UNEP Global Outlook on Methane Gas Hydrates

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Semi-Annual Report

Frozen Heat: A Global Outlook on Methane Gas Hydrates

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Prepared for:
United States Department of Energy

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ADMINISTRATIVE SUMMARY

The UNEP Global Outlook on Methane Gas Hydrates project has received funding from the US Department of Energy under award number DE-FE0003060. The project director is Yannick Beaudoin and the recipient institution is Stiftelsen GRID-Arendal in Arendal, Norway.

The current report is for the period starting October 1, 2010 and ending March 31, 2011.

EXECUTIVE SUMMARY

The UNEP Global Outlook on Methane Gas Hydrates seeks to provide policy makers, the general public and the media with a synthesis of aspects of natural, social and applied sciences that relate to this type of natural gas occurrence. With an emphasis on visual media, the Outlook is working to define global methane gas hydrate occurrences in their natural settings and examine the implications on communities and society of the potential use of methane gas hydrates as an energy source.

During the time period covered by the current report, the UNEP Global Outlook on Methane Gas Hydrates has achieved two major milestones, the first being the development of an initial content draft (draft 0) for each chapter of the assessment. This milestone was achieved as a result of a second meeting of the project Steering Committee (see Appendix I for full meeting report) held in Tokyo, Japan November 18 and 19, 2010.

The second major milestone involved the completion of first chapter drafts (draft 1) for most chapters. These drafts will subsequently be internally reviewed by the steering committee and then sent for external peer review.

These two milestones are clear indicators of the progress of the work to date. They are a combination of organizational, content, technical and outreach achievements consistent with the elements outlined as they key project goals.

DISCUSSION

Methodology

The Global Outlook on Methane Gas Hydrates to be produced by bringing together leading international experts from academia, business, governments and intergovernmental and non-governmental organizations selected from throughout the world. Guided by a Steering Committee of scientific and technical experts the Global Outlook on Methane Gas Hydrates will provide unbiased, credible and science based information. Where consensus in the expert community is unclear, debates and uncertainties will be highlighted and needs for new and/or continued research identified.

The drafting of the report involves teams of experts according to the key themes to be addressed. Each chapter will be subject to peer review, which will inform and broaden the editorial process. As a follow up to the Outlook, discussion, consultations and bi- and multilateral outreach initiatives will serve to disseminate the content, encourage dialogue and assist in incorporating key perspectives into policy development.

Thematic Outline

As discussed an agreed upon by the project Steering Committee, the UNEP Global Outlook on Methane Gas Hydrates will be divided into two volumes and expand on key themes deemed of importance to policy makers, industry and society.

Volume 1 examines the settings and roles of methane gas hydrates in the natural system. It begins (chapter 1) with an examination of the history of hydrate science and a basic definition of methane gas hydrates including: molecular, chemical and physical characteristics, occurrence types and their geological settings and a brief overview of the sources of methane that lead to the formation of methane hydrates. The chapter continues with a qualitative examination of global methane gas hydrate occurrences aimed at providing an overview of their global distribution by type and also of the inherent uncertainties linked to the published estimates. This section is meant to provide both a sense of scale but also to properly discriminate between the various global methane reservoirs.

The next section in the volume (Chapter 2) expands on the role of methane gas hydrates in the natural carbon cycle. A more detailed overview of the natural sources of methane (e.g. biogenic and thermogenic) will be provided including a summary of the global methane budget. Various physical processes that regulate natural methane emissions will be examined in addition to a discussion on the time scales of natural variations in gas hydrate occurrences. Examples from the past will be used to illustrate these natural variations and include: negative carbon excursions in the geological past and the role of hydrates in global transition from ice ages to warm periods. Finally, seafloor and terrestrial geomorphological issues will be discussed including slope slides in the marine/lacustrine settings and the reshaping of the ground surface in permafrost settings.

Chapter 3 will discuss chemosynthetic ecosystems that are dependant on near surface methane emissions and how these emissions may be linked to deeper methane gas hydrates occurrences. It will present the various biological processes that regulate natural methane emissions in particular in the marine/lacustrine environment. The sensitivities of the methane consuming ecosystems to natural climate and geological variations will form an integral part of this chapter.

The final section (Chapter 4) of Volume 1 will contain visual models depicting various scenarios of natural global warming and the associated impacts on global methane gas hydrate reservoirs. This is meant to provide a baseline of sensitivity for discussions related to the anthropogenic amplification of climate variability leading to global warming.

Volume 2 changes focus from natural systems to the examination of the human dimensions of methane gas hydrates ranging from key technological aspects related to methane gas hydrates as a potential large scale source of natural gas, to the development of new/sustainable economics models related to potential development, to the various societal and environmental issues surrounding their possible exploitation. The volume begins (Chapter 1) with an ambitious overview of global energy resource efficiency challenges that lead to the key drivers associated with possible methane gas hydrates extraction. These challenges include geopolitical considerations (e.g. regionalization of energy supply), the climate and energy debate, resource scarcity and global growth in energy consumption (i.e. linked to trends in population growth). Models will be used to present scenarios of the impacts (e.g. on global greenhouse gas emissions) of altering the global energy picture towards a more natural gas based economy while integrating and implementing a strategy for de-carbonising the global energy system. From a geopolitical perspective, the possible ramifications of the availability of a large scale energy source that is more globally distributed will de discussed. The environmental and social footprint of potential methane gas hydrates will also be examined in comparison to other non-conventional natural gas sources such as shale gas. Resource valuation taking into consideration ecosystem services (i.e. natural capital) will be proposed as a more realistic and holistic methodology when planning for development. Finally, the main headers of a new/sustainable economics-based business model will be developed and provided as a template for possible future resource development.

Chapter 2 details the technological considerations for the exploration side of possible methane gas hydrates development. An initial definition of the types of methane gas hydrate occurrences that could potentially be developed using existing technologies is followed by a synthesis of the methods used to detect and define these occurrences. Examples of actual real world site that have been technically defined will be used for illustration purposes.

Following the examination of exploration and delineation, the next section (Chapter 3) will detail the technologies and challenges linked to the production of natural gas from methane gas hydrates. An investigation of the recovery approaches using adapted conventional technologies will focus on key elements of the production cycle including accessing the reservoir, dissociation techniques and the requirements for achieving long term production. Disassociation techniques for methane gas hydrates include both methods that can make us of existing technology (e.g. pressure reduction) and those that require additional research and development (e.g. temperature, chemical and mechanical stimulation; CO_2 injection; kinetic inhibitors). Unique technical challenges linked to production include the management of water as a bi-product, sand production and gas leakage. This section will then address the broader environmental impacts of methane gas hydrates development based on various scenarios. Examples of impacts include: possible methane release to the atmosphere and/or hydrosphere; possible impacts on methane-based ecosystems; marine slope stability; impacts on surface morphology (i.e. in permafrost settings).

The following section (Chapter 4) addresses societal perspectives related to energy resource development. As resource development impacts society from the national to local community scale, this section seeks to illustrate various perceptions linked to energy resource development in order to help shape policies relating to potential future methane gas hydrate development. Areas with previous experience with conventional oil and gas development will provide guidance with respect to concerns related to development, the benefits on well-being of development and practical suggestions to improve the polices linked to potential future development. As occurrences of methane gas hydrates are more globally distributed, many areas with no previous experience with traditional oil and gas development may be affected by methane gas hydrates development. The advice provided in this section will be aimed at ensuring that these previously unaffected areas take into consideration the experiences of others. Case studies from areas including the Arctic region (local community scale) and countries like Japan and India (national scale having not experienced large scale traditional oil and gas development) will be used to illustrate different realities linked to energy resource development.

The final section of volume 2 (Chapter 5) will seek to summarize the main points emphasized in the entire Outlook into the context of sound policy making. Challenges, opportunities, policy responses and options will be provided for stakeholders from government, the private sector, community leaders and the general public in a broad wrap up of the key messages and discussions contained in the Outlook. This section will also examine past experiences in relation to policy issues and how these can be improved upon to shift away from unsustainable practices in global energy resource use towards the most sustainable development possible of non-renewable, finite resources. A development model for methane gas hydrates based on the conversion of financial revenue to new forms of capital (e.g. social capital in the form of national wealth sharing funds; natural capital in the form of revenue diversion towards the longer term need to develop renewable energy sources to replace exhausted hydrocarbon reserves) will be expanded upon to provide both government and industry leaders with new management and policy options.

