conditions so that hydrate prevention/management strategies can be efficiently applied.

The main objective of this article is to present a general overview of the main experimental techniques and apparatuses used for hydrate research, with emphasis on the measurement principles, operation conditions and major outcomes.

1.2 Experimental Hydrate Research

1.2.1 Multiscale Approach

The formation of gas hydrates is a complex process that depends on many factors, including the types of phases present and the conditions under which those phases interact. While discussions presented here are limited to the flow assurance problems created by gas hydrates in flowlines, some generalization can be made to the formation of hydrates in other applications.

A hydrocarbon flowline is generally dominated by crude oil, water, gas and/or condensate. Thus, once pressure–temperature conditions are met, the potential for hydrate formation and subsequent plugging will primarily depend upon the relative amount of each phase present. Several other parameters may also play a part, such as hydrodynamic conditions (e.g. flow rate), viscosity, chemical composition of the fluids (e.g. gas composition, water salinity, natural surfactants in the oil, added chemicals, etc.), and flow patterns among others. The formation of hydrate blockages has been conceptualized in four main models: (1) oil-dominated, (2) gas-dominated, (3) gas condensate and (4) high-water cut systems (Sloan et al. 2010). All of these types of blockages are impacted by certain physical phenomena, ranging in scale from microscopic hydrate particle/film formation to macroscopic agglomeration and plugging.

Significant efforts have been made to develop practical tools capable of predicting hydrate formation. The general workflow can be summarized in three main steps: (1) small scale experiments, (2) pilot plant tests and (3) field applications and modelling. In general, laboratory experiments require only a few micro- or milli-liters of sample material and allow for the study of physical phenomena in great detail under rigorous environmental control. When increasing the experimental scale towards pilot plant tests such as flow loop experiments, conditions become more realistic and the consumption of fluids and chemicals increases significantly; liters and even barrels of water, oil and gas are normally required to obtain datapoints.

Once the phenomenon is sufficiently understood, the next step is to test the physical/mathematical models developed at the pilot plant level on real-world field cases with the help of industrial companies. As a part of the field application, physical models are integrated with predictive tools to assess the risk of hydrate formation and plugging in real scenarios. For example, the predictive tool CSMHyK can be coupled with the transient multiphase flow simulator OLGA®, and the combination can then be used to predict hydrate formation and transportability in pipelines (Boxall et al. 2009; Zerpa et al. 2012).

Figure 1.4 is an illustrative summary of the multiscale approach used in hydrate research. It lists the main phenomena involved in hydrate formation and plugging and further identifies the equipment/techniques used at each scale; the brown text identifies factors applying exclusively to oil-dominated systems.

It is worth noting that the multiscale scheme presented in Fig. 1.4 may not only be used in gas hydrate formation studies but also as a practical tool to evaluate the efficiency of both natural and commercial chemicals in the management of gas hydrates in oil and gas flowlines (Dapena 2019; Hu 2019). The physics behind each experimental technique is the main factor to be considered in defining its specific application.

1.2.2 Overview of Experimental Techniques

The number of published works found on gas hydrates is enormous, implying a correspondingly high number of equipment/techniques applied in hydrate research, as shown elsewhere (Sloan and Koh 2007). Depending on the goal of each experiment, a setup is designed or adapted to collect a specific kind of data and the experimental conditions are fixed accordingly. Key experimental techniques given in Fig. 1.4 are briefly described, and their importance as a part of the conceptual models in Figs. 1.2 and 1.3 is highlighted.

1.2.2.1 Small (Laboratory) Scale

Autoclave-type reactor. The first technique covered is the use of batch reactors such as autoclave-type reactors/cells (Giavarini and Hester 2011). They are primarily used to determine pressure and temperature conditions as well as the kinetics under which hydrates are formed/dissociated. The cell, equipped with a stirrer, is connected to a gas reservoir

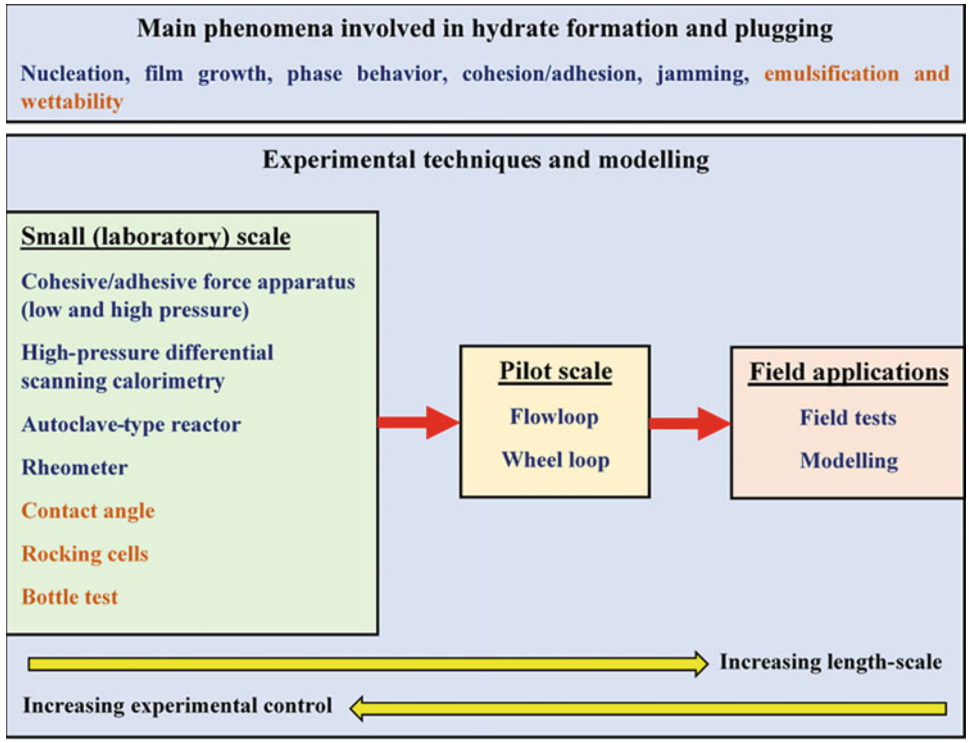

Fig. 1.4 A multiscale approach for hydrate research. Techniques and phenomena appearing in brown apply only to oil-dominated systems

and placed in a thermal bath to reach the conditions necessary to form hydrates. Sensors are placed inside the cell to determine pressure and temperature, as well as optical devices such as Particle Video Microscope (PVM) and Focused Beam Reflectance Measurement (FBRM) probes, if available, to monitor the evolution of particle size over time (Costa Salmin 2019). Autoclaves can be designed to operate at pressures up to 5,000–10,000 psi (Sloan and Koh 2007), although the PVM/FBRM probes have an operation limit of around 1,000 psi. An example of this type of reactor and its main components is shown in Fig. 1.5a.

Autoclaves can be used to quantify the kinetics of hydrate formation in both oil-dominated systems as well as water/gas systems. They are also useful in evaluating the effectiveness of various hydrate inhibitors, such as thermodynamic hydrate inhibitors (THIs), kinetic hydrates inhibitors (KHIs) and anti-agglomerates (AAs). Further, they are capable of gathering information on the flowability properties of the hydrate slurry, namely its viscosity and particle size distribution (Akhfash et al. 2017; Chen et al. 2014; Majid et al. 2014; Salmin et al. 2017; Sun et al. 2015). Figure 1.5b shows a comparison between systems that display

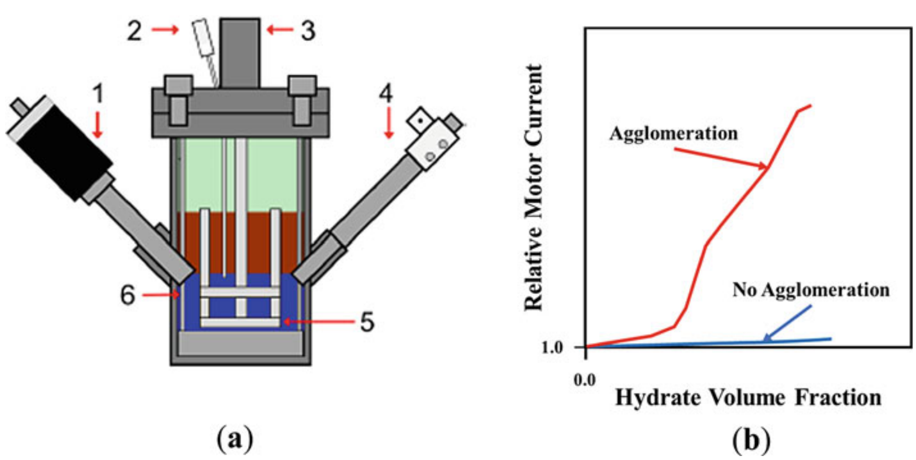

Fig. 1.5 **a** Schematic of a high-pressure autoclave reactor. Main components: (1) Video probe (PVM), (2) thermocouple, (3) motor shaft (stirrer), (4) laser-scanning probe (FBRM), (5) impeller and (6) baffles (Costa Salmin 2019). **b** Illustration of typical motor current variation as a function of hydrate volume fraction for systems with and without hydrate agglomeration

agglomeration versus systems that do not. The absolute motor current as it relates to system viscosity is illustrated as a function of the hydrate volume fraction, and it increases in systems where agglomeration is found.

High-pressure differential scanning calorimetry. Another technique often used in hydrate laboratories is called differential scanning calorimetry (DSC), which is based on the measurement of the enthalpy variation as a function of temperature during heating and cooling cycles. The thermogram recorded by a DSC allows for the identification of phase transformations, such as hydrate formation and dissociation. These instruments are designed to operate at pressures of up to around 5,000 psi and at temperatures in the range of 230–400 K, with the advantage of using a very small amount of sample. Important information such as hydrate dissociation temperature, heat capacity, heat of dissociation, hydrate agglomeration and emulsion stability with and without hydrates may be obtained through this technique (Dalmazzone et al. 2003; 2009a, b; Delgado-Linares et al. 2013; Giavarini and Hester 2011; Lachance et al. 2008; Palermo et al. 2005; Sloan and Koh 2007).

A typical thermogram for a HP-DSC hydrate experiment is shown in Fig. 1.6, where temperature and heat flow as a function of time are plotted. The peaks in the heat flow trace correspond to hydrate formation and hydrate dissociation (Lachance 2008).

Rheometer. One of the most important properties considered when dealing with flow assurance problems is the viscosity of the liquid phase. An increase in the system's viscosity generally requires more vigorous pumping and increases the likelihood of plugging. Several studies have placed focus on evaluating the rheological behavior of hydrate suspensions, using flow loops and rheometers at low and high pressures (Delahaye et al. 2008; Majid et al. 2019; Sinquin et al. 2004; Webb et al. 2012). The use of high-pressure rheometers has aided the development of some empirical and semi-empirical models to predict the viscosity variations of emulsions and hydrate suspensions and slurries at different conditions of pressure and temperature (Camargo and Palermo 2002; Majid et al. 2017; Qin et al. 2018). Pioneering research in this field has explained the aggregation of hydrate particles in oil-dominated systems through the formation of inter-particle water bridges that generate attractive capillary forces (Camargo and Palermo 2002). An empirical equation used to predict the viscosity of stable water-in-crude oil emulsions has been recently proposed as a tool for analyzing the effect of hydrate particles on the viscosity of slurries (Majid et al. 2017).

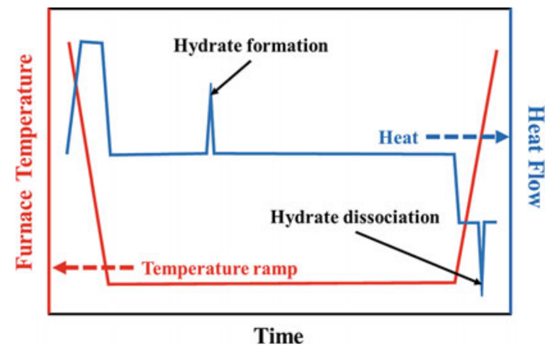

Fig. 1.6 An illustration of a typical thermogram of a water-methane system indicating hydrate formation and dissociation

Figure 1.7a is a schematic diagram of a high-pressure rheometer used in the study of hydrates. Figure 1.7b shows a typical viscosity-versus-time curve and the corresponding pressure and temperature profiles present for a system in which hydrates are formed in a water-in-oil emulsion. Four regions may be observed in this kind of system, as identified in the figure: (1) initial viscosity increase due to the cooling process, (2) viscosity remains constant, (3) viscosity rises suddenly and (4) viscosity decreases gradually.

