ECONOMIC GEOLOGY OF NATURAL GAS HYDRATE

Coastal Systems and Continental Margins

VOLUME 9

Series Editor

Bilal U. Haq

Editorial Advisory Board

M. Collins, *Dept. of Oceanography, University of Southampton, U.K.*

D. Eisma, *Emeritus Professor, Utrecht University and Netherlands Institute for Sea Research,
Texel, The Netherlands*

K.E. Loudon, *Dept. of Oceanography, Dalhousie University, Halifax, NS, Canada*

J.D. Milliman, *School of Marine Science, The College of William & Mary, Gloucester Point, VA,
U.S.A.*

H.W. Posamentier, *Anadarko Canada Corporation, Calgary, AB, Canada*

A. Watts, *Dept. of Earth Sciences, University of Oxford, U.K.*

The titles published in this series are listed at the end of this volume.

Economic Geology of Natural Gas Hydrate

By

Michael D. Max

*MDS Research & Hydrate Energy International,
St. Petersburg, FL, U.S.A.*

Arthur H. Johnson

*Hydrate Energy International,
Kenner, LA, U.S.A.*

and

William P. Dillon

*Geological Survey Emeritus and Hydrate Energy International,
Woods Hole, MA, U.S.A.*

With contributions of

Sarah Holman, Michael Kowalski, George Moridis, John Osegovic,
Shelli Tatro and George Taft

Springer

A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN-10 1-4020-3971-9 (HB)
ISBN-13 978-1-4020-3971-3 (HB)
ISBN-10 1-4020-3972-7 (e-book)
ISBN-13 978-1-4020-3972-0 (e-book)

Published by Springer,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

www.springer.com

Cover Illustration

Flare image shown by Satoh, et al. (2003). Picture taken and supplied by T. Collett. Image enhancement by Rachel Max.

Printed on acid-free paper

All Rights Reserved

© 2006 Springer

No part of this work may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, microfilming, recording or otherwise, without written permission from the Publisher, with the exception of any material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work.

Printed in the Netherlands.

DEDICATION

This book is dedicated to **Dr. Keith A. Kvenvolden**, a pioneer in the studies of gas hydrate and the broader issues of petroleum in the natural environment. Keith has been one of the most knowledgeable scientists in the field of gas hydrate geochemistry. Furthermore, he is a true gentleman who has encouraged others and has been a guiding force to his peers and younger scientists.

And also to:

Dr. Burton G. Hurdle, a well-known facilitator and scientist of the Acoustics Division of the Naval Research Laboratory for over half a century, whose personal support for younger scientists trying to do breakthrough research led directly to the passing into law of the Gas Hydrate Research Act (of 2000).

TABLE OF CONTENTS

Preface	xv
Introduction	1
National Programs for Hydrate Research	1
Countries with Developed	
National Hydrate Energy Interests	1
Countries Showing Early Interest in Hydrate	8
Terminology of Hydrate and its Processes	12
From Resource to Reserves	14
Chapter 1. Why Gas Hydrate?	17
1.1. Introduction	17
1.2. Reserves versus Markets	19
1.3. The Case for Unconventional Gas	21
1.4. Meeting Future Demand	24
1.5. Options for Increasing North American Gas Supply ...	26
1.5.1. Increased Conventional Gas Development ...	26
1.5.2. Increased LNG Imports	28
1.5.3. Concerns for LNG	30
1.6. Looking to the Future	31
1.7. The Case for Gas Hydrate	34
1.8. Current Knowledge of Gas Hydrate Occurrence ...	35
1.9. Exploration for Commercial Gas Hydrate Prospects ...	37
1.9.1. Overview of Deepwater Production ...	37
1.9.2. Models for Recovery	39
1.9.3. Business Issues	42
1.10. The Gas Economy: Enhanced Efficiency and Security ...	43
1.11. Conclusions	44
Chapter 2. Physical Chemical Characteristics of	
Natural Gas Hydrate	45
2.1. Introduction	45
2.2. Crystalline Gas Hydrate	47
2.3. Formation of Gas Hydrate	50
2.3.1. The Growth Dynamic	50
2.3.2. Hydrate Growth Inhibition	54
2.4. Nucleation	55
2.5. Growth	59
2.5.1. Effects of Diffusion	61
2.5.2. Growth from Mixtures of HFG	62