Project focused, informative web portal

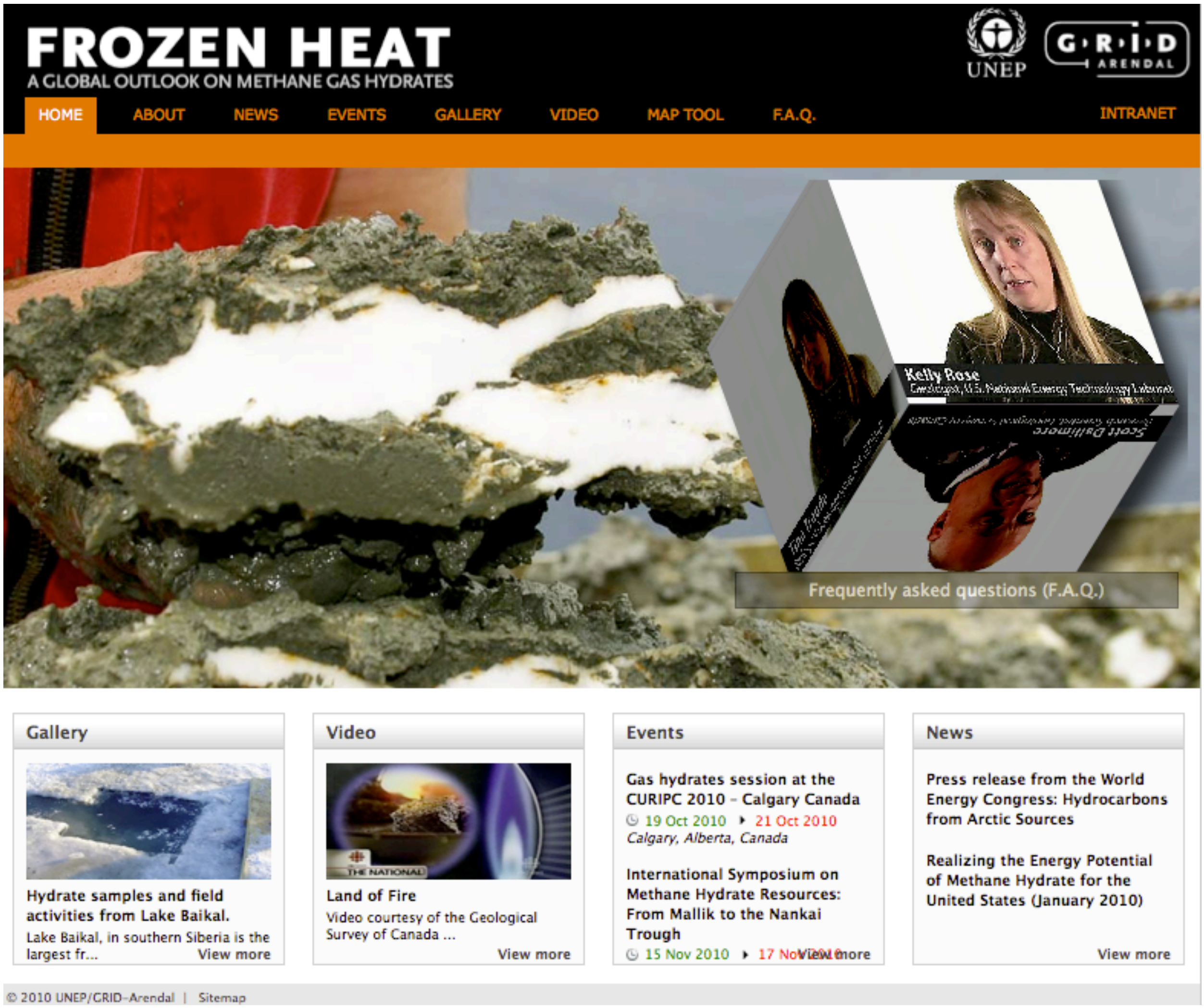
This project web-portal, www.methanegashydrates.org aims to keep all project participants informed of developments via a secure intranet facility. The public pages have been designed to provide: key project information, latest news, information on project partners, a video Frequently Asked Questions and a multimedia galley. The target audience for this initial portal includes: stakeholders knowledgeable in the subject of methane gas hydrates, policy makers, the media, scientists, and hydrates research and development experts.

Concluding remarks

It is evident from the details related to the milestones above that the UNEP Global Outlook on Methane Gas hydrates has achieved the main goals described for the current reporting period. No major impediments have occurred or are expected at this stage. The strength of the international scientific and multi-stakeholder partnership has allowed for an efficient development of the work to date. The UNEP Global Outlook on Methane Gas Hydrates is on target to achieve its primary goal of mainstream knowledge and information on the latest developments in the methane gas hydrates research community.

APPENDIX

Screen capture of project website:



Gallery

Hydrate samples and field activities from Lake Baikal.

Lake Baikal, in southern Siberia is the largest fr... View more

Video

Land of Fire

Video courtesy of the Geological Survey of Canada ...

View more

Events

Gas hydrates session at the CURIPC 2010 - Calgary Canada

19 Oct 2010 ▸ 21 Oct 2010

Calgary, Alberta, Canada

International Symposium on Methane Hydrate Resources: From Mallik to the Nankai Trough

15 Nov 2010 ▸ 17 Nov 2010 View more

News

Press release from the World Energy Congress: Hydrocarbons from Arctic Sources

Realizing the Energy Potential of Methane Hydrate for the United States (January 2010)

View more

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Table 1: Cost Plan/Status Report

Task/Subtask #	**Project Duration Start March 1 2010 End May 31 2012**										
	Project Year 1 (1 Apr-30 Sept 2010)				**PY2 (01 Oct - 31 May)**						
	Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**
Baseline Cost Plan											
Federal Share		$50 000			$50 000						
Non-Federal Share	$65 000		$45 000		$10 000	$10 000	$10 000	$55 000	$10 000	$85 000	$10 000
Total Planned (Federal and Non-Federal)	$65 000	$50 000	$45 000	$0	$60 000	$10 000	$10 000	$55 000	$10 000	$85 000	$10 000
Cummulative Baseline Costs	$65 000	$115 000	$160 000	$160 000	$220 000	$230 000	$240 000	$295 000	$305 000	$390 000	$400 000
Actual Incurred Costs											
Federal Share		$47 475	$2 525								
Non-Federal Share	$61 630		$39 855	$30 148	$6 802	$0					
Total incurred Costs-Quarterly (Federal and non-Federal Share	$61 630	$47 475	$42 380	$30 148	$6 802	$0	$0	$0	$0	$0	$0
Cumulative Incurred Costs	$61 630	$109 105	$151 485	$181 633	$188 435	$188 435	$188 435	$188 435	$188 435	$188 435	$188 435
Variance											
Federal Share	0	$2 525	0	$0	$50 000						
Non-Federal Share	$3 370	$0	$2 620	($30 148)	$3 198	$10 000	$10 000	$55 000	$10 000	$85 000	$10 000
Total Variance-Quarterly (Federal and non-Federal)	$3 370	$2 525	$2 620	($30 148)	$53 198	$10 000	$10 000	$55 000	$10 000	$85 000	$10 000
Cummulative Variance	$3 370	$5 895	$8 515	($21 633)	$31 565	$41 565	$51 565	$106 565	$116 565	$201 565	$211 565