The increase in the system viscosity in region 3 is the result of several combined factors, including the conversion of water droplets to hydrate particles, the depletion of

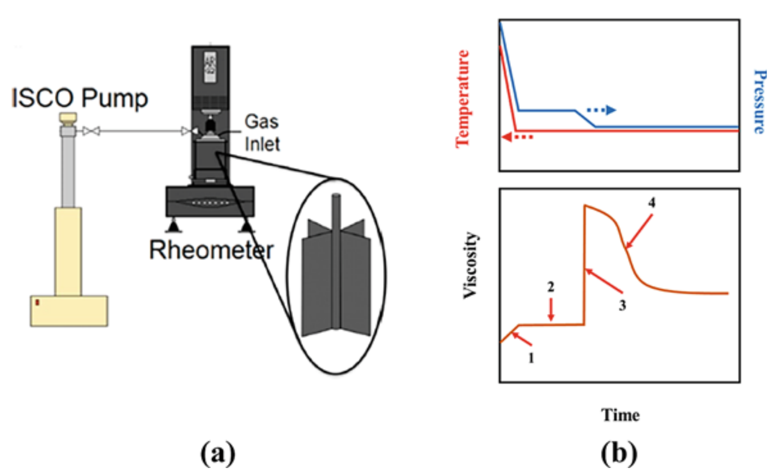

Fig. 1.7 **a** Schematic of high-pressure rheology (reproduced with license granted by the American Chemical Society from Majid et al. 2017). **b** Illustration of typical temperature, pressure and viscosity profiles for hydrates formed in a water-in-oil emulsion

methane in the liquid phase, and the formation of capillary bridges between partially/fully converted hydrate particles. The viscosity reduction in region 4 may be explained through two main hypotheses. One is the re-saturation of the liquid phase with methane (gas former), reducing the viscosity of the hydrate suspension. The other involves the breakup and rearrangement of hydrate aggregates in the liquid phase (Majid et al. 2017; Webb et al. 2012).

Cohesive/adhesive force apparatus. As can be seen in Figs. 1.2 and 1.3, the aggregation of gas hydrate particles is a critical step in the plugging of pipelines. A micro-mechanical force (MMF) apparatus has been used to measure the interaction forces among hydrate particles and to quantify the interactions between hydrate particles and solid surfaces at ambient and high pressures (Aspenes et al. 2010a; Hu and Koh 2017; Lee and Sum 2015; Taylor et al. 2007; Yang et al. 2004). The experimental procedure for measuring hydrate interaction forces consists of 4 steps (Aman et al. 2012a; Hu and Koh 2017): (1) two water droplets are each attached to a glass fiber cantilever and converted to hydrate particles, (2) the particle on the top is moved against the bottom particle in order to provide a preload force for a specific period of time (3) the particle on top is raised at constant velocity, and (4) the movement is stopped when the particles are broken apart at a distance Δd. Hook's Law is then applied to calculate the cohesive force (Fa), as follows:

$$Fa = k\,\Delta d \tag{1.1}$$

where k is spring constant of the glass fiber.

The MMF technique measures the impact of important operational parameters on the interaction of hydrate particles, such as subcooling, annealing time, contact time, and nature of dominant phase. In oil- and gas-dominated systems, hydrate interaction forces mainly originate from the formation of water capillary bridges between hydrate particles; on the other hand, in water dominated systems, the hydrate interactions are the product of solid–solid cohesion. It has also been shown that an increase in contact time may induce the sintering of hydrate particles and thus significantly increase the cohesive forces (Aman et al. 2011; Aman et al. 2012a; Hu and Koh 2017). A schematic of a high-pressure MMF apparatus and its main components are depicted in Fig. 1.8a. Figure 1.8b shows the general trend of the variation of cohesive force as a function of contact time for a pair of gas hydrate particles in a hydrocarbon liquid phase at high pressure (Hu and Koh 2017).

Measurements of cohesive forces have also been used to evaluate the effectiveness of natural and commercial AAs in oil-dominated systems, taking into account experimental parameters such as additive concentration, salinity, contact time and oil nature. Results indicate that the better the anti-agglomerant, the lower the interactions between hydrate particles (Aman et al. 2012b; Dieker et al. 2009; Hu and Koh 2020; Morrissy et al. 2017; Wang et al. 2020).

Contact angle. As depicted in Fig. 1.4, there are some techniques and setups applicable almost exclusively to systems with a significant amount of oil; the first of these is measuring the contact angle. Measurements of the contact angle (θ) of a water droplet placed on a hydrate surface/particle (see Fig. 1.9a) will give an indication of the wettability of the hydrate surface, thus a higher contact angles may be correlated to hydrophobic surfaces (Brown et al. 2018). This finding is very important considering that hydrate plugging in oil-dominated systems has been associated with the occurrence of water-wet hydrates at a low contact angle (Aspenes et al. 2010b). The contact angle technique has also been used to determine the hydrate-philicity of metal surfaces (Fig. 1.9b). According to the criterion mentioned above, higher contact angles account for low affinities between hydrates and solid surfaces (Brown et al. 2017). It has been

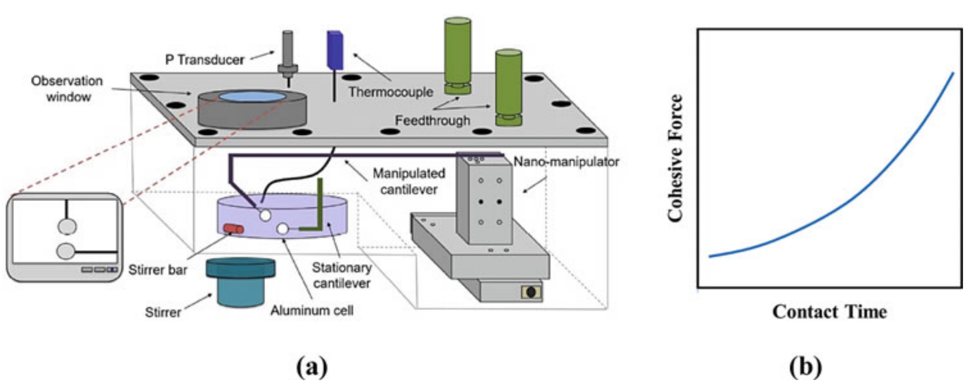

Fig. 1.8 **a** Schematic of a high-pressure MMF apparatus (reproduced with license granted by the American Chemical Society from Hu and Koh 2017). **b** Illustration of typical variation of cohesive forces versus contact time for gas hydrate particles in a hydrocarbon liquid phase at high pressure

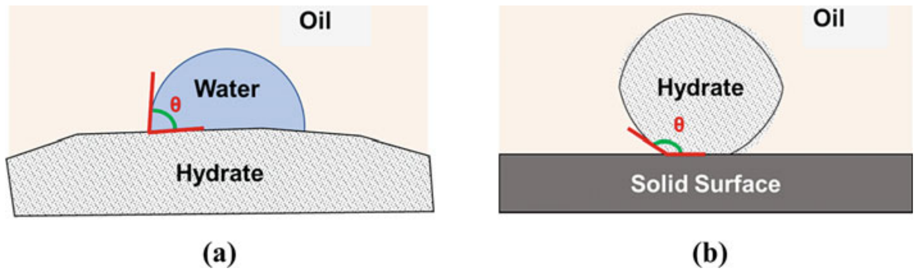

Fig. 1.9 Contact angle measurements **a** between a water droplet and a hydrate particle; **b** between a hydrate particle and a solid surface

recently demonstrated using contact angle measurements, among other experimental techniques, that the application of coatings and surface chemical treatments can efficiently reduce hydrate adhesion to metal surfaces (Brown et al. 2017; Das et al. 2019; Pickarts et al. 2019).

Rocking cells. A rocking cell apparatus is one of the most common devices used for flow assurance studies, and is another item used exclusively in oil-dominated systems. As the name suggests, it consists of a relatively small high-pressure visual cell coupled with a rocking mechanism. These are generally designed to operate at pressures of up to 5,000 psi and are often equipped with a metal ball to facilitate the mixing of phases; in some devices, the time required for the ball to travel from one end of the cell to the other end is recorded by two run-time sensors. Pressure and temperature may be recorded, which allows induction time, gas consumption, water conversion to hydrates and hydrate agglomeration to be determined (Chua and Kelland 2013; Dong et al. 2017; Frostman 2000; Sloan and Koh 2007). Rocking cells have been widely used to evaluate the performance of AAs as well as THIs; the visual assessment of hydrate agglomeration is based on the size and flowability of hydrate particles so that the results may vary from a “pass” to a “fail” test with one or more intermediate grades (Costa Salmin et al. 2019; Delgado-Linares et al. 2020; Gao 2008, 2009; Gupta et al. 2011). The effect of variables such as water cut, salinity, AA concentration and subcooling on hydrate agglomeration can be determined by using this kind of apparatus.

Some authors have proposed a variation of the rocking cell concept to study hydrates at different flowing conditions (e.g. a 1–5 L rock-flow cell larger than the conventional ~35 mL rocking cell) with capabilities to modify the rocking angle/speed to provide different flow regimes (Sa et al. 2019).

Bottle test. The final technique covered here exclusive to oil-dominated systems is the bottle test, which is used to evaluate the stability of emulsions. In the classical bottle test, the volume of the phases when separated from an emulsion is recorded over time. For water-in-crude oil emulsions, the volume of the internal phase (water) that has separated is registered, as well as other aspects related to the separation such as appearance of the interface and clarity of the separated water. Due to its simplicity, bottle tests enable field operators to obtain information about the kinetics of emulsion separation in a relatively short period of time. This technique has also been successfully used to evaluate the performance of commercial demulsifiers in the oil industry (Delgado-Linares et al. 2016; Goldszal and Bourrel 2000; Leopold 1992; Salager 1990; Smith and Arnold 1987; University of Texas 1990). Published works have suggested a relation between the stability of water-in-oil emulsions and gas hydrate transportability in crude oil systems; as a consequence, the bottle test is an important tool for potentially evaluating natural hydrate anti-agglomeration (i.e. naturally occurring surfactants responsible for the stabilization of crude oil emulsions may play a key role in gas hydrates dispersion) (Costa Salmin et al. 2019; Delgado-Linares et al. 2020; Lachance 2008; Salager and Forgiarini 2012; Sjöblom et al. 2010). The main limitation of this technique is that it is generally not performed at the high pressures of gas hydrate formation.

1.2.2.2 Pilot Scale

Flow loop. Industrial and research institutions have constructed pilot-scale flow loops to simulate the flow behavior in pipelines, and can thus obtain results closer to those in real-world conditions, as shown in Fig. 1.4. These apparatuses control the temperature and track hydrate formation kinetics by observing gas consumption at constant pressure and/or volume, pressure drops, and visually using windows/particle probes. Data acquisition systems record data from thermocouples, pressure sensors, flow meters, in-situ imaging probes, and windows for visual observation (Costa Salmin 2019; Sloan and Koh 2007). The total volume of flow loops is variable, but it may be in the range of 80–670 L, with a required volume of oil between 28 and 445 L (Costa Salmin 2019). Some of the flow loops used in hydrates studies worldwide include the ExxonMobil Friendswood flow loop in Texas (U.S.A) with 93 m length and 9.7 cm of internal diameter, the IFP flow loop in Solaize (France) with 140 m length and 5 cm of internal diameter, the University of Tulsa

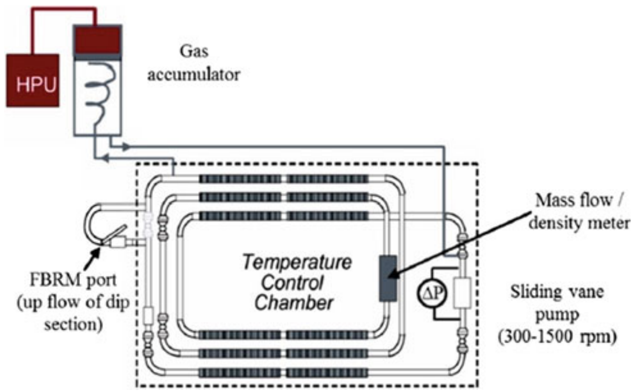

Fig. 1.10 Schematic of ExxonMobil flow loop with its main components (reproduced with license granted by Elsevier from Joshi et al. 2013)

flow loop in Tulsa (U.S.A.) with 49 m length and an internal diameter of 7.6 cm, and the flow loops at SINTEF Multiphase Flow Laboratory in Trondheim (Norway) with three loop facilities, namely one of small scale (50 m length with 2.54 and 5.08 cm of internal diameters), one of medium scale (50 m length with 6.35, 7.62 and 10.16 cm of internal diameters) and one of large scale (800 m length and 20.32 cm of internal diameter) (Anon 2020; Boxall 2009; Giavarini and Hester 2011; Sloan and Koh 2007). Figure 1.10 displays a schematic of the ExxonMobil flowloop and its main components (Joshi et al. 2013).