2.5.3. Hydrate Growth from Different Types of Solution	63
2.5.4. Example of Hydrate Growth	66
2.6. Hydrate Dissociation and Dissolution	67
2.6.1. Hydrate Dissociation	68
2.6.2. Hydrate Dissolution	70
2.6.3. Dissociation and Dissolution: A Surface Phenomenon	72
2.6.3.1. Hydrate Dissolution in a Nearly Saturated Environment	74
2.6.4. “Self Preservation”	74
2.6.5. The Phase Boundary and Apparent Stability of Hydrate	78
2.7. Hydrate Growth Models	79
2.7.1. Circulation of HFG Enriched Groundwater	80
2.7.2. Diffusion in Solution	82
2.7.3. Diffusion Through Hydrate and Other Solids	85
2.7.4. Formation in Gaseous HFG Through Water Vapor Diffusion	86
2.7.5. Variable Supersaturation	90
2.7.6. Direct Contact between Gaseous HFG and Water	92
2.8. Kinetic Considerations	93
2.9. Best Conditions for Hydrate Concentration	94
Appendix A. Background Chemistry	95
A1. Phase Diagrams	95
A2. Henry’s Law	97
A3. Number of Water Molecules per Dissolved HFG Molecule	98
A4. Chemical Potential of Saline Hydrate Inhibition	98
A5. Mol of Gas Hydrate	99
A6. Diffusion Mechanism for Hydrate Breakdown	100
A7. Concentration	103
A8. Chemical Equations	103
Chapter 3. Oceanic Gas Hydrate Character, Distribution, and Potential for Concentration	105
3.1. The Character of Oceanic Gas Hydrate	105
3.2. Where Gas Hydrate is Found	105
3.2.1. Where is Gas Hydrate Stable?	105
3.2.2. Where Do We find Gas Hydrate in Nature	108
3.3. Identification of Gas Hydrate in Nature	110
3.3.1. Measuring Gas Hydrate in Wells and Cores	110
3.3.2. Remote Sensing of Gas Hydrate	114

3.4. Concentration of Gas Hydrate in Nature	118
3.4.1. Two Modes of Gas Hydrate Concentration	118
3.4.1.1. Diffuse Gas-flow Model	119
3.4.1.2. Focused Gas-flow Model	122
3.4.2. Lateral Variations that Create Trapping of Gas and Gas Hydrate Concentrations	123
3.4.2.1. Structural Trapping	123
3.4.2.2. Physical Variations that Cause Gas Hydrate Concentration	125
3.4.2.2.1. Fault-controlled Gas Flow	125
3.4.2.2.2. Influence of Salt Diapirs	126
3.4.2.2.3. Tectonic Uplift	128
3.4.2.2.4. Tectonic Subsidence	129
3.5. Conclusion	130

Chapter 4. Natural Gas Hydrate: A Diagenetic Economic

Mineral Resource	131
4.1. Introduction	131
4.2. The Source of Hydrate: Generation of Hydrocarbon Gases	133
4.3. The Rock and Sediment Host	138
4.3.1. Porosity	138
4.3.2. Permeability	140
4.3.3. Secondary Porosity and Permeability	142
4.4. Hydrate Growth Regimes	145
4.4.1. Hydrate Mineralization: The Role of Water in Porous Strata	145
4.4.2. Permafrost Hydrate: Water Vapor Diffusion in an HFG Atmosphere	150
4.4.3. Implications for Concentration of Hydrate near the Base of the GHSZ	156
4.5. Gas Hydrate: A Diagenetic Economic Mineral Deposit	157
4.5.1. Contrasts between Conventional Gas and Gas Hydrate Deposits	158
4.5.2. Hydrate Mineralization	161
4.6. Classification of Gas Hydrate Deposits	163
4.6.1. High Grade Deposits	163
4.6.2. Low Grade Deposits	165
4.7. Migration of Hydrate-Forming Gas Into and Through the HSZ	166
4.7.1. Chimneys	168
4.7.2. Vents	169
4.8. Implications for Hydrate Concentrations not Directly Associated with a Seafloor-simulating BGHS	174