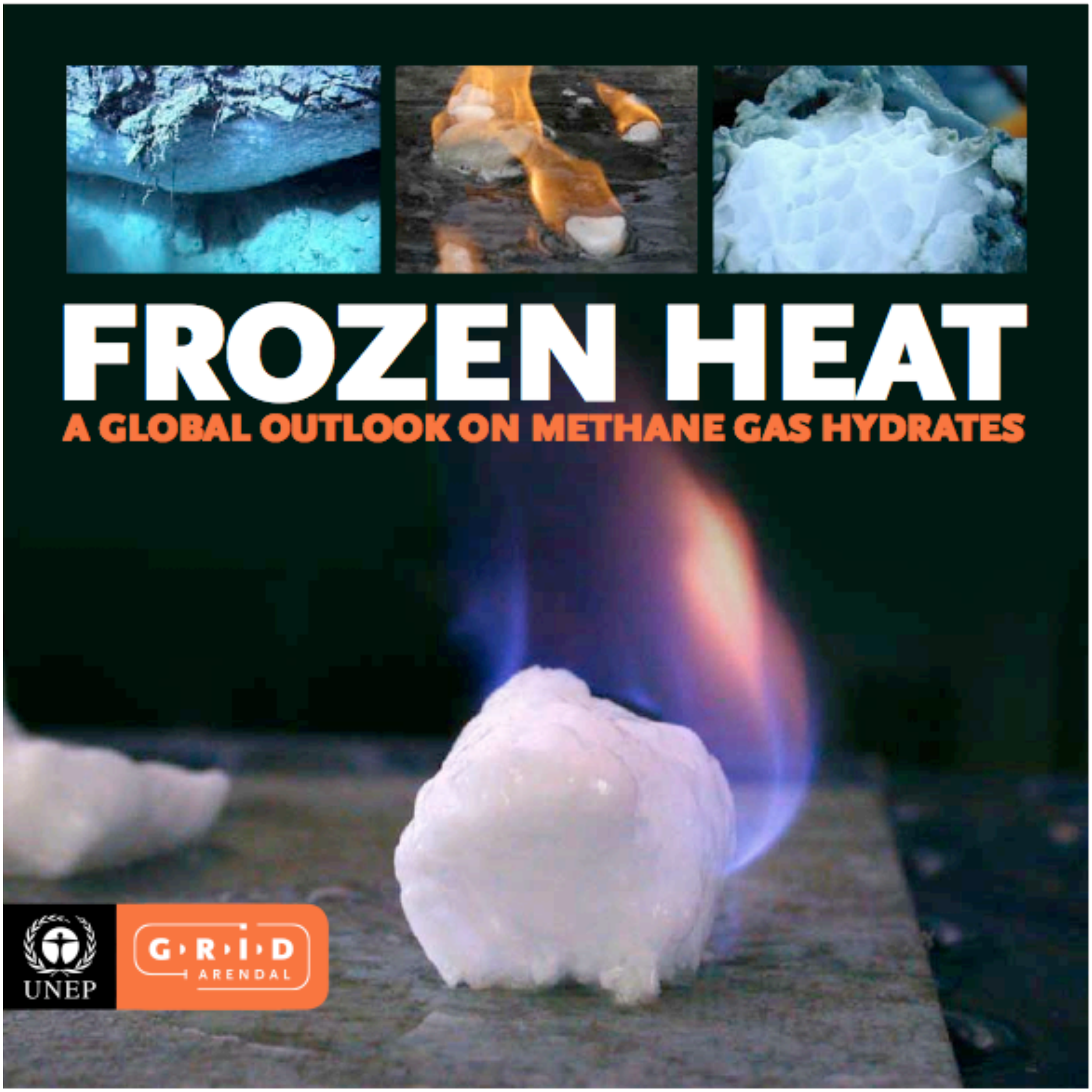
Table 2: Milestone Status Report

Task/Subtask #	**Project Milestone Description**	**Project Duration Start March 1 2010 End March 1 2012**							
		Project Year 1				**PY2**			
		Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Task 1.0	Project Infrastructure Development		completed						
subtask 1.1	Project Website Development		completed						
subtask 1.2	Virtual Office Development		completed						
subtask 1.3	Project Steering Committee	completed							
Task 2.0	Development/Approuval of Assessment Work Plan and Guidelines		completed						
Task 3.0	Establishement of Content Development Teams			completed					
Task 4.0	Draft Assessment Content Development and Vetting				draft 0 completed				

APPENDIX I: Meeting report of second Steering Committee Meeting (including draft 0 for each chapter)

UNEP GLOBAL OUTLOOK ON METHANE GAS HYDRATES

Tokyo Meeting Report



Tokyo drafting session
November 18-19, 2010

Background

Global reservoirs of methane gas have long been the topic of scientific discussion both in the realm of environmental issues such as natural forces of climate change and as a potential energy resource for economic development. Of particular interest are the volumes of methane locked away in frozen molecules known as clathrates or hydrates. Our rapidly evolving scientific knowledge and technological development related to methane hydrates makes these formations increasingly prospective to economic development. In addition, global demand for energy continues, and will continue to outpace supply for the foreseeable future, resulting in pressure to expand development activities, with associated concerns about environmental and social impacts.

Understanding the intricate links between methane hydrates and 1) natural and anthropogenic contributions to climate change, 2) their role in the carbon cycle (e.g. ocean chemistry) and 3) the environmental and socio-economic impacts of extraction, are key factors in making good decisions that promote sustainable development.

As policy makers, environmental organisations and private sector interests seek to forward their respective agendas which tend to be weighted towards applied research, there is a clear and imminent need for a an authoritative source of accessible information on various topics related to methane gas hydrates. The 2008 United Nations Environment Programme Annual Report highlighted methane from the Arctic as an emerging challenge with respect to climate change and other environmental issues. Building upon this foundation, the proposed project aims to provide a multi-thematic overview of the key aspects of the current methane hydrate debate for both the land-based Arctic deposits and those in the marine environment.

It is proposed that for purposes of clarity and coherence, the report be 'divided' into 2 sections: 1) section covering the various thematic issues related to gas hydrates (based on the approved thematic scope) and 2) a section assembling key case study sites emphasising the various elements of the thematic section.

In this outline, the subtopics are suggested to assist in developing a consistency in flow and treatment of the topics. They are, however, suggestions and will be adapted as the writing progresses.

Acknowledgments

As coordinating institution for the UNEP Global Outlook on Methane Hydrates, UNEP/GRID-Arendal would like to extend special thanks to the Japan Oil, Gas and Metals National Corporation (JOGMEC) for their hosting of the Tokyo drafting meeting. UNEP/GRID-Arendal would also like to thank the respective organizations of the Tokyo drafting meeting participants for special allowances made to extend time spent in Tokyo in support of this project.

Results of meeting

Workshop Goals

1) To assemble a draft 0 of the content of the UNEP Global Outlook on Methane Gas Hydrates
2) To review and discuss provided content material and focus of Chapters
3) To set the direction for the next phase of work leading to a draft 1 that will be subject to external peer review.

Highlights of discussions and decisions made:

- Volume 1, Chapters 1, 2 and 3: It had been agreed amongst the relevant Chapter leads that the original Chapter 2 entitled ‘Global Outlook of Methane Gas Hydrate Occurrences’ shall be phased into Chapters 1 and 3 along logical content themes. As per the updated Chapter Outline (next section) Volume 1 has been adjusted.
- Volume 2, Chapter 1: It was concluded that this Chapter would benefit from more direct discussion between the Steering Committee and the content contributing organisation (particularly Forum for the Future with respect to the Futures Scenarios work). Some immediate feedback suggests a re-focus of the Scenarios from a ‘state of the world’ viewpoint to a more ‘state of hydrates in the energy mix’ viewpoint in the context of the varying estimates of possible hydrate extraction. For example:
    - Different possible timelines for the production of natural gas from hydrates would be constrained by existing economic, social, environmental and geopolitical conditions at that time. Therefore Futures based on, for example, a 10 year, 15 year, 20 year and 25 year timeline to production would highlight key potential issues that a policy maker should consider today.
    - Also important to highlight one of the key uniquenesses of hydrates,their more global distribution and how this impacts Futures.
- Project web component: The second version of the project web portal, with a particular focus on public outreach and engagement is tentatively set for a Q1 2011 launch. The new portal will also contain a hydrate site knowledge base designed to provide users with an experience of respective global field sites of of methane hydrate research. A pre-launch version of the site will be reviewed by the Steering Committee once ready.

Near term follow up actions:

- Main focus from now until end of March 2011 will be the completion of a first content draft (text) that can be prepared for external review by May 2011.

- Layout and graphics design for print and e-book version of the Outlook will begin in December 2010.
- Set up web-based Dropbox for document sharing.
- Fundraising: Continued fundraising efforts to secure USD100,000 to USD150,000 will continue in 2011. Relatively safe prospects for USD80,000 have been identified.
- Development of global hydrate research site knowledge-base to be completed by March 2011.
- Preparation of all relevant material to support external peer review process for Chapters of draft 1.

Future meetings:

- Organise 1-2 ours Web conference between Forum for the Future and the project Steering Committee to discuss the evolution of Chapter 1, Volume 2. Tentative date: January 25th, 2011.
- Evaluate the option of hosting the next production and review meeting on July 22, 2011 in Edinburgh, Scotland, immediately following the 7th International Gas Hydrates Conference. This session would be dedicated to:
    - completing any changes recommended by external reviews during the draft 1 review process
    - commenting on any graphic and layout designs produced by that time
    - discussing possibilities for project launch in 2012

Updated working chapter outline:

Comments: Please note that although the general themes of an updated chapter outline are presented below, the final chapter and sectional titles and headers will likely continue to evolve as necessary. Authours should feel free to suggest titles they think are appropriate. These will be reviewed in due course.

EXECUTIVE SUMMARY AND HIGHLIGHTS

(1) Reasons/objectives for work

(2) Particular deposits of interest from a resource perspective

(3) Particular deposits of interest from an ecosystem and environment perspective

(4) Perspectives of hydrates in comparisons to other recent non traditional gas development (shale gas)

VOLUME 1: METHANE GAS HYDRATES IN THE NATURAL SYSTEM (max 200 A4 pages)

1. Chapter 1: What are Methane Gas Hydrates? (40 pages)

Introduction

State of the knowledge and history of the science of hydrates

Formational Environments Introduction

Global outlook of methane gas hydrate occurrences

Conclusions

1. Chapter 2: Methane Gas Hydrates in the Natural Carbon Cycle (40 pages)

Introduction

Sources of methane

Natural methane emissions from hydrates and their regulation by physical processes

Time scales of natural variations in gas hydrate occurrences

Possible examples from the past

Sediment stability issues related to gas hydrates

Conclusions

1. Chapter 3. Marine ecosystems associated with near surface methane hydrates (40 pages)

Introduction

Natural methane emission from hydrates and their regulation by biological processes

Sensitivities of communities to climate and geological variations

Conclusions

2. **Chapter 4: Global scenarios of Sensitivity of Methane Gas Hydrates to Global Warming (30 pages)**

Introduction

Impacts of warming scenarios on methane gas hydrates stability

VOLUME 2: METHANE GAS HYDRATES AND HUMAN SYSTEMS: (max 200 A4 pages)

1. **Chapter 1: Sustainable Economics For Methane Gas Hydrates Resource Development (50 pages)** ***It has been suggested that this chapter be moved to the end of the volume in conjunction with Chapter 4.***

Resource efficiency challenges in a global context

Drivers, demand, scarcities

Futures Scenarios

A new economics business model for methane gas hydrates resource development

2 Chapter 2: Hydrates as a Global Resource for Natural Gas (40 pages)

Introduction

Global inventory of methane gas hydrates

Definition of a resource according to traditional valuation methods

Detection and delineation methods

Examination of currently known quantified occurrence at specific sites

3 Chapter 3: Technologies related to potential development (50 pages)

Introduction

Accessing the reservoir

Disassociation Techniques: Conventional and novel

Achieving long term production

Timeline of gas hydrate development

Future trends in technical development and impacts on development

Environmental Impacts based on production scenarios

Conclusions

4 Chapter 4: Societal Perspectives of Hydrate Development (30 pages)

Introduction

Arctic communities perspectives

Marine coastal communities perspectives (is this possible at this stage??)