Flow loop tests have been carried out to evaluate the hydrate transportability for oil- and gas-dominated systems; the formation of agglomerates and deposits are detected by an increase in pressure drop (Di Lorenzo et al. 2014; Majid et al. 2016). Hence, flow loops can be a valuable tool to evaluate the effectiveness of hydrate AAs (Dapena et al. 2017; Lachance et al. 2012).

Wheel loop. An apparatus smaller than an industrial flow loop is a wheel loop. It is commonly comprised of a wheel/torus of 2–5 inch pipe at a diameter of 2 m, with a rotation velocity of 0.3–5 m/s when filled with gas and liquid (<50% liquid loading). Hydrate formation is determined visually or by a sharp increase in the torque required for rotation (Sloan and Koh 2007). The torque data may be used to evaluate the effect of AAs on the hydrate plugging potential of oil-dominated systems (Hemmingsen et al. 2008; Kelland et al. 2006).

1.3 Final Considerations

Gas hydrates have become a major topic of research for industry and academia during the last several decades, mainly due to their enormous potential as an energy resource and the necessity to avoid/manage them in oil and gas flowlines. Much effort has been dedicated to understanding how hydrates form and behave in different systems where the dominant phase may be liquid or gas, and where the flow conditions are variable.

This multiscale approach has been developed by the Center for Hydrate Research (Colorado School of Mines) after many years of intensive research on gas hydrates in flow assurance. The vision outlined here will allow for the incorporation of the described phenomena/mechanisms studied at microscale into integrated models developed to explain and predict hydrate behavior in real-world conditions. It is, however, a large task given the high numbers of parameters to consider. The unification and scaling-up of microscopic models to robust predictive models applicable in field situations will be the key challenge for hydrate researchers in upcoming years.

Acknowledgements The authors would like to thank the Department of Energy, DOE-NETL, Award#DE-FE0031578 for funding. Special thanks to present and past hydrate busters for their dedication to the hydrate world.

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Shallow Gas Hydrates Near 64° N, Off Mid-Norway: Concerns Regarding Drilling and Production Technologies

2

Martin Torvald Hovland and Srikumar Roy

Abstract

Geophysical features such as bottom-simulating reflectors and acoustic wipe-out zones are common at locations where natural gas hydrates form in deep-sea sediments. This is also the case at two locations off mid-Norway in the Norwegian Sea: the Nyegga hydrocarbon seep area and the Husmus shallow gas location. In addition to the aforementioned features, the Nyegga area at 730 m water depth boasts complex pockmarks (up to 300 m wide and 12 m deep), gas hydrate pingoes, giant blocks of carbonate-cemented sediments, and exotic fauna. In contrast, the Husmus shallow gas location on the nearby continental shelf at 330 m water depth also contains a strong and very shallow bottom-simulating reflector (located only 4–5 m below seafloor), some distinct pockmarks, and putative coral reefs. But the deepest location, the Ormen Lange producing hydrocarbon field at 950 m water depth, contains no seep features on the seafloor or geophysical expressions of gas hydrates in the sediments. Here, formation of natural gas hydrates was triggered by a small amount of methane seepage from a drilled well. The methane spontaneously formed hydrate-coated bubbles in addition to some unstable hydrate cement. Thus, these three locations demonstrate the wide range of features and effects caused by gas hydrates in situ. This article describes these settings and discusses concerns related to drilling, production, transport technology and the environment in general. Perhaps one of the least studied aspects of deep-sea natural gas hydrates is their impact on local and regional biodiversity and fauna, which may represent an important topic for future consideration.

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2.1 Introduction

It is well known that in situ gas hydrates hosted in oceanic, low-permeability sediments have the ability to deform these near-seafloor deposits (Soloviev and Ginsburg 1994; Ginsburg and Soloviev 1998; Clennell et al. 1999; Hovland et al. 2001; Wang et al. 2018). Gas hydrates have, therefore, been long regarded as a possible hazard to industrial deep-sea activity, such as oil/gas extraction (Kvenvolden 1994; Plaza-Faverola et al. 2010; Hassanpouryouzband et al. 2020) and seafloor pipeline installation. Based on experience obtained from the scientific drilling and sampling of gas-prone and hydrate-bearing sediments, concerns remain regarding the in situ formation of gas hydrates in deep water sedimentary environments (Kvenvolden 1993; Wang et al. 2018).

There are two locations offshore mid-Norway where gas hydrate-related features are found. These features include pockmarks, anomalous seismic reflections (both regional and local), sediment mounds such as hydrate pingoes, bottom simulating reflectors (BSRs), vertical 'gas chimneys' and high concentrations of 'exotic organisms' such as chemosynthetic tubeworms, bacterial mats, and cold-water corals. These two locations are (1) The Nyegga complex pockmark region and (2) The Husmus hydrocarbon field location. Whereas Husmus is situated on the continental shelf at ~330 m water depth, the Nyegga location is situated on the continental slope at 730 m water depth. The average seafloor water temperature at Husmus hovers around 6–7 °C and is considered 'normal' for this region. This is in stark contrast to the mean seafloor water temperature at the deeper Nyegga location, which has below-zero temperatures around −0.7 °C (see Fig. 2.1). The low ambient water temperature is caused by the freezing water masses from the north, which partly form the well-known North Atlantic Deep Water (NADW) mass of the Norwegian Greenland Basin, feeding into the Norwegian Basin, making it salty and dense (Schäfer et al. 2001). We will also describe the effects

J. Mienert et al. (eds.), *World Atlas of Submarine Gas Hydrates in Continental Margins*,
https://doi.org/10.1007/978-3-030-81186-0_2

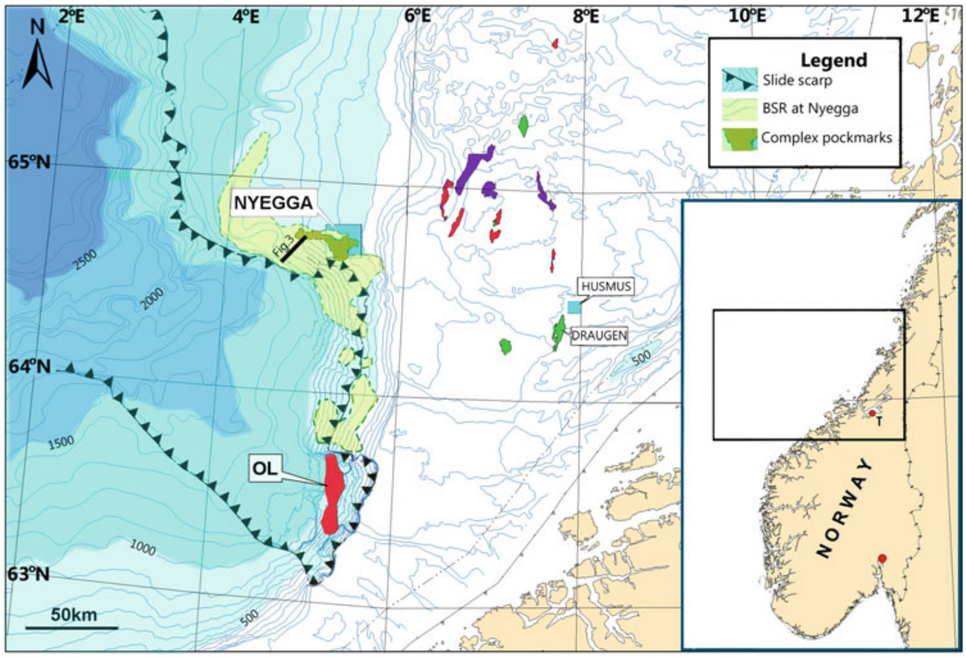

Fig. 2.1 Location map showing the Storegga Slide scarp and the three locations described above: Nyegga and Husmus are marked in blue and the Ormen Lange (OL) is marked in red. Other features identified are the nearby gas (red), condensate (violet) and oil (green) fields off mid-Norway. The occurrence of BSRs and complex pockmarks at Nyegga are also included on the map (see legend) (Modified from Bünz and Mienert 2004, Hovland et al. 2005 and Hjelstuen et al. 2010)

of a gas seep found at the even deeper (900 m) and colder (−0.9 °C) Ormen Lange hydrocarbon field, also identified in Fig. 2.1.

The objective of this chapter is to document the wide variety of gas hydrate-related features found at the three specific locations mentioned above and to identify some of the main concerns found in each of these environments with respect to drilling and hydrocarbon production and transportation.

2.2 The Nyegga Gas Hydrate Location

2.2.1 General

The seabed in the Nyegga region has a general slope angle of only 1° and represents the westward continental slope leading to the abyssal depths of the Norway Basin at about 3,000 m. A pockmark field of approximately 2,000 km^2 in size is found here, just to the north of the Storegga slide scarp, as shown in Figs. 2.1 and 2.2. Geophysical hydrate-indicators such as BSRs occur here, along with numerous pockmarks underlain by chimney-like features called gas chimneys (e.g. Vogt et al. 1994; Mienert et al. 1998; Bünz et al. 2003; Hovland et al. 2005; Hovland and Svensen 2006; Plaza-Faverola et al. 2010). Our study area in Fig. 2.2 lies only 2 km north of the northern headwall scarp of the Storegga Slide (Bugge 1983; Bryn et al. 2003; Haflidason et al. 2005; Bondevik 2019).

2.2.2 The BSR

The discovery of a prominent BSR on the landward side of the Storegga Slide was made by Bugge in 1983. At that time, the area was generally referred to as the 'Vøring Plateau,' but was later changed to the 'Nyegga' region on official Norwegian hydrographic maps. Early studies of the BSR and its characteristics were further conducted by Mienert et al. (1998), Posewang and Mienert (1999), Bouriak et al. (2000), Andreassen et al. (2000), and Gravdal et al. (2003). In high-resolution seismic data it is generally characterized as an abrupt upper boundary of increased reflection amplitude (Bouriak et al. 2000; Bünz et al. 2003). The BSR at Nyegga is alternatively characterized by an abrupt termination of enhanced reflection amplitudes beneath the sediment. It runs parallel to the sea floor and is easily identified by cross cutting into the nearly horizontal layers of sediment strata (see Fig. 2.3). Continuous BSR occurrence has been illustrated by Bünz et al. (2005) along the northern flank of the Storegga Slide, featuring the sparse distribution of a double BSR. The distribution of gas hydrates in the mid-Norwegian margin seems to be controlled by the nature of the host sediments in which they are found. For example, contouritic and hemipelagic deposits are favorable for hydrate formation, whereas fine-grained preglacial deposits do not allow it. Polygonal fault systems seem to inhibit gas hydrate formation as they reduce the pore size and water content of the sediments considerably; porewater content is crucial for hydrate formation (Plaza-Faverola et al. 2010).