4.9. Examples of Stratabound Mineral Deposits	180
4.10. Conclusions	181
Appendix B1	182
Chapter 5. State of Development of Gas Hydrate	
as an Economic Resource	191
5.1. Introduction	191
5.2. Mallik	192
5.2.1. Background	193
5.2.2. The 1998 Mallik Program	193
5.2.3. The 2002 Mallik Program	193
5.2.4. Planned follow-up and Options	195
5.3. Nankai	195
5.3.1. Background	196
5.3.2. 1999-2000 Nankai Drilling Program	196
5.3.3. 2004 Nankai Drilling Program	197
5.3.4. Future work	198
5.4. Gulf of Mexico	198
5.4.1. Background	198
5.4.2. ChevronTexaco Joint Industry Program	199
5.4.3. MMS Gulf of Mexico Gas Hydrate Assessment	200
5.5. Alaska	201
5.5.1. Background	201
5.5.2. BP Exploration Alaska	202
5.6. Cascadia Margin	202
5.6.1. Background	202
5.6.2. ODP Leg 204	202
5.6.3. IODP Expedition 311	204
5.7. Messoyakha	204
5.8. India	204
5.9. Comment on Hydrate Research: Objectives and Progress	205
5.10. Conclusions	206
Chapter 6. Oceanic Gas Hydrate Localization,	
Exploration, and Extraction	207
6.1. Introduction	207
6.2. Gas Hydrate Provinces	208
6.3. Semi-Quantitative Evaluation of Hydrate Likelihood	209
6.4. Remote Sensing for the presence of Oceanic Hydrate	211
6.4.1. Seismic Effects of Hydrate Formation	
and Exploration	212
6.4.1.1. Blanking	214
6.4.1.2. Accentuation	216
6.4.1.3. Seafloor Acoustic Imagery	217

6.4.2. Sulfate Reduction Identification	217
6.4.3. Natural Gas Analysis and Application	218
6.4.4. Heat Flow / Vent-related Seafloor Features	219
6.4.5. Electromagnetic Methods	220
6.5. Exploration for Natural Gas Hydrate Deposits	221
6.6. Issues concerning Recovery of Gas from Hydrate Deposits	221
6.6.1. Reservoir Characterization	222
6.6.1.1 Contrasts Between Hydrate and Conventional Gas Reservoirs	224
6.6.2. Producing Gas from Oceanic Hydrate In-Situ	225
6.6.2.1. Extraction Methodology	227
6.6.3. Drilling	228
6.6.4. Artificially Induced Permeability	232
6.6.5. Hydrate and Natural Fracturing	236
6.6.6. Volume-Pressure Relationships for Hydrate Dissociation at Depth	238
6.6.7. Safety	241
6.7. Unconventional Gas Recovery from Hydrate	241
6.7.1. Dissolution	242
6.7.2. Low-Grade Deposit Special Issues	246
6.8. Conclusions	248
Chapter 7. Gas Production from Unconfined Class 2 Oceanic Hydrate Accumulations	249
7.1. Introduction	249
7.2. Background	249
7.3. Description of the Geologic System	250
7.4. Objectives	252
7.4.1. Case 1: Gas Production from a Single-Well System	252
7.4.1.1. Geometry and Conditions of the System	252
7.4.1.2. Domain Discrimination and Simulation Specifics	253
7.4.1.3. Results of the Single Well Study	254
7.4.1.4. Effect of the Initial S_H in the HBL	257
7.4.2. Case 2: Gas Production from a Five-Spot Well	258
7.4.2.1. Geometry and Conditions of the System	258
7.4.2.2. Domain Discrimination and Simulation Specifics	259
7.4.2.3. Results of the Five-Spot Study	259
7.5. Summary and Conclusions	265
7.6. Acknowledgements	266