Impacts of infrastructure development

"Advice" for areas without experience

Impacts on well-being

Conclusions

5 Chapter 5: Challenges, opportunities, policy responses and options (20 pages)

UNEP GLOBAL OUTLOOK ON METHANE GAS HYDRATES

APPENDIX 1: PRELIMINARY CHAPTER DRAFT

VOLUME 1, CHAPTER 2 (combined old chapter 2 and 3)
Methane Gas Hydrates in the Natural Carbon Cycle

Chapter Lead: Kelly Rose

As of November 18, 2010 (Kelly Rose)

Revised working outline (draft and evolving as more input arrives) -

I. **Intro:**
  Short term vs. long term methane and carbon cycle introductions…

~~**II. Sources of CH4 gas in the natural environment**~~
  - ~~**a.** Thermogenic~~
  - ~~**b.** Biogenic~~
  - ~~**c.** Recycled~~

~~**III. Sinks:**~~
  - ~~**a.** Microbial~~
  - ~~**b.** reservoirs,~~
  - ~~**c.** free gas,~~
  - ~~**d.** water column,~~
  - ~~**e.** sediment~~

IV. Methane Cycle
  - **a.** Overview/introduction to the methane cycle in general
  - **b.** Methane budget (Reeburgh) IPPC report has modern methane cycle w/ sources and sinks. Largely terrestrial sources; Atmosphere is sink.
  - **c.** Modern methane cycle is interesting but keep this brief because it will show that hydrates operate on time scale that is longer than this…then segue into the capacitor?

V. Carbon cycle
  - **a.** Overview/introduction to the carbon cycle in general
  - b. NGH Role in the Carbon Cycle
    - **i.** Output and regulation by physical processes
      - **1.** Biologic controls
      - **2.** Geochemical controls
      - **3.** Physical controls
    - **ii.** Time Scales, build up slowly so may not be as important on human time scale as much as geologic time scale.

VI. Methane capacitor - use this concept as a segue into the next two sections?
  - a. Introduction to the MH capacitor concept
  - b. Use the capictor to set up comparison and evaluation of hydrate inventories over different time scales (modern time frame vs. geologic time)

VII. Seafloor and terrestrial geomorphological manifestations related to gas hydrates
  - a. Physical/geomechanical changes

b. Slope slides in the aqueous environment

c. Seafloor and terrestrial geomorphological manifestations

VIII. Outstanding questions about the role of NGH

a. Negative carbon excursions:

  i. e.g. possible case study: PETM example

  ii. Snowball Earth? ß How far back do we want to try and take this discussion?

b. Role of hydrates in transitions from ice ages to warm periods

c. “Clathrate Gun” hypothesis

“Mythbuster” box:

- ○ **Bermuda triangle**
- ○ **Storegga slide**

Bermuda triangle

The Bermuda Triangle, a region in the Atlantic Ocean extending from Bermuda to Miami to Puerto Rico (see map), earned its moniker in an article published in 1950 which drew attention to the mysterious manner in which some vessels and aircraft which have disappeared over the past 400 years within its borders. The first recorded vessel lost in the region was *The Sea Venture* which sank off of Bermuda in 1609. However, one of the most famous disappearances within the Triangle involved Flight 19 during which all five planes with a U.S. Navy squadron disappeared in 1945 during a routine training mission off the coast of Florida. The aircraft and their personnel were never found so their fate remains a mystery.

The area encompassed by the Bermuda Triangle receives a significant amount of air and water traffic annually, even as far back as the 1600’s the islands were utilized by ships for trade, recreation, and exploration. So the overall percentage of vessels lost is not unusual, however, the mysterious circumstances and lack of information about a few of the disappearances led to the Triangle’s distinctive reputation. Over the years different theories to explain the loss of vessels within the Triangle have been evaluated, ranging from supernatural influences to more natural phenomena such as severe storms, hurricanes, and the turbulent nature of the Gulf Stream which crosses the region.

In the early 1980s the first article was published hypothesizing that mysterious disappearances of craft within the Triangle may be related to the sudden release of methane from hydrate. The theory gained popularity in 1998 when a scientist from England further postulated that the sudden release of methane from hydrate could potentially lead to catastrophic submarine landslides, resulting in a massive release of methane gas bubbles into the water column that could cause ships or airplanes to sink or explode. Essentially these theories postulate that large volumes of gas in the water column would reduce the density of the water, causing the buoyancy of a ship at this location to decrease and sink. If a release was large enough, it was believed that the methane would escape from the water to the atmosphere where aircraft flying in that area could either cause the methane to catch fire, or cause the engines to quit due to a decrease in the concentration of oxygen.

Methane hydrate is located in near-seafloor sediments worldwide at water depths where there is sufficient pressure and low enough temperatures (generally in the region of the Bermuda Triangle this would be >300 meters water depth) to provide the necessary conditions for them to form. Studies have confirmed that gas hydrate deposits exist off the East Coast of the United States, however, no significant occurrences have been documented in the area of the Bermuda Triangle. The theory that natural gas hydrate is responsible for mysterious losses of craft in the Bermuda Triangle is implausible for several reasons:

- Scientists have mapped and studied the seafloor within the region and found no evidence for large-scale disruption of the seafloor (submarine slides, vents, seeps, mud volcanoes, etc.) that can be associated with the release of methane from hydrates or other subsurface sources.
- Studies and subsurface maps of the region also have not identified any areas with high concentrations or large areas of methane hydrate deposits near or at the seafloor.
- There are other locations around the world with large concentrations of methane hydrates near the seafloor that do not have corresponding issues with water and aircraft.
- Similarly, there are other locations around the world where seeps allow methane gas to enter the water column, but these sites do not have corresponding issues with water and aircraft either.
- Many of ships and planes that have disappeared in the Triangle are in areas where natural gas hydrates are unlikely to exist because the water is not deep enough to allow hydrate to form. (see map ???)
- The frequency of releases of methane from hydrates would be so rare it might happen only once every 400 years. (Reference back to section Vd above?)
- The “probability problem:” Methane released from hydrate systems would have to filter through hundreds to thousands of feet of sediment, and then thousands of feet of ocean water to reach the surface. In areas of the world where methane plumes in the water column have been documented, the methane rarely makes it to the surface because it is oxidized or dissolves away quickly. Thus, the chances of enough methane making it to the sea-surface (even in locations elsewhere around the world where releases are known to occur) to disrupt water or aircraft, AND the probability of a ship being over the precise spot at that exact time is mathematically astronomical.

Other reading:

http://www.bermuda-triangle.org/html/methane_hydrates.html
Geotimes: http://www.agiweb.org/geotimes/nov04/geophen.html

SHIPS	YEAR	LOCATION
The Sea Venture, sailing ship	1609	Right off Bermuda
Its rescue boat	1609	Right off Bermuda
Nuestra Senora de Guadalupe's three accompanying galleons	1750	North Carolina coast
Patriot, packet ship carrying aaron Burr's daughter	1812	In Gulf Stream
Wasp, US warship	1814	Off coast of S. Carolina

Mary Celeste	1872	
The Spray, sloop	1909	
The Cyclops, USN fuel ship	1918	On way from Barbados to Norfolk, Va
Porta Noca, passenger ship	1926	Took off from Isle of Pines near Cuba
Sandra, freighter	1957	Out from Savannah
Renovoc, yacht	1958	Took off from Key West
The Enchantress	1965	50 miles southwest of Charleston, S. Carolina
Witchcraft	1967	Off Miami
Scorpion, nuclear powered sub	1968	Off the Azores
AIRCRAFT	**YEAR**	**LOCATION**
Flight 19, 5 avenger bombers	1945	Coming back from Bimini
Martin Mariner, PBM flying boat in search	1945	From Patrick AFB
Star Tiger, commercial airliner	1948	En route from Azores to Bermuda
DC-3 charter flight	1949	
Star Ariel, commercial airliner	1950	En route to Kingston
Air Force Tender	1962	En route Va. to Azores
Private plane	1962	Off Nassau
U.S. Superfortress	since	
British Army Transport	since	
Two US Navy Patrol planes	since	

http://www.greatdreams.com/ships.htm

Chapter 2 latest contributor & reviewers list (evolving) -

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reeburgh@uci.edu	Y	Y	Y	Reeburgh
	~~N~~	~~N~~	maybe	~~Ruppel~~
jrutqvist@lbl.gov	Y			Rutqvist
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sowers@geosc.psu.edu	Y			Sowers
mtorres@coas.oregonstate.edu	Y	Y	Y	Torres
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China, paleo-seep discussion?
Methane cycling discussion would require other contributors;

- Bob Berner (Yale) longer scale cycles ß reviewer?
- Dan Schrag (snowball earth expert; negative carbon excursions…) (Howard Univ.)
- Klauss' work as well for longer scale cycles
- IPCC report (figures and short term methane and carbon cycles)

VOLUME 1, CHAPTER 3 (formerly Chapter 4)
Marine Ecosystems Associated With Near Surface Methane Hydrate