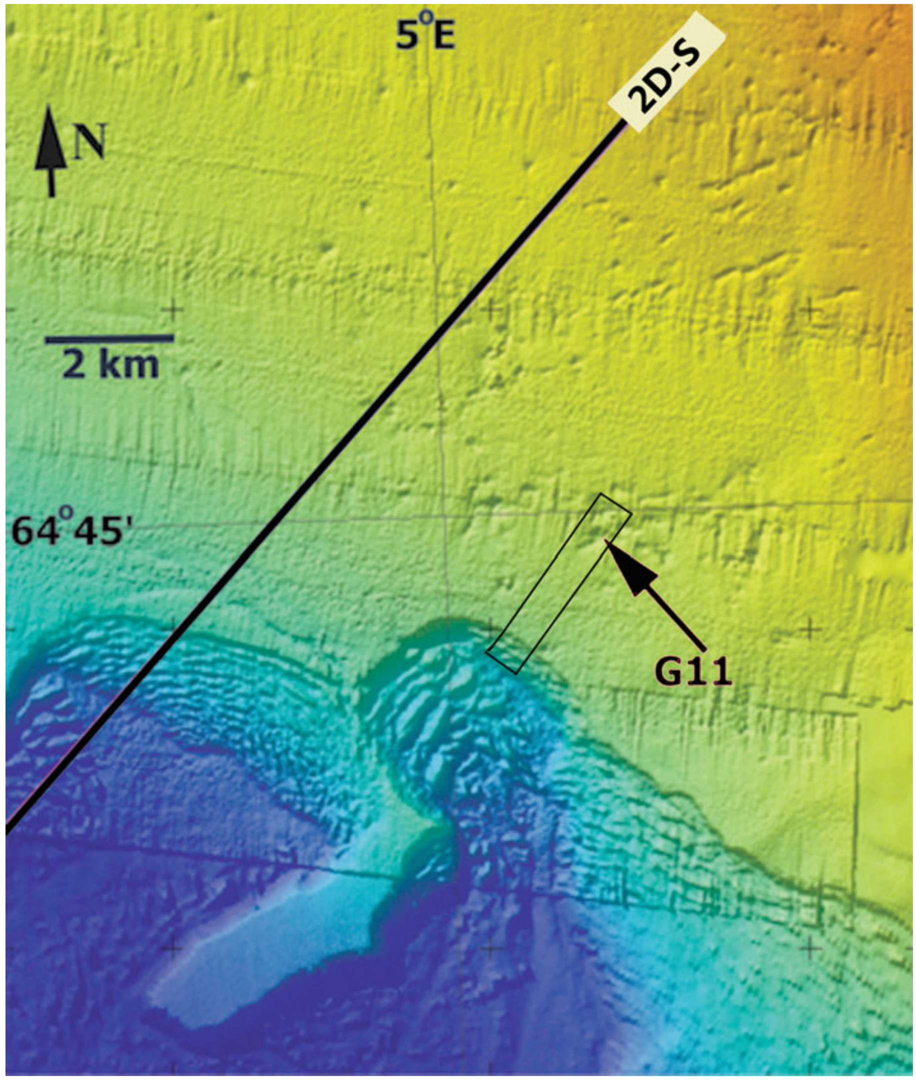

Fig. 2.2 Location of the 2D-seismic survey line (2D-S) at Nyegga (see Fig. 2.3). Also shown is the location of the high-resolution ROV survey area, identified by the rectangle featuring pockmark G11 (see also Figs. 2.4, 2.5, and 2.6). Notice the very prominent Storegga headwall scarp (Modified from Hovland et al. 2005)

Analysis of multi-component seismic data does not show a BSR in the shear-wave components, indicating that these hydrates do not increase the shear stiffness of the local sediments (Andreassen et al. 2003; Bünz et al. 2005), possibly due to low hydrate saturation values. The presence of a BSR in the slide area also indicates that the hydrate system continues to dynamically adjust to post-slide pressure/temperature equilibrium changes (Bouriak et al. 2000; Bünz et al. 2003) after the Storegga slide event some 8150 BP (Bondevik et al. 2012). Bryn et al. (2005) conclude that another slide at Storegga is likely to occur as a consequence of new glaciogenic deposits eventually left by a future glaciation event. Furthermore, they do not believe that hydrates and fluid flow, such as gas seeps, triggered the original slide.

2.2.2.1 BSR-Related Drilling and Engineering Concerns

Prior to 1993, the occurrence of a BSR was thought to be a risk to gas/oil exploration and production drilling (Tucholke et al. 1977). However, careful work by the Deep Sea Drilling Project (DSDP), the Ocean Drilling Program (ODP) and the current International Ocean Discovery Program (IODP) concluded that there is very little risk for blowouts or gas leaks due to such drilling. At first, the DSDP's Pollution Prevention and Safety Panel (PPSP) adopted a general policy that riser-less (i.e. uncontrolled) drilling would not be approved beneath BSRs: "…*because the reflector was evidence for gas occurrence, and because the gas hydrate layer was thought to act as a seal for high pressure gas accumulation*" (Hovland et al. 1999). This advice remained in

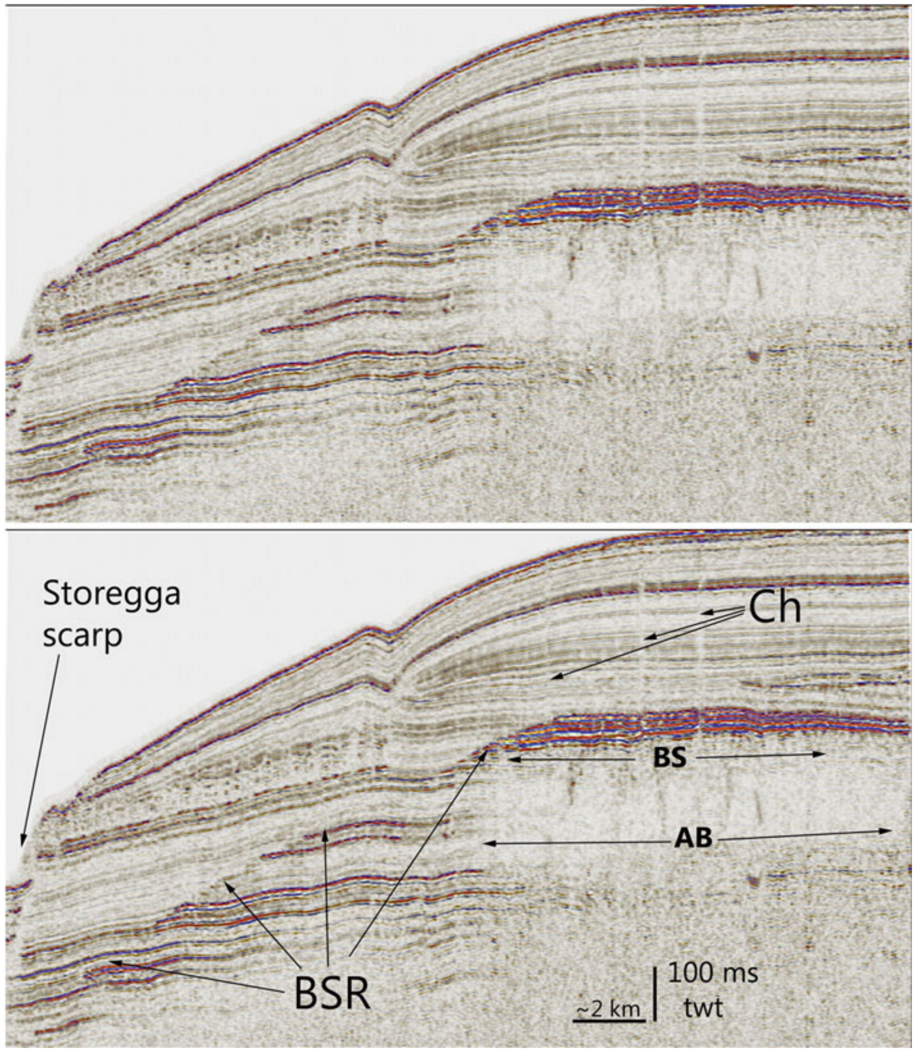

Fig. 2.3 High-resolution 2D-seismic profile (2D-S) showing the BSR and the prominent Storegga slide scarp to the left. Ch = acoustic chimney structures, discussed in the text. Note also the prominent 'brightspot' below the upper portion of the BSR. It is caused by free gas accumulation trapped beneath the relatively impermeable hydrate layer. However, the free gas volume is low, at an estimated <1% of the available pore-space. Below the brightspot there is a zone of 'acoustic blanking', probably caused by an absorption of energy by the free gas. For location, see Fig. 2.2 (Modified from Hjelstuen et al. 2010)

place until scientists working for *ODP Leg 112: Peru continental margin* were given permission to drill through a break in the regional BSR at Hole 688 (Suess et al. 1988), and did so safely.

After this uneventful drilling experiment, and despite successful recovery of gas hydrates at 141 mbsf (meters below sea floor) in Hole 688A, it was evident that the PPSP guidelines were overly restrictive. A new justification for future drilling was developed, "*…based on a theoretical analysis showing that gas hydrates probably could not act as a seal for high-pressure gas accumulation in marine sediments, as long as excess water is present*." This is because the base of a gas hydrate is a 3-phase (gas, liquid, solid) equilibrium boundary in a 2-component (methane, water) system: "*Any build-up of gas pressure beneath this boundary would cause additional reaction of gas with excess water, until the pressure was relieved by restoration to the prevailing equilibrium pressure*" (Hovland et al. 1999).

After several successful ODP 'gas hydrate' Legs (particularly Leg 146A at Cascadia Accretionary Wedge, now known as 'Hydrate Ridge', and Leg 164 at Blake Outer Ridge), the PPSP and the current Environmental Protection and Safety Panel (EPSP) of the IODP, recommends the following: "*…drilling through a BSR does not pose a severe hazard for either blowout or pollution. However, the experience base is still quite limited, with only about a dozen such holes drilled to date. Because the BSR is now confirmed as a reflector associated with small volumes of unknown porosity and permeability, similar precautions to those used when drilling in areas with a general gas hazard should be taken*." (Hovland et al. 1999). Thus, there is a need for high resolution 2D-, and if possible, 3D-seismics, processed and analyzed to determine the occurrence of shallow gas hydrates as proposed by Heggland et al. (1996) and Roberts et al. (1996).

2.2.3 Complex Pockmarks

The largest pockmarks at Nyegga are morphologically more complex than 'normal' seabed pockmarks found on continental shelves globally (King and MacLean 1970; Judd and Hovland 2007). They appear as near-circular depressions that reach 12 m deep and 300 m wide with distinctive heaps of large carbonate rocks protruding from the center up to the seafloor level, sometimes even slightly higher (see Figs. 2.4 and 2.5). A total of five complex pockmarks, located at a water depth of 600–730 m, were investigated by Hovland et al. 2005. While they contained a variety of different carbonate morphologies, they were dominated by low $\delta^{13}C$ aragonite (MDACs, methane derived authigenic carbonates), which is commonly found in close association with gas hydrates (Mazzini et al. 2006). These pockmarks are identified as A, C, G8, G11 and G12 in Fig. 2.4.

G11 is the deepest of the pockmarks investigated at Nyegga. During the visual ROV survey of the G11 area, a total of seven local sediment mounds, suspected to be pingoes, were discovered. Shallow push-cores from G11 revealed the presence of occluded and adsorbed light hydrocarbon gases in the upper sediments, as shown in Table 2.1 (Hovland et al. 2005; Plaza-Faverola et al. 2010).

According to 2D-seismic records (see Fig. 2.5), the pockmarks lie immediately above vertical 'chimneys' or pipes (also called 'wipe-out zones' or 'blow-out pipes'), which extend down to and sometimes beyond the BSR, reaching 300 m below the seafloor at their lowest point (Mienert et al. 1998; Bünz et al. 2005; Ivanov et al. 2010; Hjelstuen et al. 2010). It is hypothesized that they represent endmembers of a megapolygonal fault system (Ho et al. 2018), to be described later.

At Nyegga, the regional background sum of adsorbed gases is expected to be approximately 100 ml/l. All values reported here are up to 3.8 times greater than this value, indicating that complex pockmarks at Nyegga represent locations of active gas seepage (see Table 2.1).

2.2.4 Hydrate Pingoes

Typical pingoes made from water-derived ice are usually found in onshore permafrost regions (Shearer et al. 1971; Bondarev et al. 2002). 'Pingo-like structures' made of hydrate-derived ice, however, can be found on the seafloor in Barklay Canyon on the northern Cascadia Margin, Pacific Ocean (Chapman et al. 2004). The Barklay Canyon structures are large bodies of partially exposed gas hydrates covered by a very thin dusting of sediment, which is probably a consequence of a continuous macro-seepage of gas (e.g. ebullition on the seafloor). The structures described at Nyegga, on the other hand, are completely covered by sediment (equivalent to the ice in terrestrial pingoes), as only micro-seeps are found there without ebullition of free gas.

The seven hydrate pingoes investigated inside G11 were named 'Ice1' to 'Ice7', and their locations inside G11 are shown in Fig. 2.6. G11 also features several large irregular ridges with sediment basins lying between (see Fig. 2.6) (Fig. 2.7).

Figure 2.8 shows two typical hydrate pingoes inside G11: Pingo '1' and '4' (location in Fig. 2.6).