Chater 8. Regulatory and Permitting Environment		
	for Gas Hydrate	267
8.1.	Introduction	267
8.2.	Regulatory and Permitting Framework	268
8.2.1.	Territorial Sea	268
8.2.2	The 200 Nautical Mile Exclusive Zone	269
8.2.3.	The Continental Shelf	270
8.2.4.	The Commission on the Limits of the Continental Shelf ..	277
8.2.5.	Rights of the Coastal State over the Continental Shelf ..	279
8.2.6.	Legal Status of the Superjacent Waters and Air Space and the Rights and Freedoms of Other States ..	279
8.2.7.	Submarine Cables and Pipelines on the Continental Shelf	280
8.2.8.	Artificial Islands, Installation and Structures on the Continental Shelf ..	280
8.2.9.	Drilling on the Continental Shelf	281
8.2.10.	Payments and Contributions with Respect to the Exploitation of the Continental Shelf Beyond 200 Nautical Miles ..	281
8.2.11.	Delimitation of the Continental Shelf Between States with Opposite or Adjacent Coasts. ..	282
8.2.12.	Tunneling ..	283
8.3.	Statement of Understanding Concerning a Specific Method to be Used in Establishing the Outer Edge of the Continental Margin ..	283
8.4.	The Area Beyond the Limits of National Jurisdiction ..	284
8.5.	The Relationship of the Central Government to Local Authorities ..	287
8.6.	Conclusion	288
	Author Comment	288
Chapter 9. Conclusions and Summary ..		289
9.1.	Conceptualization of the Hydrate Gas Resource ..	289
9.2.	Gas Hydrate; A New Hydrocarbon Resource at the Right Time ..	291
9.3.	Gas Hydrate Characterization	292
9.3.1.	Permafrost Hydrate	292
9.3.2.	Oceanic Hydrate	293
9.3.3.	Hydrate Natural Gas Quality	293
9.4.	Hydrate Exploration and Recovery	294
9.5.	Commercial Hydrate Natural Gas Development	295

Table of Contents	xiii
Glossary of Terms	297
Selected References	309
Miscellaneous Information	339
Author Address List	339
Gas Hydrate Fresh Water Reservoirs	340
Earliest Record of Artificially Produced Gas Hydrate	341
CD ROM	

Preface

This book is a companion to “Natural Gas Hydrate in Oceanic and Permafrost Environments” (Max, 2000, 2003), which is the first book on gas hydrate in this series. Although other gases can naturally form clathrate hydrates (referred to after as ‘hydrate’), we are concerned here only with hydrocarbon gases that form hydrates. The most important of these natural gases is methane. Whereas the first book is a general introduction to the subject of natural gas hydrate, this book focuses on the geology and geochemical controls of gas hydrate development and on gas extraction from naturally occurring hydrocarbon hydrates. This is the first broad treatment of gas hydrate as a natural resource within an economic geological framework. This book is written mainly to stand alone for brevity and to minimize duplication. Information in Max (2000; 2003) should also be consulted for completeness.

Hydrate is a type of clathrate (Sloan, 1998) that is formed from a cage structure of water molecules in which gas molecules occupying void sites within the cages stabilize the structure through van der Waals or hydrogen bonding. Hydrate crystallizes naturally in permafrost cryosphere and marine sediment where water and sufficient gas molecules are present, and pressure and temperature conditions are suitable to support spontaneous nucleation and growth (Chapter 2). Hydrate is mainly composed of water and a hydrate forming gas (Fig. P1). When gas hydrate forms, it concentrates the gas in the hydrate crystal lattice. Where methane is the hydrate forming gas, about 164 m³ of methane (at STP) can be contained within the solid crystalline hydrate at any pressure-depth. This element of concentration and the large volumes of hydrate known or projected, are the attributes that render hydrate a potential economic resource of combustible natural gas on a national or world scale.

Natural gas hydrate is stable in a zone of that extends downward from some depth below the Earth’s surface in permafrost regions to a greater depth than water ice is stable (4.4.2; Fig. 4.9). In oceans and deep lakes, gas hydrate is stable from some depth in the water column down to some depth below the seafloor that is also determined by rising temperature (3.2.1; Fig 3.1). Natural gas hydrate that forms in the water, however, is positively buoyant and floats upwards and naturally dissociates. Hydrate that forms on the seafloor may be held in place by intergrowing with sediment. A region referred to as the gas hydrate stability zone (GHSZ) includes hydrate on the seafloor and hydrate formed in sediments beneath the seafloor, as well as the analogous zone of hydrate development in permafrost regions.

The general physical chemistry of gas hydrate, its formation in relation to its general location and the depth of GHSZs in which hydrate may occur, are

relatively well known. Our concern is to apply those aspects of the physical chemistry of natural gas hydrate that are most important to identifying the best conditions for the formation of hydrate concentrations of economic proportions. Also, we identify and discuss difficulties that must be overcome in both finding and recovering the natural gas, as well as pointing out hydrate-specific opportunities in the developing field of commercial recovery of gas from natural gas hydrate deposits.