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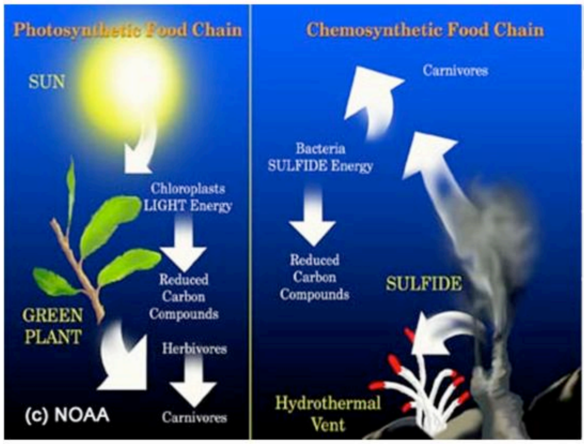
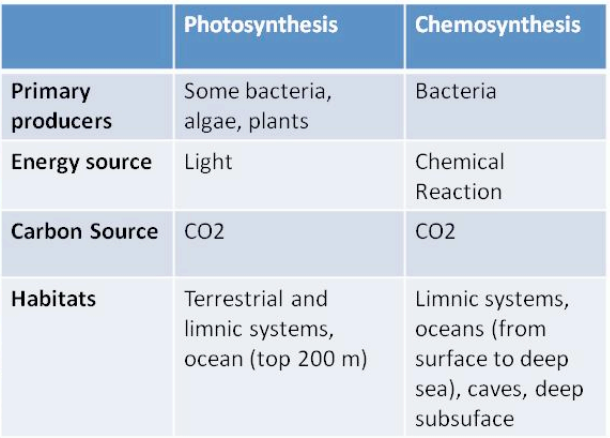
4. 1 Introduction

The term "chemosynthesis" refers to metabolisms that synthesize biomass through the utilization of chemical energy. Is the carbon source that is assimilated into biomass inorganic, i.e. CO_2, we call the organisms that mediate chemosynthesis "chemoautotrophs". With respect to their energy source chemoautotrophs are the opposite of photoautotrophs, i.e. organisms which utilize energy from light to mediate photosynthesis. With respect to their carbon source, chemoautotrophs differ from chemoheterotrophs, i.e. organisms that utilize organic carbon sources. In the marine world algae are for example photoautotrophs, shrimps that are feeding on algae are chemoheterotrophs, and giant sulfur bacteria, that gain energy by the oxidation of reduced sulfur compounds, are chemoautotroph.





	Photosynthesis	Chemosynthesis
Primary producers	Some bacteria, algae, plants	Bacteria
Energy source	Light	Chemical Reaction
Carbon Source	CO2	CO2
Habitats	Terrestrial and limnic systems, ocean (top 200 m)	Limnic systems, oceans (from surface to deep sea), caves, deep subsuface

Fig. #. Photosynthesis vs. Chemosynthesis.

Copyright left picture: NOAA

Chemoautotrophic, i.e. chemosynthetic, processes can be based on different chemical reactions. The probably most well known reaction is the oxidation of reduced sulfur compounds, e.g., hydrogen sulfide. Other chemosynthetic reactions include the oxidation of ammonium, reduced iron, and methane. Organisms mediating such processes are consequently found in ecosystems that offer a rich and steady source of these compounds. When hydrothermal vent systems were first discovered in the deep sea in 1977, they became the embodiment of ecosystems thriving on chemical energy in the dark. Hydrothermal vents offer reduced sulfur compounds, hydrogen, and methane to form the bases for food chains that seem to be completely independent from sunlight – although that this is not fully the truth (see Mythbuster Box #). The reduced compounds are produced abiologically when seawater interacts with hot magma at the spreading zones of oceanic plates, i.e. at places where new seafloor is created. Almost a decade later the first cold seep systems were discovered in the Gulf of Mexico. Different to hydrothermal vents, cold seeps exhibit temperatures that are around ambient conditions and they are manly found on sediment covered seafloor or carbonate outcrops. Typically for cold seep systems is the release of methane, higher hydrocarbons, and sometimes crude oil. The hydrocarbons usually arise from deeper sources and are transported by different mechanisms (e.g., plate subduction, salt domes, overpressurization by dewatering) to the sediment surface, where they are consumed by the chemosythetic community. Hydrocarbons at cold seeps often originate from fossil sources. The origin of methane can be either biological or thermodynamic. With less than 30 years of research, cold seep studies are still in their infancy and only slowly increasing together with the development of more advanced deep-sea technology. Nevertheless we assume already today that these ecosystems are relatively common features along the continental margins and in tectonically active areas on the seafloor. Investigations of ancient rocks, such as authigenic carbonates that often form in the sediments of cold seeps, tell us that cold seeps have been an oasis for life on the seafloor since millions of years.

A special type of cold seep is created, when seepage is located within the gas hydrate stability zone (GHSZ, see Chapter #). Outside the GHSZ, hydrocarbons, especially gaseous methane quickly migrate through focused gas channels in the sediment, thereby partly passing the chemosynthetic communities. Gas hydrate on the other hand represent an intermediate storage of methane and can form layers in sediments that spread over vast areas (the methane capacitor, see Chapter #). Organisms that live out of methane, virtually "chew" on the hydrates (see also Myth Buster Box #). When they feed on methane that is dissolved in the sediment, it is slowly replaced from the hydrates, while new hydrates form from venting gas and water. Through this seemingly endless mechanism, hydrate-bearing sediments enable a more wide-spread establishment of chemosynthetic communities on the seafloor than focused gas vents.

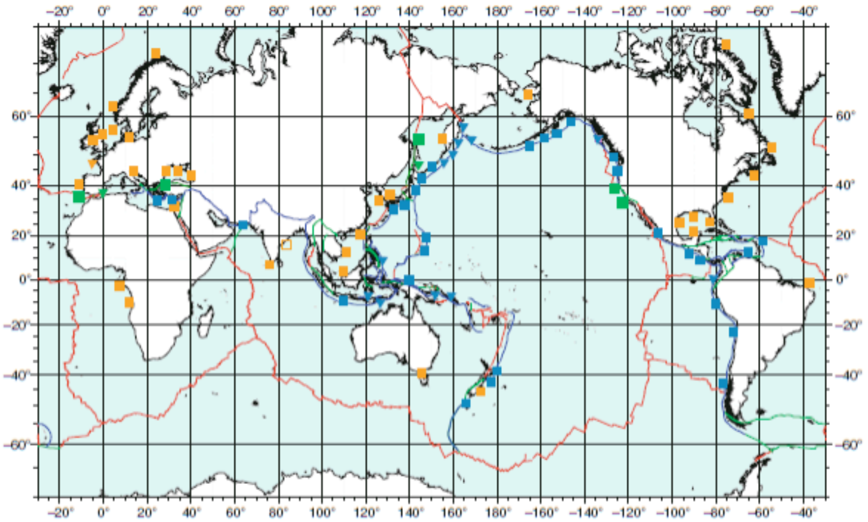


Figure 1

Seep locations with hydrocarbon-metazoan-microbe-carbonate characteristics; active margin sites (*blue*), passive margin sites (*orange*) including groundwater seeps; sites at transform margins (*green*). Distribution based on first seep location maps by Campbell et al. (2002) and Campbell (2006) with complete site references. New sites are from Coleman and Ballard (2001), Jeong et al. (2004), Loncke et al. (2004), Olu et al. (2004), Judd et al. (2007), Mastarlerz et al. (2007), Hovland (2007), Han et al. (2008), Pape et al. (2008), Sahling et al. (2008), Geli et al. (2008), Hilario and Cunha (2008), Sellanes et al. (2008); dead seep clam site off India from Collett et al. (2008); revisited sites from Sahling et al. (2008), Olu-Le Roy et al. (2007a, b), Naudts et al. (2006), Pape et al. (2008). Sites based on dredged tube worms (*triangles*), mostly from deep-sea trenches, are from Ivanov (1963) prior to recognition that seep communities at plate boundaries are sites of hydrocarbon seepage. Up-dates of new site locations are found in Zhang and Lanoil (2004), Garcia-Gil and Judd (2007).

Fig. #. World-wide distribution of known cold seeps.
From: Suess, E. 2010 Marine cold seeps. In: K. N.Timmis (ed.), Handbook of Hydrocarbon and Lipid Microbiology, vol. 1, part 3, p 187-203; Springer-Verlag, Berlin Heidelberg DOI 10.1007/978-3-540-77587-4_12 à mark the ones that have hydrates (based on water depth)

Myth Buster Box #1

Are complex chemosynthetic ecosystems, such as we know from the hydrothermal vents, completely independent from sunlight? The answer is: no!

Who has not seen the fascinating pictures of giant tube worms, clams and shrimps thriving on chemical energy from hydrothermal vents in the permanent darkness? Often we are told in documentaries that these ecosystems persist totally independent from sunlight. On a first view this seems right, because the primary producers, i.e., the organisms that form the first biomass in the ecosystem's food chain, gain their energy and carbon from inorganic compounds in the absence of light. However, the compounds that they need to oxidize the reduced molecules from the vents such as hydrogen sulfide and methane, are oxygen and nitrate, the so-called electron acceptors. Both oxygen and nitrate were very rare when the oceans developed in the very early times. Only through photosynthesis oxygen accumulated and lead to the formation of nitrate from reduced nitrogen compounds. Hence, modern complex chemosynthetic ecosystems, especially those including higher organisms, are not completely independent from sunlight, because they depend on compounds that would not be available without photosynthesis.