2.2.4.1 A Qualitative Model for Hydrate Pingo Formation

A terrestrial pingo is a distinct geomorphologic structure found in regions of permafrost; Bates and Jackson (1987) describe

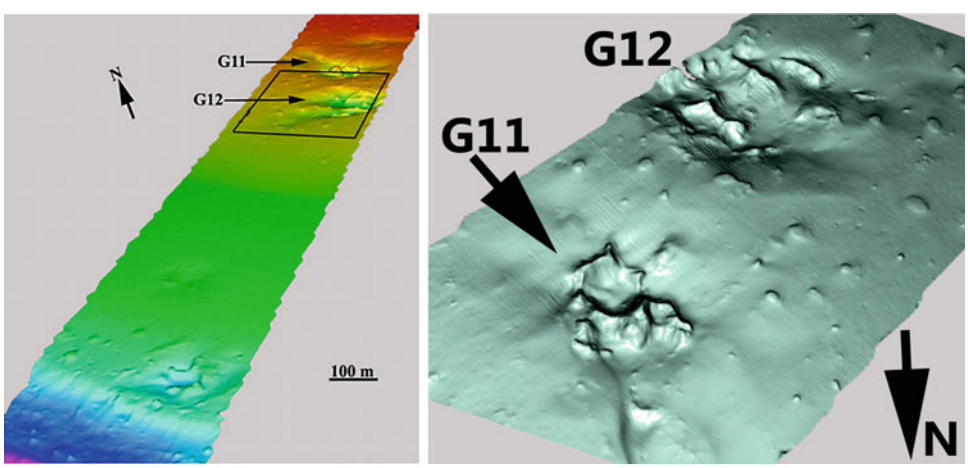

Fig. 2.4 Left: Oblique-view topographic shaded relief map of a rectangular area at Nyegga surveyed with high-resolution (MBE), ROV-based bathymetry. Two of the 'complex pockmarks', G11 and G12, were investigated in particular detail (the location of survey area is seen in Fig. 2.2). Notice the Storegga slide scarp, bottom left. It is adjacent to another, un-named complex pockmark. Right: The various topographic details of G11 and G12 are clearly seen in this oblique-view monochrome shaded relief image

Table 2.1 Geochemical results (concentrations given in ml/l) from the analysis of adsorbed light hydrocarbons in sub seafloor sediments (Hovland 2008). The cores are up to 0.5 m long. The location of sediment samples G11-1 and G11-2, are shown on Fig. 2.6a, as *28 and *22, respectively

ID	Methane	Ethane	Propane	n-Butane	Sum
C-3	262.70	50.61	28.50	12.75	354.56
G8-5	153.53	14.37	6.44	2.69	177.03
G11-1	202.74	37.68	24.60	12.54	277.56
G11-2	275.54	55.13	36.17	18.20	385.04

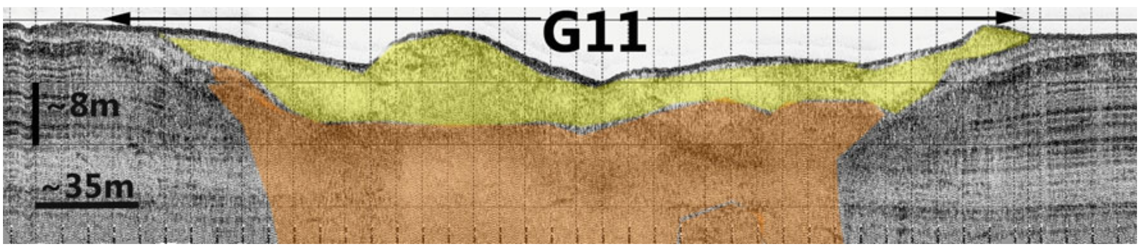

Fig. 2.5 High-resolution 2D-seismic (Chirp) profile across the G11 complex pockmark at Nyegga (see Fig. 2.4). Note the mounds, which are partly produced by heaps of MDACs and partly made up of sediment-hosted gas hydrates (e.g., submarine hydrate pingoes). Yellow: Disrupted porous and permeable upper sediments inside G11. The two highest 'ridges' seen here consist of irregular carbonate blocks and rubble (see Fig. 2.6). Orange: The disrupted 'gas chimney', based about 250 m deeper (see Fig. 2.14)

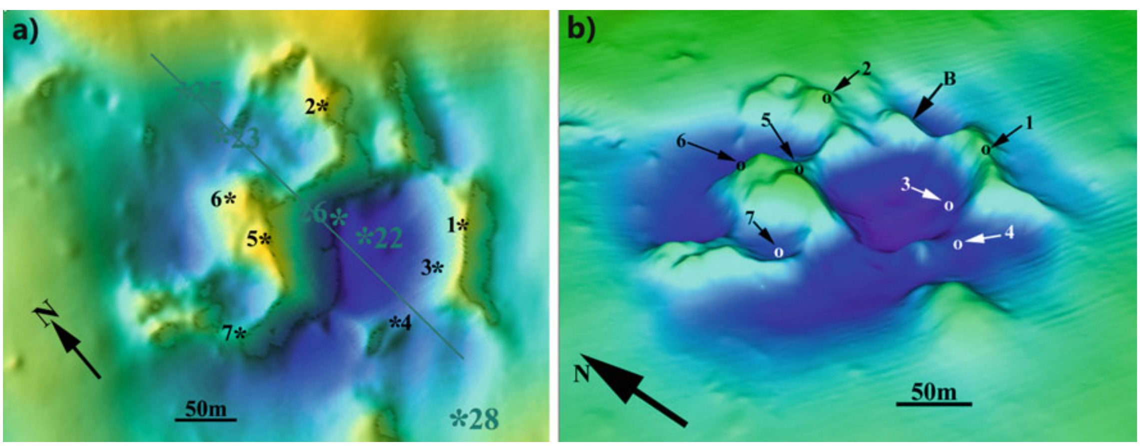

Fig. 2.6 Left: Shaded relief map of complex pockmark G11, where high ridges consist of irregular carbonate blocks and rubble. The seven numbered stars represent sediment-dominated 'seep-mounds' (e.g. hydrate pingoes). The asterisks numbered as '22' and '28' represent geochemical sediment samples (see Table 2.1). Right: In this oblique perspective view of G11, it is easier to see the exact position of the pingoes. They are numbered as in the left image. The pingoes are numbered circles 'o' (1–7). Note that the pingoes occur adjacent to carbonate ridges

them as a "…*relatively large conical mound of soil-covered ice (commonly 30–50 m high and up to 400 m in diameter), raised in part by hydrostatic pressure of water within or below the permafrost of Arctic regions*…" They are formed in low-permeable soils as a result of groundwater migration towards the partial low-pressure water–vapor areas that exist at the freezing front (Miller 1980; Konrad and Duquennoi 1993). Here, ice will accumulate as more and more water migrates to the freezing front, thus causing local ice accretion.

Given the evidence described (see also Clennell et al. 1999 and Hovland et al. 2005), the hydrate pingoes are thought to have formed in the manner outlined below. The prerequisites for hydrate pingo formation are: (1) a relatively high-flux, focused hydrocarbon gas flow through the seafloor, (2) cool bottom water temperatures (less than ~4 °C) and (3) water depths beyond about 400 m, thus ensuring supercooling of the fine-grained environment where the gas hydrates would form (Clennell et al. 1999).

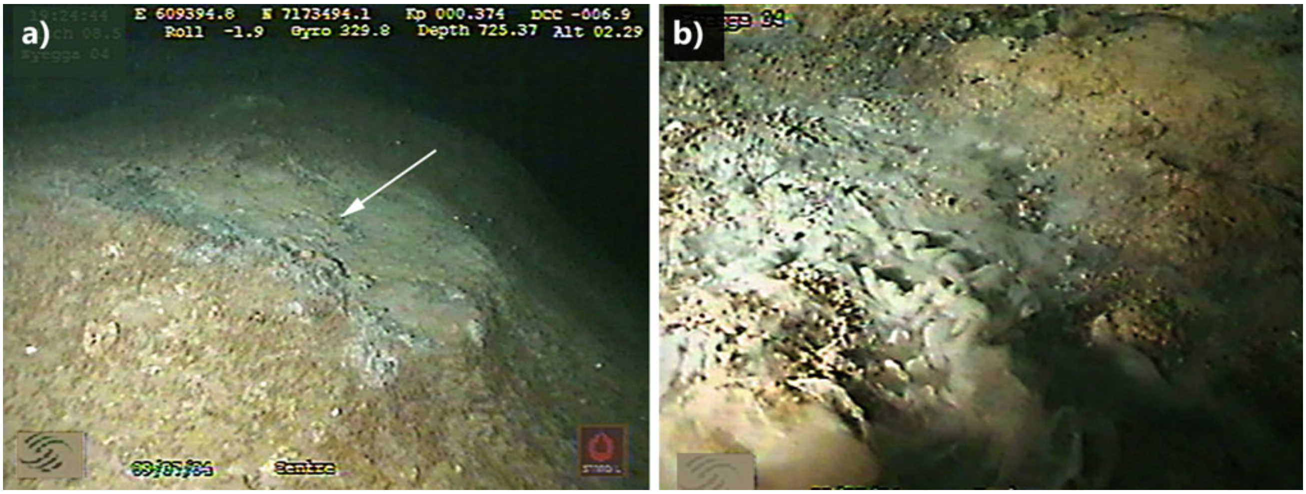

Fig. 2.7 Left: Image of pingo-location "Ice2" (labelled '2' in Fig. 2.6). There are two small pingoes here, located inside a crevasse between two large carbonate blocks (see Fig. 2.10, left, identified by an arrow). The image shows the largest of the two pingoes. It is partially coated in a thin white and grey bacterial mat and is also partially covered by a carpet of small tubeworms resembling a grass-carpet. Note the close proximity to the large carbonate blocks in the background, indicating that the fluids passing through the pingo are likely channeled from below the carbonate. Right: Evidence of fluidized sediments occurring due to local pressure increase on a pingo in G11. The pressure increase was caused by landing the ROV. There is a dense growth of tube worms in this fluidized soil

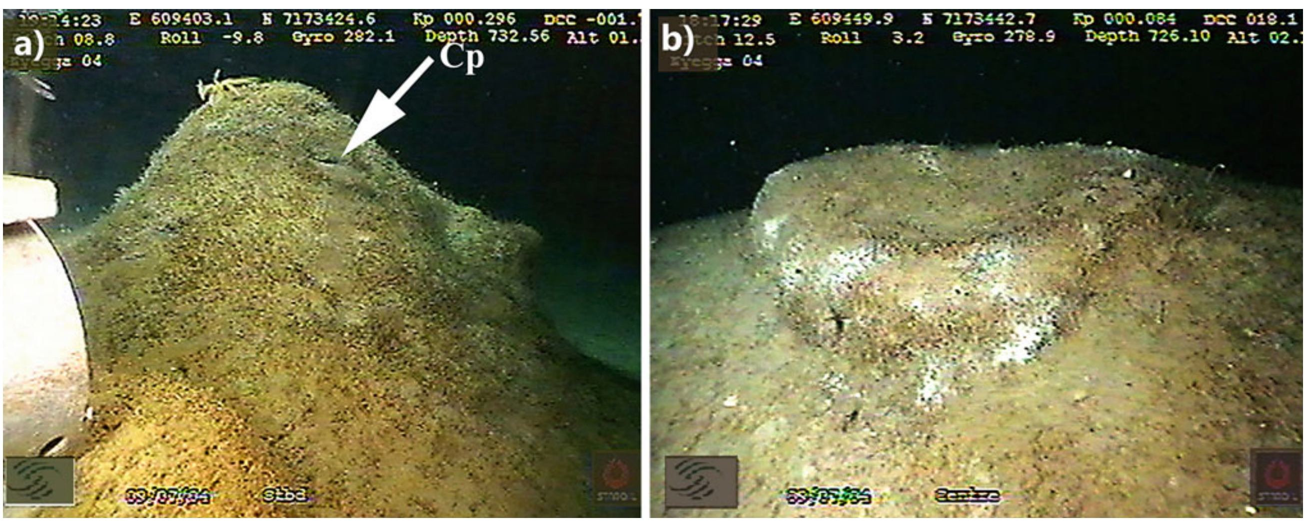

Fig. 2.8 Left: Image of pingo '4' (see Fig. 2.6). It is about 1 m high and has a parabolic geometric shape. In contrast to other pingoes, this one has only a little bacterial mat cover but abundant tubeworm cover. The arrow points at a small corrosion pit labelled 'Cp'. Note the small stream of fluidized sediments below the pit, indicated by the arrow. Parts of ROV sampling gear are visible on the left. Right: Pingo '1' (see Fig. 2.6). It measures about 1 m across and has rims that protrude ~25 cm out of the seafloor. These rims are partly coated in thin bacterial mats, suggesting active seepage. The pingo has a central sag, indicating sub-surface dissolution of hydrates, and is located on top of a dome-shaped portion of the seabed. This pingo was revisited 7 years later in 2010, and was found to have an altered shape although its volume appeared the same, suggesting a steady-state formation and dissolution over time

Based on the G11 pockmark-evidence, it is suggested that the flux of hydrocarbons through the floor of the pockmark is heterogeneously distributed and that the flux may vary over time. Water and methane are essential elements in the formation of gas hydrates, alongside favorable temperature and pressure levels. We surmise that pingoes will only form where the gas flux is highest, where seawater can easily enter through the adjacent seafloor sediments to exchange and replenish the seawater consumed by the gas hydrate formation (see Fig. 2.9).