Figure P1. Proportional volumetric relationship between water, gas, and hydrate in a fully saturated hydrate. The compressional attribute of hydrate formation and its concentration of natural gas within the hydrate make concentrations of hydrate potential energy resources.

In some respects, a book on the topic of gas hydrate economic geology is premature because there are no proven economic deposits of gas hydrate, with the possible exception of the Messoyakha gas field of western Siberia. Even at Messoyakha, however, there is considerable uncertainty about extraction of the natural gas bound up in the permafrost hydrate. Although Makogan (1981) identified about 5 billion m³ (Bm³) of gas from dissociated gas hydrate, Collette and Ginsberg (1997) suggested that hydrate has not substantially contributed to the volume of extracted gas.

Large volumes of natural gas hydrate, at least in its oceanic environment however, appears to occur widely (Kvenvolden & Lorensen, 2001; Soloviev, 2002a, 2002b) although Laherrere (2000) and Lerche (2000) draw attention to the uncertainty of estimates. For instance, over 65% of a 20,000 km² area of the seafloor off Taiwan in the northern sector of the South China Sea appears to have well developed BSR (Bottom Simulating Reflector on reflection seismic records) (3.3.2) in water depths from 700 m to 3,500 m, where hydrate was originally identified from poor reflection seismic records (McDonnell et al., 2000), (Liu et al., 2004, pers. com, 2004). The widespread BSRs off the U.S.

east coast are well known, and have been subject to ground truth studies by well constrained drilling (Dillon & Max, 2003; Goldberg et al. 2003). In addition, new discoveries and valuation of permafrost hydrate, which may be more amenable to near-term commercialization, provide an starting point for development.

There are no existing industry-standard practices for detailed delineation of economic hydrate deposits or for volumetric assessment of 'grade' or 'value' as there are for conventional hydrocarbon and mineral deposits. Nor is there any economically constrained extraction experience on which to base commercial valuation of other gas hydrate deposits. In fact, methods for identifying potential concentrations of hydrate that may have economic potential do not yet exist. The most ubiquitous indicator of the presence of gas hydrate is the first order identifier of BSR on seismic records (3.3.2), but a BSR actually identifies the top of a gas-rich zone beneath sediments whose porosity may be effectively sealed by hydrate. The existence of a BSR does not identify high-grade hydrate concentrations. In addition, drilling has proven little about geologic models that are proposed by us as controlling hydrate development and distribution (Chapters 2, 4, 6). There is presently no undisputed methodology for identifying the extent, reservoir character and strength, or the volume of in-situ hydrate development. Finally, it is not yet known whether hydrate actually constitutes a producible energy resource on the scale of its apparent volume of up to twice the combustible content of all conventional hydrocarbons on Earth or whether it constitutes any potential as an energy resource.

Until recently, gas hydrate has been regarded as a scientific curiosity. Lee et al. (1988) for instance, although identifying the replacement of petroleum by natural gas as the main source of the Earth's combustible energy, make no mention of natural gas hydrate as an economic gas resource. Industrially, hydrate has been, and continues to be as an impediment to flow assurance in gas and petroleum pipeline systems while its potential for separation of materials has gone largely unresearched. Indeed, industry is still spending on the order of two million dollars a day on inhibiting and remediating unwanted gas hydrate (OTC, 2004). Attention is now turning to the potentially very large energy resource possibilities of naturally occurring hydrate (Kvenvolden and Lorenson, 2001). The equivalent of giant and super giant gas fields may occur in concentrated and economically exploitable hydrate deposits. Gas hydrates constitutes a new unconventional gas play, and may prove to be one of the major energy resources of the 21st century. For a number of countries, hydrate may be the only indigenous option for non-renewable, combustible energy resources.

This book examines broadly the economic geologic potential of gas hydrate in both permafrost and oceanic environments. We have developed geologic and paragenetic models for hydrate concentration and extraction that merge lessons learned from experiments nucleating and growing hydrate in natural seawater, which is similar in composition to the pore water of marine sediments in which natural gas hydrate occurs. Suggestions are made for

exploration and extraction scenarios, especially of oceanic hydrate where geological structure may not have the same significance as it does in permafrost hydrate deposits.