Highlight differences hot vents and cold seeps → cold seeps even more dependent on photosynthesis (organic matter production)

4.2. Natural methane emission from hydrates and their regulation by biological processes

4.2.1 Microbial processes in sediments: benthic methane filter

Tina Treude

When methane is migrating through marine sediments usually not all of it finally enters the water column. Depending on the strength of the methane flux a major fraction of the methane is consumed inside the sediment by a microbial process called anaerobic oxidation of methane (AOM). This process converts methane into bicarbonate while it reduces sulfate to hydrogen sulfide.

CH_4	+	SO_4^{2-}	-->	HCO_3^- +	HS^-	+	H_2O
Methane		sulfate		bicarbonate	sulfide		water

Sulfate, which is available from the seawater, is the electron acceptor in this anaerobic metabolism, i.e. it has the same function as oxygen in aerobic processes: the microbes "breathe" sulfate to "burn" their energy source, the methane. AOM is ubiquitous in marine sediments wherever methane occurs. At cold seeps, however, and especially when surface-near gas hydrates are present, AOM converts so much methane that this has (positive) consequences for the environment: the large amounts of hydrogen sulfide that are produced serve as an energy basis for chemosynthetic communities (see 4.2.2). The bicarbonate on the other hand reacts with calcium ions in the seawater and precipitates as calcium carbonate (calcite or aragonite) creating vast carbonate landscapes on the seafloor, which serve as an anchor for sessile organisms such as corals, sponges, and tunicates (ROV pictures) or as refuge for crustaceans, mollusks, and fish (ROV pictures). Hence, AOM not only prevents methane emissions into the water column but also creates new habitats for benthic marine ecosystems.

Who are the microbes doing AOM? Their identity has been revealed only in the year 2000. AOM is mediated by a consortium of two types of organisms – more specifically between two domains of life: archaea and bacteria. All life forms are grouped into three domains of life: the eukaryotes (which include us humans), the bacteria, and the archaea (see Info Box #). The last two together form the prokaryotes. AOM is mediated by methane-oxidizing archaea (anaerobic methanotrophs = ANME) and sulfate-reducing bacteria (Consortium picture). While the archaea do the first step of the process, the bacteria take over the last part of the reaction. Thereby they exchange an intermediate, which is still unknown. The two organisms finally have to share the little amount of energy that is released during AOM. That is why different to many other prokaryotes, their growth is very slowly. In laboratory studies it was found that the AOM organisms divide only every 4-7 months. For comparison, many aerobic bacteria can divide every 20 minutes under optimum growth conditions. However, in the deep-sea, where external food is generally rare, AOM organisms can comprise up to 90% of the microbial biomass in methane-rich sediments.

Globally it is estimated that AOM consumes 80-90% of the methane that is produced in ocean floors. Hence, the process is relevant for our climate because methane is a very potent greenhouse gas. When does methane escape this benthic filter? There are environments, e.g. some mud volcanoes, where the fluxes of fluids that are carrying the methane to the sediment surface are so high that sulfate cannot penetrate into the sediment from the water column. Here, AOM fails to establish as a benthic filter. Other loopholes for methane are gas bubbles. The microbes can access methane only in the dissolved form. When released as free gas, methane can pass the microbial filter. We hence expect much more methane to be released from the sediment into the water column in shallow regions, i.e., beyond the gas-hydrate stability zone where free-gas seepage occurs. At cold seeps with stable near-surface gas hydrates, on the other hand, methane dissolution and consumption are closer to equilibrium, enabling a more effective prevention of methane releases. It is currently debated, how much methane could escape the sediment if gas hydrate are destabilized, e.g. by global warming. In the end it would probably depend on the release rate of methane and whether the methane dissolves in the sediment porewater or escapes as free gas.

The strength of the methane flux to the sediment surface is often reflected by the establishment of characteristic chemoautotrophic communities (see also 4.2.2), which utilize the hydrogen sulfide produced during AOM. At places with high methane fluxes, enormous amounts of sulfide build up even at the sediment water interface. In this case, the sediment surfaces are often inhabited by free-living sulfide-oxidizing filamentous bacteria (scheme + pictures), which form visible white or orange bacterial mats. When the methane flux is intermediate, sulfide levels increase only after some centimeters below the sediment surface. Here, symbiont clams, harboring sulfide-oxidizing bacteria in their body, settle on the sediment and pick up the sulfide with their long food from deeper sediment layers. When methane fluxes are lowest, creating only small levels of sulfide in the deeper sediment, symbiont clams or tubeworms are found that are able to mine for the deep sulfide through their burrows or roots, respectively. Scientists use these "indicator organisms" to find near-surface gas hydrates or to estimate methane fluxes over large cold-seep areas.

- ➔ Give some examples from Hydrate Ridge, GoM, Eel River Basin

4.2.2 Chemosynthetic communities linked to methane degradation

Lisa Levin & Craig Smith

Overview of biological communities at cold seeps

The animals at cold seeps can be large or tiny, form bushes, dense beds, reefs or live alone, and grow very quickly or exceptionally slowly. Biological communities at cold seeps include a host of single-celled organisms (protozoans) and multi-celled animals (metazoans). Most of the metazoans are invertebrates, and nearly all depend one way or another, on microbial production, which in turn is linked to methane. Best known are the structure-forming taxa that create visually distinctive microhabitats. Most common among these are bathymodiolin mussels that form massive beds associated with carbonate (Fig a), vesitmentiferan tube worms (family Siboglinidae) that grow in dense bushes (Fig. b), vesicomyid (Fig c), lucinid (Fig d) and solemyid (Fig. e) clams that form dense beds within seep sediments, and frenulate (i.e. pogonophoran) polychaetes that form grass-like fields where sulfide sources occur deep within sediments (Fig f). All of these taxa are relatively large compared to non-seep faunas in the deep sea. They have reduced or absent digestive systems, and house symbiotic bacteria that provide the host with nutrition through sulfide and/or methane oxidation.

These groups are considered to be ‘ecosystem engineers’ or sometimes ‘foundation species’ because they support a wealth of grazing, predatory and deposit-feeding taxa, by providing substrate for attachment, access to reduced compounds, entrainment of organic-rich particles, and access to microbial, protozoan or metazoan prey. The presence and distribution of the large, symbiont-bearing species is often dictated by fluid flow rates and by specific combinations of geochemical and substrate conditions. The calcium carbonate precipitated by archaeal/sulfate reducing microbial consortia forms crusts, rocks, boulders and chemoherms at seeps. These can support high densities of mussels, tubeworms, or grazing gastropods (Fig. g). Where methane and sulfide fluxes are highest, dense mats of sulfide-oxidizing bacteria occur at the sediment-water interface (Fig. h). The combination of microbial mats, the beds, bushes and fields formed by the engineering/foundation species and the microbially-precipitated carbonates, create a heterogeneous, highly patchy habitat structure that contributes significantly to the overall biodiversity of seep ecosystems.

Mussels, clams, and siboglinid worms (vestimentiferan tubeworms and pogonophorans) are typically present at locations where gas hydrate dissociation releases methane and AOM ensues, but they are rarely in direct contact with the solid form of gas hydrate. Only a single megafaunal taxon, the ice worm *Hesiocaeca methanicola* (Fig i), has been documented to live directly in or on methane hydrate. This species attains relatively large size for a hesionid polychaete (2-4 cm) and occurs at high densities (2500-3000 ind./m^2) on gas hydrates in the Gulf of Mexico. Studies suggest that *H. methanicola consumes* free-living microbes associated with the hydrate, and that the worm's oxygenation activities, which involve forming depressions and creation of small-scale water currents at the hydrate surface may promote microbial growth and speed hydrate decomposition. The association of *Hesiocaeca methanicola* with gas hydrates occurs both at the sediment-water interface and at least 10 cm below the surface. Elsewhere there has been limited direct sampling of solid methane hydrates to assess metazoan associations. Exposed methane ice at Hydrate Ridge does not appear to be colonized by metazoans although dissociated methane supports dense, colorful bacterial mats (Fig. j) and high densities of infauna. The presence of gas hydrate just below bacterial mats at Hydrate Ridge may actually exclude some animal species.

Info Box #1

How does symbiosis between a host animal and a sulfide- or methane-oxidizing bacterial symbiont work?

Chemosynthetic symbioses were first discovered in giant tube worms (*Riftia pachyptila*) from deep-sea hydrothermal vents. In such symbioses, metazoans host within their tissues a bacterial garden that produces organic material from carbon dioxide and energy-rich chemicals such as sulfide and methane. Within a decade of the discovery of chemosynthetic symbiosis at hydrothermal vents, similar symbiotic metabolisms were recognized in a wide range of deep-sea and shallow-water habitats, including at deep-sea cold seeps and whale falls, and in organic-rich settings in shallow water including seagrass meadows and mangrove swamps.

Animals sustaining chemosynthetic symbioses are often abundant and large in body size at colds seeps; these animals frequently include bathymodiolin mussels, vesicomyid clams, and siboglinid tubeworms. Such mussels, clams and tubeworms harbor their chemosynthetic bacterial symbionts in specific body tissues; within the gills for clams and mussels, and in a special organ called a trophosome (or "food body") in the siboglinid tubeworms. In most of these animal hosts, the bacteria live within the animal host's cells, and rely on the host's blood system to transport reduced chemicals (sulfide and/or methane), oxygen and carbon dioxide from the external environment to the internal bacterial garden. The host animals obtain oxygen and carbon dioxide from ocean bottom waters overlying the cold seeps; however, energy-rich methane and sulfide may not be so easily obtained. Tubeworms use long "roots" to "mine" sulfide from the porewater of deep sediment layers as much a meter below the seafloor. Vesicomyid clams use a vascularized foot to dig centimeters down into sulfide-rich layers, providing the energy source for their bacterial symbionts.