Because gas hydrates are not in chemical equilibrium with normal seawater, the seawater will be able to corrode and dissociate the outer portion of hydrate, resulting in points of dissolution (see Fig. 2.9). This likely causes the observed erosional pits and the local fluidization of the covering sediment (e.g. 'corrosion pits'), allowing methane

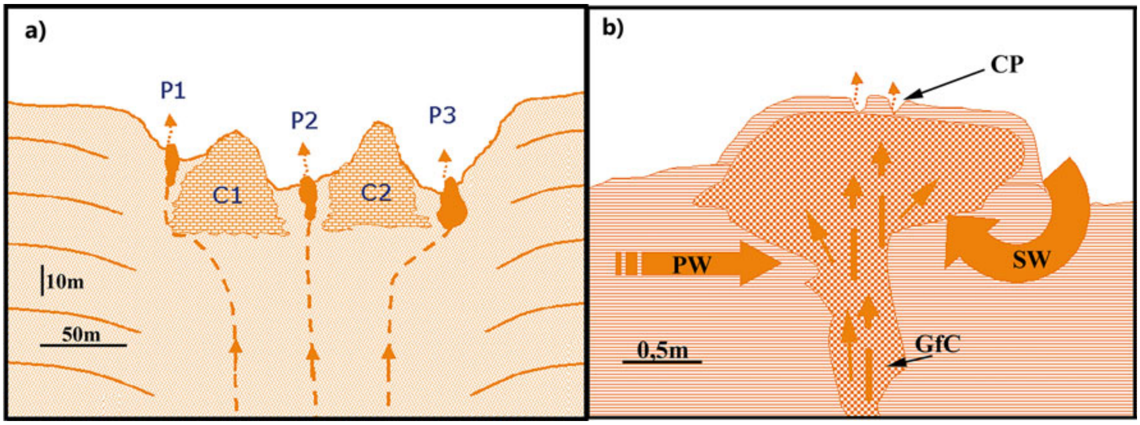

Fig. 2.9 Left: Conceptual sketch, outlining the suspected fluid pathways and the general physical situation inside complex pockmark G11. Because the pingoes and bacterial mats were consistently found in the large carbonate blocks adjacent to carbonate ridges and inside of crevasses, the upward migrating fluids are likely channeled around them. The fluids must migrate through distinct conduits, which remain active for long periods, such that pingoes can form and grow. C1 and C2 denote such carbonate masses. The dark bodies in the figure, marked P1–P3, are pingoes. Right: A close-up sketch of a pingo at Nyegga. It is shown in a 'matured' stage with corrosion pits (CP) on the surface of the sediment cover where the seawater has infiltrated. The two arrows within the sediment indicate suspected flow of porewater (PW) and of seawater (SW). GfC = gas flow conduit (Modified from Hovland and Svensen 2006)

and hydrate-bound water to be released into the surrounding environment. As documented in G11, bacteria utilize the gas-charged, anoxic water that is emitted, most likely after a 'steady-state' flow has been achieved.

2.2.5 Carbonate Rubble

Figure 2.10 shows a huge carbonate ridge inside G11, close to location '2' in Fig. 2.6. Further investigations have proven that the lush patches of marine life on the large carbonate slabs identified in Fig. 2.10 are situated immediately above the hydrate pingoes. These macrofauna 'hot-spots' are likely evidence of the flow-paths of nutrient-rich water streaming past the carbonate rocks.

The first analyses of authigenic carbonates sampled from the Nyegga area were reported by Mazzini (2005), acquired by expeditions in 1998 and 2000 (Kenyon et al. 1999, 2001). More detailed ROV in-situ observations and analyses of the carbonate rocks sampled from G11 and G12 were further reported by Mazzini et al. (2006) and by Paull et al. (2008).

2.2.6 Pockmark-, Carbonate Rubble-, and Pingo-Related Engineering Concerns

Modern offshore hydrocarbon exploration and production involves operations that may significantly alter seafloor conditions. In relation to the occurrence of in-situ gas hydrates, installations that cause the disturbance of pore-water pressure (loading) as well as temperature increases are of particular concern.

The revelation of abundant pingoes forming inside the investigated pockmarks at Nyegga raises the question of how common these features are on the 'normal' intra-pockmarked seafloor. According to Ivanov et al. (2010), there may also be small sediment mounds between the pockmarks, but these are of unknown origin and may not represent hydrate pingoes. In fact, tentative investigations in 2010 have proven that some of these features represent carbonate crusts of apparently 20–30 cm in thickness, likely caused by local, single-point seepage.

The development of offshore hydrocarbon fields may also include the installation of sub-marine production templates, which are linked to flowlines, signal cables and injection flowlines for the transportation of water, gas or oil. Thus, there may be a significant amount of infrastructure to be installed over the production lifetime of such a field.

The stability of the seafloor is, therefore, a key question to consider before planning these installations. Furthermore, the product being transported inside some of the flowlines will be warm, and it will probably be necessary to make sure that none of these pipes are installed within approximately 2–3 m of the hydrate pingo mounds, even those made in small diameter (20–30 cm) and of flexible materials. The reason for such limitations are two-fold: (1) the possibility of damage to the infrastructure (i.e. the pipes) due to local changes in elevation and (2) the unknown consequences of destroying/melting a large hydrate pingo, where the hydrate inside the pingo would dissociate due to elevated temperatures induced by the seafloor infrastructure.

Because the hydrate pingoes at Nyegga are suspected to rely on a relatively constant supply of methane fed from below, their destruction may result in an active seepage of

Fig. 2.10 Left: Pingo '2' (see Fig. 2.6). There are two small pingoes here (not visible) located inside a crevasse between two large carbonate blocks identified in the image with an arrow. Note the abundant sessile organisms growing partly on the underside of the largest block. Also note the lights from another ROV perched ~15 m from the viewing ROV. Centre: The largest individual carbonate block found inside any of the investigated pockmarks (~4 m × 3 m × 2 m, i.e. volume of ~24 m^3). The block is divided by a vertical crevasse of ~1.5 m width. The sediment surface inside the crevasse contains two small pingoes, one shown in Fig. 2.7. Right: A different point-of-view showing the same macro-faunal 'hot-spot' as in the image on the left

gas from the seafloor. This could mean that an operator would prefer to install hot flowlines away from any hydrate pingo structures. The same could also apply to the installation of a template structure, which is secured to the seafloor with either suction anchors or piles. These reasons alone would likely be enough to justify the use of geospatial mapping to plan an alternative route for the infrastructure to avoid pingo destruction. It could also be necessary to perform further field investigations/experiments, perhaps in combination with laboratory work.

Carbonate ridges and carbonate rubble found inside complex pockmarks, on the other hand, may not pose any problem for the subsea installation of signal cables (including fiber-optic cables), but would represent a hindrance for most tubing and flowlines. This is because the carbonates at Nyegga are very rugged, with numerous 'sharp edges' that may damage the outer material providing protection and insulation to the infrastructure.

Furthermore, it must be considered that flexible flowlines are designed to move on the seafloor to some degree. Such movement is induced by cooling, heating and internal pressure fluctuations according to the production and type of fluid-flow inside the tubing.

In conclusion, the primary recommendation to an operator at a site such as Nyegga would be to keep all installations away from the complex pockmarks. If this is not possible, it will be important to perform further investigations and implement careful planning procedures before installing infrastructure on the seafloor.

2.2.7 Unique Fauna

Two of the complex pockmarks, G11 and G12, have proven to be unique places for marine life. The exotic nature of the fish and other fauna in these areas resemble a giant artificial aquarium. The two most spectacular aspects of these locations are (1) the wide variety of docile fish species and (2) the surprisingly high number of large (15 cm) pycnogonids of the species *Collosendeis proboscidea*, as seen in Fig. 2.12 (Hovland et al. 2005).

The fish appeared to be unusually docile, either because of the cold temperatures of their environment (at a water temperature of −0.7 °C) or the lack of predators capable of thriving there. Only the common skate behaved in the expected agile manner when prodded by the manipulator arm of the ROV.

The ROV surveys also documented the existence of bacterial mats, probably of the species *Beggiatoa* sp, as well as fields of polychaetes (i.e. small tube worms). They were mainly located in the deepest, soft sediment-covered portions of the pockmarks at one of the geochemical sample locations, amongst others, as shown in Fig. 2.11. In addition to the typical discoloration of the seafloor, slimy filaments were observed 'waving' in the currents. Large ophiurids (i.e. basket stars) reaching up to 1 m in diameter, as seen in the center of Fig. 2.11, were found on the pingoes from Fig. 2.6 and on many of the carbonate blocks.

There were many common fish recorded, although there is some question as to their exact identification. These include *Amblyraja hyperborean*, *Lycodes esmarkii*, *Cottunculus microbs*, *Stylocordyla borealis* and *Gaideopsarus argentalus*, as seen in Fig. 2.13. Another macrofaunal species found were feather stars (*Heliometra glacialis* and/or *Poliometra prolixa*), in addition to numerous unidentified species of stalked crinoids, sea anemones, brittle stars, corals, etc.

Chemosynthesis drives certain parts of the food-chain at the Nyegga complex pockmarks. This is equivalent to the fauna composition described at the giant Haakon Mosby

Fig. 2.11 Left: The location of this grey and white bacterial mat is shown in Fig. 2.6, labelled *28. An ROV-sediment sample was acquired there for geochemical analysis (see Table 2.1). The sediments contain relatively high concentrations of methane to pentane hydrocarbons, indicative of active micro-seepage. A large pycnogonid (shown in Fig. 2.12, right) also appeared at this location during sampling operations. The inset to the lower left shows the hole that remained in the clay after sampling. For scale: black 10 cm bar. Centre: A selection of images showing hydrate pingoes, bacterial mats, and prolific mega-faunal growth adjacent to the pingoes. A group of three large pycnogonids were seen sitting on the vertical wall of the carbonate block in the unspecified location on the upper left image. Right: Five giant stalked crinoids were caught perching on a carbonate slab. A close-up image is shown in Fig. 2.13, right (Modified from Hovland et al. 2005)

Fig. 2.12 Left: Image of a giant pycnogonid with a large white foraminifer on its back, from location '7' in Fig. 2.6. Numerous large pycnogonids (probably of the species *Collosendeis proboscidea*) are found inside complex pockmark G11. Right: Image of the pycnogonid observed during sampling, located in Fig. 2.11. on the left (Modified from Hovland et al. 2005)

Mud Volcano (HMMV) in the Barents Sea (Vogt et al. 1997). The ecological system at HMMV has, at its base, primary producers (PP) such as "*sub-bottom, methanogenic bacteria*" and "*seafloor methanotrophic bacteria*", both relying upon chemosynthesis to survive. This trophic level forms the nutritional basis for secondary consumers (SC) including "*benthic suspension feeders*" and "*benthic deposit feeders*", followed by primary consumers (PC) at the end of the food chain, such as the "*predatory amphipoda*" and a diverse number of "*telostei*" (i.e. ray-finned fish) (Vogt et al. 1997). A similar faunal composition is evident at the Nyegga complex pockmarks (Figs. 2.11, 2.12 and 2.13).

2.2.8 Fauna-Related Drilling and Engineering Concerns

Sustainable development and operations are currently part of any industrial operation, with a particular focus on the potential disruption of biodiversity and bio-density in such areas. Therefore, there are two relevant aspects to consider when dealing with places like Nyegga: (1) the degree to which the recognized fauna composition is protected by international and/or state law against industrial interference and (2) the degree to which the operator takes exceptional responsibility to protect the faunal composition at the site.

Fig. 2.13 Left: Unidentified fish lying on the seafloor inside pockmark G11. Right: One of the five stalked crinoids perched on top of a carbonate slab (see also Fig. 2.13, right). Note the fish, perhaps an eelpout, resting next to the crinoid, which is touching the fish with some of the stalks. The low fish activity at the Nyegga location is probably a result of the low ambient temperature (−0.7 °C) and/or the lack of predators in this special environment

With respect to aspect (1), there is no doubt that although international law does not automatically protect all chemosynthetically-based ecology, some states have strict rules to prevent interference. This does not, however, necessarily include Norway. With respect to aspect (2), it would be in the interest of any renowned company or operator to avoid disruption/damage to the whole or parts of the chemosynthetic community at places like Nyegga.