Chapter 1 discusses hydrate as part of a spectrum of naturally occurring hydrocarbon resources. Specifically, different sources of conventional and unconventional gas deposits are discussed including coalbed methane, which may provide the most relevant commercial development model for bringing an unconventional gas resource into production and profitability. Because the energy needs and national economic and political parameters governing decision-making may vary considerably, the impetus driving development of hydrate is urgently felt in some countries while it is ignored in others. Superdemand for energy worldwide has also lifted hydrocarbon prices to a new plateau. Energy prices are likely to be maintained substantially above the levels of the inexpensive world energy paradigm that previously had been controlled by the United States.

Chapter 2 focuses on those elements of gas hydrate nucleation and growth that are important to the formation of hydrate concentrations. Growth media, including both gaseous and aqueous environments, are discussed, along with the natural mechanisms that are likely to yield high pore saturations through heterogeneous nucleation and slow growth as a result of naturally modulated supply of hydrate-forming reactants. The principals of both dissociation and dissolution are also described because these are important for recovery of natural gas from hydrate. Physical chemistry is used to illustrate growth models that have been tested through experimentation, and are constrained by thermodynamics, to produce solid hydrate. This section contains enough physical chemical information to allow a geologist or economic geologist who is not a specialist in physical chemistry and hydrate paragenesis to better understand the hydrate system and environmental constraints that may lead to the formation and recovery of natural gas from economic deposits of hydrate.

Chapter 3 characterizes hydrate as part of the geological environment. Gas hydrates comprise an unconventional diagenetic hydrocarbon mineral-like deposit that may be associated with conventional deposits of natural gas. One of the present difficulties hampering many petroleum geologists and geophysicists is that hydrate, and especially concentrations of hydrate, are not governed by the same rules as are conventional hydrocarbon deposits. Gas hydrate is unique among hydrocarbon resources in that it is a solid crystalline material in the natural state, which can rapidly transform to its constituent water and gas in response to changing pressure and temperature.

Porous sediments containing high concentrations of hydrate have been investigated through drilling in the Mackenzie Delta of Canada and in the deep continental shelf margin offshore Japan. Data derived from drilling is now

providing the ground truth needed for realistic assessment of hydrate grades and values.

Chapter 4 summarizes known hydrate localities in both permafrost and oceanic areas from the point of view of their modes of formation. Clear distinctions between them are described, as are the similarities and distinctions between them and conventional gas deposits and the means available for recovery of the natural gas from hydrate deposits. Hydrate is identified as an economic mineral deposit and compared with other solid, crystalline stratabound mineral deposits of diagenetic origin, with which there are many similarities. A great deal is understood about both metallic and non-metallic mineral deposits with similar paragenesis. Application of that knowledge should aid in the identification of geological settings most appropriate for hosting significant concentrations of hydrate economic targets or ‘sweetspots’, so as to guide exploration.

Chapter 5. Natural gas derived from hydrate may be inherently more expensive to recover than most conventional gas deposits because the equivalent of secondary recovery methods must be applied from the beginning. Whereas conventional gas and petroleum deposits are artesian or only have to be pumped to the surface, the hydrate must first be converted to gas. The three main methods for converting the hydrate to recoverable gas (Depressurization, inhibitor stimulation, and thermal stimulation) require different infrastructure and materials and consequent costs. It is also likely that more than one method may be used together in some way, for instance, heating and depressurization. Existing exploration and assessments of hydrate developments are described. Nonetheless, because of the higher energy cost levels that are likely to persist, and because better economic cost and extraction models for hydrate are being developed, extracting natural gas from hydrate may become an attractive investment.

Chapter 6 takes forward the current knowledge of hydrate formation and models likely economic deposits of oceanic gas hydrate. Oceanic hydrate deposits are diagenetic and have grown in place in the sediment by incorporating pore water, under pressure and temperature conditions similar to those in which they now exist. Identification of BSR (3.3.2), is a first order technique for identifying the phase boundary between the hydrate stability zone and underlying gas (Chapters 3 and 5), but more refined techniques are required to identify economic deposits of hydrate. The different models for economic deposits of hydrate are assessed for their response to seismic and other exploration methods and some guidance is offered. Permafrost hydrate deposits appear to be fundamentally different from oceanic hydrate deposits. For the most part, they have been formed from existing conventional gas deposits that were converted to hydrate through the depression of the cryosphere across at least part of the gas zone during intensification of glacial periods, rather than being formed through the migration of hydrate-forming gas into the GHSZ.