Not unexpectedly, there is variability across animal groups in the types of chemosynthetic symbioses hosted within their tissues. Some seep mussels have dual symbiosis with both thiotrophic (sulfide "eating") and methanotrophic (methane "eating") living bacteria simultaneously in their tissues. In contrast, siboglinid tubeworms (and other species of mussels) have only a single metabolic type of symbiont able to use either sulfide or methane (but not both) as an energy source. Only sulfur- oxidizing symbionts have been found within the gills of vesicomyid clams.

The mode of transfer symbiotic bacterial symbiontts across generations also varies between animal groups. Siboglinid tubeworms and bathymodiolin mussel appear to obtain their symbionts from the surrounding environment. This is particularly remarkable for the large vestimentiferan tubeworms, whose nutrition as adults is completely reliant on the highly specialized garden of bacterial symbionts living in their trophosome. In contrast, the vesicomyid clams pass their symbionts from mother to progeny within the egg. This has facilitated co-evolution of hosts and symbiotic bacteria in these clams.

Non-symbiontic communities linked to seepage: Who else is there and what advantage to other organisms have from living in this environment?

While symbiont-bearing animals are large, and often comprise the majority of seep biomass, the non-symbiont bearing taxa form much of the biodiversity present at methane seeps. These are heterotrophic species that obtain their nutrition by consuming microbes, detritus or other animals. Among these, annelids in the families Polynoidae, Hesionidae, Dorvilleidae and Ampharetidae are often prevalent. Some of these live symbiotically on or within seep bivalves (polynoids, hesionids, and natuliniellids), but many occupy sulfidic sediments. These and other seep taxa such as the orbinid polychaete *Methanoaricia dendrobranchiata* have the ability to cope with the exceptionally low oxygen and high sulfide concentrations characteristic of active seep sites. Adaptations involve expanded gill areas, high hemoglobin affinity for oxygen, and extreme anoxia and sulfide tolerance. The dorvilleid, hesionid, and ampharetid polychaetes are abundant in microbial mats and appear to consume microbial biomass and detritus. At least one dorvilleid is suspected to incorporate carbon derived from archaea involved in anaerobic oxidation of methane. Microbe-grazing gastropods dominate as epifauna of hard and biotic substrates at seeps. Multiple species of lepetodrilid, pyropeltid, and lepetopsid limpets, and provannid snails can occur at high densities on mussel shells, carbonates, vestimentiferan tubes in the presence of active seepage. Hyalogyrindae (snails) are common on microbial mats at Hydrate Ridge. Mobile heterotrophs, many of which themselves consume large microbes or prey on the grazers and deposit feeders, include alvinocarid shrimp, brachyuran, galatheid and kiwa crabs, isopods, buccinid gastropods and zoarcid fish. Selected cnidarians and echinoderms also prey on seep species, and are common in upper slope settings of the Pacific Northwest.

Not all species present at methane seeps are endemic to (i.e. found exclusively in seep environments), and only a subset incorporate carbon directly from methane-oxidizing microbes. While a host of annelid, mollusk, crustacean, cnidarian and to a lesser extent echinoderm species rely on seep microbial production or prey on seep animals, some of these are also present in the background community. It is rare to have background community sampling sufficient for accurate estimation of seep endemism. Among seep macrofauna at Hydrate Ridge (770 m) and Eel River Basin seeps (525 m), approximately 50% of the infaunal species also occur in non-seep slope sediments. Common among these are cirratulid, cossurid, and paranoid polychaetes.

Investigation of small eukaryotes (e.g., fungi, protozoa, and metazoan meiobenthos) associated with surficial gas hydrates are limited. Work at Hydrate Ridge suggests elevated biomass of these small sized organisms in clam beds but not bacterial mats, and implicates interaction with allothonous phytoplankton production. Nematodes biomass is elevated near gas hydrates in the Barbados Accretionary prism. Cilliates may play a key role in trophic transfer of methane from microbes to metazoans, via methanotroph symbiosis and by consuming free living bacteria.

Linkage of chemosynthetic communities with methane/oil fluxes

Because the main structure-forming taxa depend on availability of reduced compounds, there is often a tight relationship between the geochemical fluxes of seep fluids, the concentrations of sulfide and methane, and the distribution of seep taxa. There are distinct habitat patches that form concentric circles across flux gradients or form disjunct features where fluxes vary; examples include those documented at Barbados Accretionary seeps, Haakon Mosby, Monterey Bay, Hydrate Ridge, Eel River Basin, off W. Africa, in the Gulf of Cadiz and the Eastern Mediterranean. As a general rule, fluid fluxes are strongest in barren mobile sediments or in microbial mat covered-sediments high to moderate in mussel beds and tubeworm fields, and less in vesicoymid clam beds and pogonophoran fields.

Fluid flow has proven to be unexpectedly variable in space and time, but is often greatest where there are permeable substrates, faults, cracks or conduits from deep in the crust (such as on mud volcanoes or seamounts). Methane may emerge as strong ‘gushers’, vigorous or mild bubbling, or diffuse seepage. The distributions of organisms reflect these seepage features and have been used by researchers to locate new cold seep sites.

The fluids that support seep communities may contain sodium, magnesium and potassium-based brines, petroleum compounds, sediment pore fluids, dewatered crustal elements and fresher groundwater, as well as methane dissociated from gas hydrate. There has been no systematic effort to link community types to fluid sources, but it appears that the major habitat-forming taxa occur anywhere that sulfide and methane concentrations are sufficient. There is however a tremendous amount of local endemism among smaller annelids and nematodes, with some dominant species described only from single locations. These limited distributions could reflect evolved tolerances to toxic PAHs, to high or low salinities, anoxia or excessive sulfide concentrations associated with specific seeps sites. However, animal distributions may also reflect hydrographic features, such as anoxic water columns in the Black Sea, geological features such as evaporates in the Gulf of Mexico and the Eastern Mediterranean Sea, and even warmer thermal regimes at Barbados and Costa Rica.

Animal-microbe feedbacks

While external forcing by fluids clearly dictates the global distribution of seeps (Fig x) and the meso-scale patch structure of seep communities, the pumping, burrowing, irrigation, chemical uptake and release activities of the animals themselves modify geochemical conditions on cm scales in sediments and possibly in porous carbonates as well. Animals will routinely filter overlying water to obtain oxygen (mussels), pump oxygen and sulfate-laden water into sediments to facilitate burrowing (clams), and extract sulfide from pore fluids with root-like structures (vestimentiferan and pogonophoran (siboglinid) worms) or a foot (vesicoymid, lucinid, thyasirid clams). Sulfide uptake acts to thermodynamically favor anaerobic hydrocarbon oxidation. A key driver of megafaunal activity may be the need for sulfate replenishment in order to maintain required sulfide production by sulfate reducing bacteria. Tubeworms release sulfate, possibly ventilating through the tube, as a byproduct of sulfide oxidation, and clams inject sulfate-rich waters at depth; both stimulate production by anaerobic methane-oxidizing microbial consortia and thus generate sulfide. These activities are proposed to create a ‘rhizosphere’ within sediments that is beneficial to seep microbes. These interactions are considered to be ‘geochemical engineering’, microbial farming, and mutualistic relationships. Animal-microbe interactions within carbonate rocks have yet to be investigated directly. Recent studies suggest that isotopic differences in tubeworm- vs. mussel-associated carbonates in the northern Gulf of Mexico (tubeworm carbonates have lighter d^{13}C) are linked to the mussel uptake of ^{13}C-depleted methane, mussel filtering action that dilutes the DIC pool with seawater CO_2, and/or tubeworm stimulation of sulfate reduction coupled to methane oxidation, increasing the supply of ^{13}C-depleted carbonate ions. Observations of large burrows containing cirratulid, ampharetid and dorvilleid polychaetes combined with active anaerobic oxidation of methane inside seep carbonates on the Costa Rica margin and at Hydrate Ridge (Fig.?) suggest a strong potential for endolithic (rock-dwelling) animals to influence microbial activity and the fate of methane within carbonates.

Biogeography of cold-seep organisms

Cold seeps are widely distributed along continental margins, and are formed by a broad range of geological processes, which my influence the composition, flux and seafloor distribution or reduced chemical species. The broad range of processes influencing reduced chemical distributions and fluxes, as well as the natures soft sediments and solid substrates (e.g., authigenic carbonates) cause seep habitats to be extremely patchy within sites, across sites and within regions. Despite the wide occurrence of seeps on all continental margins of the oceans, the seep fauna is very poorly sampled on global scales, and no large-scale biogeographic synthesis is possible at present. Nonetheless, we do know that seep community structure, and hence biogeography, does appear to change with depth. For example, in the deep Gulf of Mexico (the best studied seep-rich margin in the ocean), there is a transition zone for seep biota between depths of 1000-2000 m; seep communities shallower than ~1000 m, or deeper than ~2000 m, are similar across thousands of kilometers, but exhibit little species overlap across the transitional depth zone (1000-2000 m). The deep Gulf Mexico appears to be bathed by a single water mass, so other factors related to depth appear to drive the depth transition. Water mass characteristics can also play a role in the large-scale distribution of seep fauna; On the Chile margin, where water masses (including the oxygen minimum zone) change with depth down slope, there can be greater community change along depth contours, then with depth. Thus far, there is no evidence of differences in the list of seep species present at hydrate versus non-hydrate bearing seeps.