This does not need to hinder any operator from installing subsea engineering infrastructure in such an area. It would be crucial to refrain, however, from disturbing the world-class, rare bio-communities and/or significant biostructures such as those at Nyegga, or the giant bio-mounds found off the coast of Ireland, for example (Hovland et al. 1994). It is well-known that even in densely populated deep-water coral 'sanctuaries', such as the Morvin hydrocarbon field off mid-Norway, it is possible to continue production drilling and infrastructure installation/operation while simultaneously protecting the nearby corals (Hovland 2008). The cost of such an operation is relatively high, but it can be done with an emphasis on careful planning and monitoring throughout all stages with full transparency to the public and authorities.

2.2.9 Gas Chimneys

According to Ivanov et al. (2010), the peculiar "*vertical sub-bottom zones of acoustic wipe-out*" (see Fig. 2.3) were originally identified as vertical seismic zones with"…*widths between 150 and 500 m and vertical extensions up to 700–800 ms TWT*". Later, these gas chimneys were investigated by seafloor tomography technology and 3D imaged by ocean bottom seismometers (Hustoft et al. 2007; Ivanov et al. 2007; Westbrook et al. 2008; Plaza-Faverola et al. 2010). This led to a detailed velocity investigation, the results of which are summarized by Plaza-Faverola et al. (2010): "*In seismic reflection sections, chimneys are represented by zones of low coherence, scattering and low amplitude that is, at least in part, a consequence of the seismic scattering in the shallowest parts of the chimneys. The surrounding strata appear truncated at the margins of the zone of incoherence and may also be flexed upward in the flanks of the chimney. Some of the truncations may only be apparent because of seismic visibility loss in the zone of incoherence, but in other cases, diffractions from points where strata meet the zone of incoherence show that truncations are real.*"

Several studies have been undertaken to estimate the true gas hydrate saturation and free gas content at Nyegga. Velocity analyses of seismic data provided further information for such estimates (Bünz and Mienert 2004; Bünz et al. 2005; Plaza-Faverola et al. 2010; Westbrook et al. 2008). Hydrate saturations have been estimated from ocean bottom seismic (OBS) data and range from 2–15% of pore-space. These values are also in agreement with Mienert et al. (2005), who estimated a value of 7–9% of the pore-space to be occupied by hydrate overlying a free-gas zone with average pore space concentrations ranging from 0.15–0.90%. Bünz et al. (2005) estimated the concentrations more specifically: in the sediments overlying the BSR, the concentration of hydrate ranged between 3–6% of the pore-space, whereas 0.4–0.8% free-gas concentration was found in sediments extending up to 80 m beneath the BSR. In conclusion, these two estimates are quite similar, as also supported by Minshull et al. (2020).

According to Plaza-Faverola et al. (2010): "*Over a short-period formation scenario, the chimney contains a fracture network where mainly gas hydrate is currently emplaced. The formation is explained in four steps involving migration of gas from deep sources and its passage through the GHSZ. The gas-rich layer supplies the methane for hydrate formation inside the chimney. Doming of the strata seems to be related to hydrate accumulation. Carbonates form above the chimney at the seafloor and immediate sediments*" (Plaza-Faverola et al. 2010). The four stages mentioned here include: (1) vertical migration of gas through polygonal faults (not shown here), (2) "*Gas migration through the more permeable-porous units, accumulating in conventional stratigraphic and structural traps at the base of the GHSZ*", (3) "*When the gas achieves a critical overpressure, it migrates rapidly into the GHSZ by creating fractures and forming hydrate in veins*" and (4) "*The input of gaseous methane decreases with time as a consequence of diminution of the process driving gas migration from deeper, but water with methane in solution continues to migrate upward, forming small amounts of hydrate throughout the GHSZ and authigenic carbonate close to the seafloor and supporting chemosynthetic biota*".

Plaza-Faverola et al. (2010) conclude their comprehensive 3D-seismic tomography study of pockmark related gas chimneys at Nyegga as follows:

(1) The core of the CNE03 chimney is 500 m in diameter at its base and 200 m in diameter near the seabed, with a zone of anomalously high P-wave velocity. Vp increases laterally at the center of the chimney. Beneath the GHSZ, the velocity distribution in each layer is homogenous with no major lateral changes in velocity.
(2) There is a 230 m depth extent of the high-velocity zone, which is wholly within the GHSZ but non-existent below the BSR.
(3) The seafloor and sediment layers within the GHSZ are domed over the center of the chimney. It appears that the hydrates occur in veins and fractures, which perhaps created the doming through volume increase.
(4) "*We suggest a predominantly fracture-filling model as appropriate for the formation of hydrate in the fine-grained sediments*" (Plaza-Faverola et al. 2010). The highest hydrate concentration is near the base of the GHSZ and may reach as high as 27% of the total volume. However, it is likely that the maximum hydrate concentration is much less than 27% and may not exceed 14% of the total volume. Although the researchers did not state this explicitly, it is our own inference that the chimney is likely to have originated as a vigorous gas venting system that generated a fracture network in which hydrates formed.

2.2.10 Gas-Chimney Related Drilling, Production, and Engineering Concerns

There is little doubt that the gas chimneys below some of the complex pockmarks at Nyegga represent locations with the highest concentrations of in-situ gas hydrates at between 14–27% of their volume, according to Plaza-Faverola et al. (2010). This means that the chimneys are hydrate 'sweet-spots' that could possibly represent 'reservoirs' for future exploitation. However, because the mid-Norwegian continental shelf and slope is a well-known and prolific hydrocarbon province containing an array of active oil, gas and condensate fields (as illustrated in Fig. 2.1), the chimney structures at Nyegga are very unlikely to attract commercial exploitation interest. This is especially compounded by the fact that hydrate production technologies are still in the development phase. The total energy density found in the gas chimneys is very low, so it is therefore unlikely that any commercial operator will target these locations for exploration and production (Hovland 2000).

In other global realms, however, this may have proven otherwise. Had these chimneys existed in hydrocarbon-poor provinces such as those found in the Pacific Ocean, there could have been potential for utilization. There are, in fact, several projects investigating the energy of such gas hydrates, such as the initiatives taken by the Chinese, Japanese and Indian governments (Boswell et al. 2018; Fujii et al. 2016; Li et al. 2018). This has led to modern communications discussing the challenges of such drilling and exploitation of gas hydrate resources, even suggesting the use of casings, controlled drilling, blow-out preventers and mud to balance overpressures: "*As changes in drilling fluid properties, borehole stability issues, well cleaning, and cementation problems will follow. However, these issues can be successfully mitigated by appropriate drilling techniques just like we can adjust the drilling fluid according to the formation properties change. Secondary generation of methane gas hydrates within blowout preventers, as well as changes in the rheology of the drilling fluid through the formation of barite scale and the subsequent blockage of pipework within the blowout preventer, may occur, but these effects can be reduced by appropriate composition of the drilling muds. If foundations have to be piled into or laid on top of these deposits, then the seabed stability can be reduced if the pressure–temperature regime is disrupted with subsequent damage to the structures, associated pipelines, and communication cables*" (Wang et al. 2018).

Modern impact reviews and assessments of hydrate drilling and exploitation have also been recently covered by Hassanpouryouzband et al. (2020), providing a glimpse into topics beyond the scope of this article: "*Understanding of the mechanical behavior of clathrate hydrates and the internal mechanisms of their deformation as well as their interaction with the host sediment is essential in gas production from natural gas-hydrate-bearing sediments, environmental and climate impact studies*."

2.3 Husmus Geological Setting

2.3.1 General

The Husmus location lies over a relatively small hydrocarbon reservoir on the mid-Norway continental shelf, located just NE of the producing Draugen field (see Fig. 2.1). This seafloor area has some relatively strange sedimentary features which are likely caused by the occurrence of shallow gas and gas hydrates (Hovland 2008). The four main features are:

(1) A very shallow BSR, occurring intermittently at about 4 mbsf
(2) Distinct, relatively normal pockmarks (see Fig. 2.14)
(3) Acoustically turbid sediments beneath pockmarks and sedimentary ridges (see Fig. 2.15)
(4) Cold-water coral mounds on some of these ridges (see Fig. 2.15).

In general, the whole continental shelf off mid-Norway is renowned for being rich in cold-water corals occurring at water depths between 250–400 m. These were investigated and mapped with modern acoustic systems by Freiwald and Roberts (2005) and with high resolution acoustic systems and video by Hovland et al. (1998) and Mortensen et al. (1995).

2.3.2 The Shallow BSR at Husmus

Based on water depth, sediment type and seismic records, this suspected reversed polarity strong acoustic reflector is interpreted as a BSR, which represents the boundary between free gas underlying gas hydrate-hosting sediments. This interpretation is in agreement with an array of previous research (Hovland 1990, 1991; Hovland and Svensen 2006; Ivanov et al. 2007; Minshull, et al. 1994; Flemings et al. 2003; Tréhu et al. 2006). The reflector must 'dissolve' beneath the pockmarks and ridges as the gas hydrates dissociate, releasing free gas (mainly methane and minor ethane) and low-salinity (hydrate-bound) water, saturating the sediments and seeping into the water column above.

The coral mounds/reefs, therefore, are believed to occur at the locations on the seafloor where these fluids (gases and low-salinity water) enter the seawater. We interpret this as an

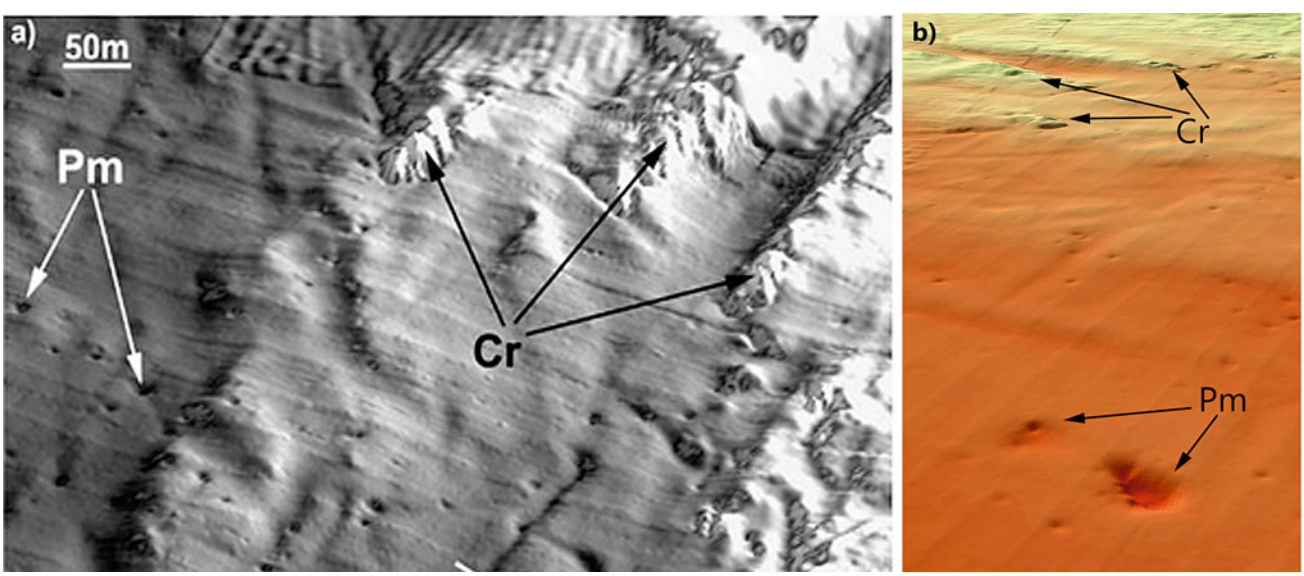

Fig. 2.14 Two oblique views of a shaded relief map of the Husmus seafloor. The seafloor is unusual. Left: a section of the seafloor terrain, about 600 m across. Normal pockmarks (Pm) occur in areas with a smooth layer of glacimarine, layered mud. Where the ridges and coral mounds (Cr) occur, the seafloor consists of glacial till and a rugged terrain. Right: a colored view with enhanced perspective to improve the impression of the relationship between the pockmarked zone (foreground, SE) and the ridge and coral reef zone in the background (NW). The shallow BSR occurs between the pockmarks and disappears under the ridges, upper right on both images. See text for further information