Hydrate will not be mined, of course. It will be converted to its constituent natural gas and recovered as gas. But extraction models in some deposits in weaker geological strata may do well to follow mining practices for extraction where some of the ore is left behind in order to promote reservoir stabilization and prevent collapse. This chapter focuses on applying different hydrate nucleation and growth models from Chapter 2 in different natural groundwater systems and geological situations.

Chapter 7 presents one of the most recent thermodynamic models for In-Situ Conversion of Gas Hydrate to Natural Gas that is particularly applicable for high-grade oceanic hydrate deposits, which will probably be the initial source of natural gas from oceanic hydrate. Physical cases of hydrate occurrence that are likely to be encountered in potential economic deposits of gas hydrate are analyzed and shown to have significant economic potential for safely converting and extracting natural gas from hydrate.

Chapter 8 considers the offshore regulatory and permitting environment for gas hydrate, which is governed by UNCLOS, the Law of the Sea. The articles that pertain to the geographic position of likely hydrate deposits along continental margin, as well as examples for particular countries, are explained in detail. National exploration and extraction resource legislation is only briefly discussed. Existing and potential claims for areas beyond the present limit of 200 nmi are not discussed, because the framework for resolution of those claims and for competing claims to continental shelf areas claimed by more than one nation exist in the present UNCLOS documents and procedures.

Chapter 9 summarizes the main characteristics for both permafrost and oceanic natural gas hydrate and the timeliness of the recognition of natural gas hydrate as the likely next big gas play. Emphasis is placed upon the sufficiency of the present level of technology in deep water drilling and hydrocarbon exploration, extraction, and infrastructure for recovering natural gas from oceanic and permafrost hydrate deposits.

Glossary. References are mainly from mining, hydrocarbon exploration, physical chemistry, and geological sources.

References from the text are included in this selected list only where they are not already referenced in the first book for brevity and because the two books are intended to be complementary. There are also a number of references in this list that are not referenced in the text. This is particularly true in the case of some foreign references and where a large number of references have a common theme. In this case, one or only a few references are used in the text.

Miscellaneous. This short section includes the full contact information for authors, a comment on the fresh water sequestered in natural gas hydrates that may be of environmental significance, and a short discussion of the first known experiment that produced gas hydrate by Joseph Priestley during ‘one frosty winter’ in January, 1779 (1790).

In addition to references of publications, cross-references between sections are made between chapters using section numbers such as (2.3.1), figure numbers (which have unique numbers in each chapter) or references to other chapters and the Glossary.

The authors of this book agree strongly with the visionary development efforts to develop natural gas hydrate as an energy source that are being carried out in a number of countries. The greatest step-increment in progress, however, took place as part of an international effort.

“March 7th 2002, an extremely cold winter night in Arctic Canada: a flare from dissociating natural gas hydrate deep below a test well burned for the first time in oilfield (hydrocarbon exploration) history. This flare is one of the products of an international joint project, “Mallik 2002 Gas Hydrate Production Research Well Program”, undertaken by a partnership of seven organizations from five countries: the Japan Oil and Metals National Corporation (renamed from: Japan National Oil Corporation, JNOC), the Geological Survey of Canada (GSC), the GeoForschungsZentrum Potsdam, Germany (GFZ), the United States Geological Survey (USGS), the Indian Ministry of Petroleum and Natural Gas (MOPNG), the BP-Chevron-Texaco Joint Venture Group and the United States Department of Energy (US DOE), with the support of the International Continental Scientific Drilling Program (ICDP)” (Tsuji & Emmermann, 2003).

The image of the gas flare shown on the cover of this book was the immediately visible result of an in-situ stimulation test of controlled changes in temperature and pressure in the Mallik 5L-38 hydrate well that was designed to convert solid gas hydrate in a permafrost hydrate reservoir into its constituent gas and water and to produce a sustained gas flow. The conversion produced pressurized gas that was vented, and flared, according to industry practice. This image has been shown in a lower resolution format a number of times before but it is included here in uniquely high resolution, as it may be the most important symbol of progress in the development of natural gas hydrate as an energy source. This moment may come to be regarded as Time-Zero in the practical development of economic exploitation of natural gas hydrate resources.