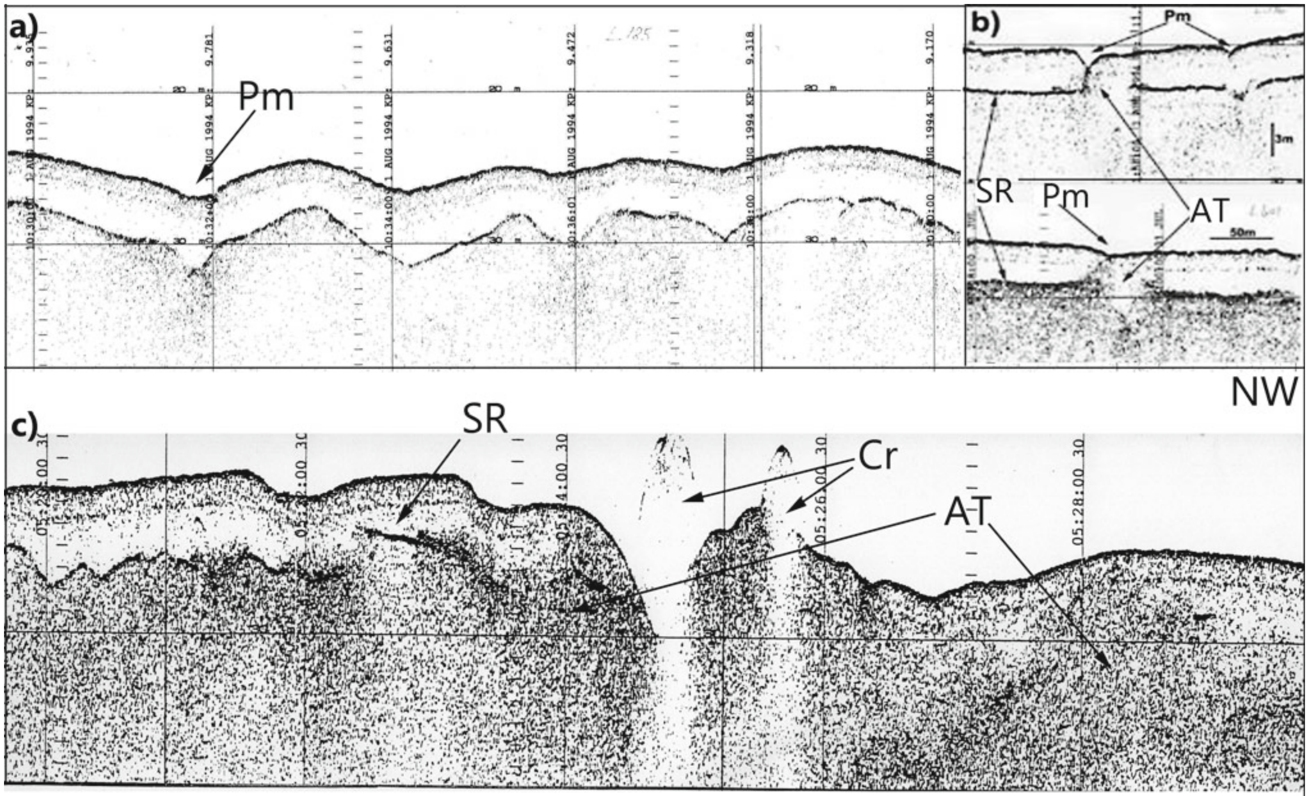

Fig. 2.15 Three samples of high-resolution (Chirp) sub-bottom profiler images from the area shown in Fig. 2.14. On the left side are two images (top and bottom) displaying the pockmarks in the smooth seafloor. Notice the strong reflection (SR) at only 4 mbsf. Wherever pockmarks occur, the reflector disintegrates and seems to cause a migration of fluids (gas and water) through the seafloor inside the pockmarks. This causes acoustic turbidity (AT). On the right is a profile crossing the ridges and coral reefs (Cr). The strong reflector is only visible to the left, and is interpreted as the transition from hydrate-charged sediments above to free gas-charged sediments below the reflector

analogy to Nyegga, where filter-feeding coral species also benefit from extra nutrients and micro-organisms originating from below, as first discussed by Hovland (1990). At other, larger hydrocarbon fields, such as the Kristin and Morvin fields further to the north and west on the mid-Norway continental shelf, the coral reefs form inside some of the seafloor pockmarks found there (Hovland 2008).

According to theoretical calculations of gas hydrate stability and porewater pressures (2008), methane hydrates reach their stability limit at water depths of 280–290 m and temperatures between 5–7 °C, as occurs at Husmus. Therefore, it is believed that the hydrocarbons migrate upward through the sediment, likely originating from the Husmus reservoir, and are trapped in the shallow low-permeability sediments as free gas below a boundary of upper gas hydrates. Because these bounding gas hydrates are balancing at their thermobaric stability level, only slight perturbations, such as annual temperature changes of less than one degree Celcius and/or lunar tidally induced pressure cycles, could be sufficient to induce the formation and dissociation of near-surface gas hydrates. Thus, it is hoped that more geobiological work can be performed at this location in future.

2.3.3 Husmus-Related Drilling and Engineering Concerns

According to Judd and Hovland (2007), because the volumes of gas hydrates and the free gas in the upper sediments at Husmus must be very low (estimated at 1–3% of the sediment volume), drilling, sampling and seafloor interventions would likely be problem-free in this area.

2.4 Ormen Lange Gas Seeping Event

Despite the numerous large surveys conducted at Nyegga for several weeks per project over 15 years, there have never been reports of acoustic ‘flares’ recorded there. Flares have not been recorded at Husmus, either. This means that seafloor ebullition (i.e. macro-seeps, Judd and Hovland 2007;

Hovland et al. 2012; Chand et al. 2012), like those commonly observed over several hydrocarbon fields in the shallower North and Barents Sea, is not occurring at these two locations. Seepage from these hydrate-prone regions is of the ‘micro-seepage’ type, whereby the seepage is only possible to document with visual observation (i.e. detection of bacterial mats and/or macro-fauna anomalies) and/or geochemical sampling and sediment/water analyses (Judd and Hovland 2007). When seepage of free gas occurs in regions within the GHSZ, there must be an abundance of excess gas, which cannot turn into hydrates due to a high migration rate or lack of sub-surface water.

While the Ormen Lange gas field (see Fig. 2.1) is well within the methane hydrate stability field at over 900 m water depth and an average bottom temperature of −0.9 °C, there are no seep features nor geophysical expressions of sediment gas hydrates. There have been no incidents associated with shallow gas or gas hydrates during exploration drilling there, either (Bryn et al. 2003). There exists some information, however, regarding a rather interesting incident documented only in narrative form (Hovland pers.com. 2008). This information is included here to demonstrate how hydrates may build up suddenly and clutter mechanic operations, potentially affecting the safety of marine-based operations.

The incident occurred after a well had been completed at Ormen Lange. ROV video showed that a presumably insignificant seepage of gas bubbles, likely pure methane, occurred from below the wellhead and its steel base plate. The methane was exposed to the seawater, instantly forming white, hydrate-coated bubbles, in addition to some solid hydrate-cement on the plate. Although this seemed uneventful at the time, it proved that the bonding strength of the cementing hydrate was much higher than expected. Several attempts to free the blow-out preventer and the well-head installation from the base plate failed, and personnel were required to dispatch an ROV fitted with a hot-water hose to dissociate the cementing hydrate manually so that the well-head could be detached from the base plate and recovered.

2.4.1 Gas Seepage-Related Drilling and Engineering Concerns

There have been reports of gas hydrates from leaking well-heads rendering the blow-out preventer useless as the hydrate formed around the leakage. The cementing hydrates caused normally moving items into non-moving masses of hydrate. In addition to such problems with hydrate cementation due to leaking well-heads, there seems to also be a problem with gases seeping naturally through the sediments within the HSZ. Such a location was drilled during ODP Leg 146A (Hydrate Ridge) at Site 892, located adjacent to a major fault in the seafloor sediments (Westbrook et al. 1994). There is a continuous and prevailing stream of gas emitting into the water column from this fault.

This event revealed an unexpected consequence of an active seepage system: the formation of abundant H_2S in the surrounding sediment. This was totally unexpected by the both the drilling team and the general scientific community. Although the H_2S alarm sounded when the first 9 m cores came to the drill-floor of the JOIDES Resolution drilling vessel, it was only after they had been prepared the core for confined storage that the concentration levels were found to be dangerously high. H_2S at concentrations higher than 10 ppm in ambient air can be lethal, so special precautions had to be taken to prevent exposure. The personnel had to wear both protective gear and breathing apparatuses and were forced to store the cores on the open-air deck to maintain safety aboard the vessel (Westbrook et al. 1994; Hovland et al. 1995).

This precaution is now highlighted in the EPSP drilling procedures guidelines and must be implemented in any hydrate-prone areas. It has been discovered that the small H_2S-molecule is also a gas hydrate-forming guest molecule, as it was found to be a constituting gas of the hydrate nodules on the seafloor at Site 892 (Hovland et al. 1995).

2.5 Conclusions

This article describe the wide range of features and effects caused by gas hydrates at three locations offshore mid-Norway. Concerns are discussed related to drilling, offshore facility installation, production and the environment. The Nyegga location, at a water depth of 730 m, is characterized by BSRs along with numerous pockmarks underlain by gas chimneys. The distribution of gas hydrates in this area is controlled by the nature of host sediments and the existence of polygonal fault systems. The special geological history of the Nyegga area has over time, and due to a wide range of different processes, determined the local pore-size distribution which controls free gas content and hydrate saturations. Complex pockmarks containing hydrate pingoes and large amounts of methane-derived carbonate crusts/blocks are the main characteristics of the Nyegga location. Although the thick carbonate slabs suggest a long history of hydrocarbon seepage, the more recently-formed pingoes prove that seepage is still occurring, with dissolved gases migrating up from deeper stratigraphy. The near-seafloor gas hydrates form inside the pingoes where dissociation fluids (i.e. ‘hydrate melt-water’) are also released into the water column. This is also in agreement with geochemical results obtained from shallow cores showing the presence of light hydrocarbon gases (mainly methane with small amounts of ethane and propane) in the sediments. Our findings imply that pingoes can be used as seep localizers, revealing the whereabouts of shallow gas hydrates. The occurrence of hydrate pingoes bear witness to the dynamic nature of gas hydrate formation and dissociation and provides further important information to be taken under consideration while planning subsea engineering installations. However, more fieldwork is needed at locations such as G11 before the true mechanisms of complex pockmarks and hydrate pingoes are fully understood.

The Husmus location overlying a small hydrocarbon reservoir is characterized by a shallow BSR occurrence at 4 mbsf, associated normal-sized pockmarks, acoustically turbid sediments beneath pockmarks and sedimentary ridges with cold-water coral mounds. The coral mounds occur preferentially at suspected seepage locations, where the corals filter seawater likely contains nutrients and micro-organisms originating from beneath the seafloor.

At the Ormen Lange gas field, a much deeper location reaching more than 900 m water depth, we describe the hazards imposed by instantaneous hydrate formation due to seeping methane gas, which may temporarily cement and clutter mechanic installations and hinder marine operations, potentially affecting the safety of an offshore facility. Finally, we also describe an unexpected recovery of H_2S hydrate-hosting sediment during scientific drilling and sampling from Hydrate Ridge. High concentrations of H_2S could be fatal to the personnel working on drilling or other offshore facility vessels. For offshore operations taking place in seafloor areas with gas hydrate occurrences, seafloor drilling and infrastructure installation activities may cause unwanted disturbance of sediment pore-water pressure as well as temperature increases, which may cause unfavorable conditions that could damage infrastructure and cause distress. Adequate surveying, laboratory work and evaluation is therefore necessary to make sure such operations do not cause infrastructure and environmental damage. Because locations with light hydrocarbon seepage normally host animal communities of special interest, the conservation and protection of such communities will be included in all considerations and challenges. The Husmus location has a high biodiversity and biodensity of special marine species, which may render the location unsuitable for future mineral extraction and field development. Such observations should be taken into consideration by potential developers.

Acknowledgements Srikumar Roy thanks the Irish Research Council Government of Ireland for the Postdoctoral Fellow Award (Project No. GOIPD/2018/17) and research grant from Science Foundation Ireland (SFI) under grant number 13/RC/2092, co-funded under the European Regional Development Fund and by iCRAG industry partners.Martin Hovland thanks his previous employer, Statoil (now Equinor), for all the financial support in researching the nature of seafloor seepage over a 40 year period. The investigations reported by Westbrook et al. (2008), Plaza-Faverola et al. (2010) and others also were supported by the same company. This made it possible to hire the survey vessel *Professor Logachev* to perform the 3D-tomography studies at Nyegga over several weeks in 2006. We thank the reviewers, especially Anne Tréhu, for their help. Thanks also go to Berit Oline Hjelstuen for helping with a seismic image and to Stein Bondevik for positive suggestions.

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