4.2.3 Methane consumption in the water column

Samantha Joye

Outline:

- Importance of the water column aerobic methane biofilter
- Patterns of water column aerobic methane (MOX) in the oceans
- MOX hot-spots
- MOX microbiology
- Regulation and controls on MOX in the oceans, what we know, what we don't know, and what we need to know.

4.2.4 Natural processes linked to the evolution of the communities

Lisa Levin & Craig Smith

Overlap with hydrothermal vents and whale falls

At higher taxonomic levels (genus and above), there is substantial faunal overlap between cold seep faunas and those of hydrothermal vent and whale-fall communities, including (but not restricted to) taxa with chemosynthetic bacterial symbionts. The chemosymbiotic vesicomyid clams, bathymodiolin mussels, siboglinid tubeworms (including vestimentiferans) all can occur in abundance at seeps, vents, and whale falls. Other taxa found at both seeps, vents and whale falls include gastropods in the families Provannidae, Eulimellidae, and Pyropeltidae, and polychaetes in the families Dorvilleidae, Ampharetidae, Nereidae and Polynoidae. Additional taxa in common between vents and seeps that are less common at whale falls include alvinocarid shrimp, lepetodrilid limpets, galatheid and kiwa crabs. Members of these families may be bacterial grazers, and have undergone speciation in the microbial-rich habitats at vents and seeps.

Surprisingly, there are very few species in these groups that have been recorded at more than one type of reducing habitat. When vent assemblages are considered, the greatest overlap with seep taxa is found at sedimented vent sites such as Guaymas Basin, Middle Valley, or Escanaba Trouch, where methane concentrations in porewater tend to be elevated. The tubeworm *Lamellibrachia barhami*, the polychaetes *Bathykurila guaymasensis, Arichinome rosacea, and Amphisamytha galapagensis* occur at both sedimented vents (Guaymas and/or Middle Valley) and seeps off Costa Rica, as well as at whale falls. *Branchipolynoe seepensis* occurs as a commensal in bathymodiolin mussels at vents and seeps, though it is possible that here and in some other cases of habitat overlap, cryptic species may be present. The limpet *Lepetodrilus elevatus* and the mussel *Bathymodiolus thermophilus*, occur at E. Pacific vents as well as seeps off Costa Rica. The thorough sequencing of vent and seep taxa required to establish numbers of overlapping species between hydrothermal vents and seeps has not been done, but the number, estimated at 5 in 2003, is likely small.

The overlap of species between seeps and whale falls is significantly larger. Twenty one species of clams, mussels, snails, polychaete worms, crustaceans and giant vestimentiferan worms are known to be shared between seeps and whale falls. It is clear the much of the chemosynthetically dependent fauna of seeps and whale falls share a common evolutionary history. It has been hypothesized that whale falls may act as dispersal stepping stones for seep (and vent) species, and that the evolution of whales may have facilitated the dispersal of chemosynthetically dependent fauna to isolated seep and vent habitats, ultimately promoting speciation within the seep and vent fauna. In a paleontological study of the evolution of seep fauna, studies revealed that 25% of seep genera first appeared in the fossil record synchronously with the appearance of basilosaurids, the first ocean-going whales, in the early Eocene Epoch. This is highly consistent with hypothesis that the evolution of whales facilitated the dispersal and radiation of seep (and vent) faunas, highlighting the evolutionary linkages between vent, seep and whale fall habitats.

Variations in seepage/gas hydrate reservoirs over time

The abundance of cold seep habitats on the continental slope appears to have varied dramatically over the last 150 million years, based on the frequency of carbonate-bearing formations in the fossil record. High numbers of seep formations, and cold-seep habitats on continental margins, appear to be correlated with low sea-level stands and low deep-sea water temperatures. The causality behind these correlations is not clear, but may be due to sea-level fall decreasing the thickness of the methane hydrate stability zone in the sediment, thereby increasing methane seepage and facilitating carbonate precipitation. Alternatively, cold deep-sea temperatures may stabilize and facilitate the formation of methane hydrates on continental slopes and thus increase the availability of methane to AOM microbial consortia, enhancing carbonate precipitation. Studies suggests that oscillations in sea-level and deep-sea temperatures associated with glacial-interglacial cycles, and the onset of Antarctic glaciation at the end of the Eocene, have led to an "extreme increase" in the number of seep-bearing formations on continental slopes, and by inference a dramatic increase in the availability of seep habitats on continental margins. This inferred dramatic increase in the abundance of seep habitat at the end of the Eocene (about 37 million years ago) is roughly synchronous with the first appearance in the fossil record of 25% of the extant seep genera of seep animals, suggesting an increase in seep habitat may have facilitated radiation of seep biota.

Larval Transport and Connectivity

Direct knowledge of larval connectivity between seeps is scant. Most information is derived from studies of genetic differentiation (using mitochontrial DNA, AFLP or microsatellites), or inferred from life-history research. Seep taxa appear to exhibit the same range of developmental options as hydrothermal vent species, with planktotrophic and lecithotrophic larval stages represented. Deep-water currents are known to be much slower than those at the surface, and thus species with planktotrophic larvae that develop in near surface waters, such as the larvae of bathymodiolin mussels, bathyneritid snails or alvinocarid shrimp, are likely to exhibit the greatest dispersal potential. This is consistent with observations of panmixia (a strongly mixed gene pool) for *Bathymodiolus childressi* over 550 km horizontal distance between 500-2200 m depth in the Gulf of Mexico. However even taxa with broad (e.g., amphi-Atlantic) distributions exhibit strong differentiation of populations on different sides of the ocean. Recolonization studies conducted at seeps shows strong evidence of cohort recruitment, and in some cases, such as dorvilleid polychaetes, highly localized settlement reflecting source populations in the immediate patch type. Metapopulation dynamics almost certainly apply to the majority of seep species, which may experience only limited larval exchange between isolated seep sites.

Authigenic carbonates: a new habitat

Massive precipitation of authigenic carbonate is a byproduct of anaerobic oxidation of methane at seeps, and yields structures of varying sizes and forms. These range from crusts, cobbles and boulders to platforms, mounds and pinnacles, and function as hard substrate reefs, often in a surrounding sea of sediment. While the carbonates are bathed in reduced fluids they support microbial mats and are host of mobile grazing gastropods, deposit-feeding polychaetes and attached, filter feeding or symbiont bearing invertebrates. They also support an endolithofauna, comprised largely of annelids. As seepage diminishes, these carbonate substrates host settlement of deep-water corals such as *Lophelia pertusa* and *Madrepora oculata*, other cnidarians, sponges and other background species. It is believed that deep-water, reef-forming corals and the rich invertebrate assemblages they support represent a very late successional stage in the methane seep continuum. Sometimes vestimentiferans and tube worms can be found living in close proximity but corals do not appear to rely on production from seeps. The coral stages are fragile, and highly susceptible to damage by trawling and other human disturbance.

4.3. Sensitivities of communities to climate change and geological variations

Lisa Levin & Craig Smith

There are indications in the geological record that warming/cooling trends, and oscillations in eustatic sea level, may influence methane hydrate stability, authigenic carbonate formation, slope failures (e.g., the massive Storegga slide on the Norwegian slope) and, in turn, the abundance of seep habitats. Undersea earthquakes, such as the Grand Banks earthquake and subsequent turbidity current, can also produce cold seeps and chemosynthetic habitats. However, methane hydrates on continental slopes appear to be insulated from any climate changes expected over the next century, and large-scales changes in cold- seep occurrence driven by climate warming, or other geological processes such as sediment loading, are likely to occur over millennia, and remain very difficult to constrain at present. Thus, on century time scales, the seep biota is likely to be insensitive, over large spatial scales, to climate warming, sea level rise and geological variations; on time scales of millennia, however, these processes may well alter the abundance and distribution patterns of cold-seep, influence the connectivity, biogeography and evolution of the seep fauna.

- è Connect with technical gas hydrate production chapter (Scott) in terms of possible risks for ecosystems

4.4. Conclusions

Tina Treude

VOLUME 1, CHAPTER 4 (formerly Chapter 5)
Assessment of the Sensitivity and Response of Methane Hydrates to Ongoing and Future Global Warming

Chapter Lead: Klaus Wallmann

Outline

1. Hydrates in the seabed and below permafrost: sensitivity to environmental change

Potential Authors: Klaus Wallmann, Scott Dallimore

Here, we will briefly explain the physical processes that may induce hydrate dissociation with a focus on temperature increase but considering also other potential factors such as sea-level change, erosion, slope failure, etc.
Figure: Phase diagram with arrows and scenarios

2. Observations and modeling studies on hydrate dissociation at the modern seabed and in permafrost areas

Potential authors: Graham Westbrook, Natalia Shakhova, Mat Reagan, Richard Kerr; Scott Dallimore (Arctic)

This chapter will present the observations at Svalbard (WESTBROOK et al., 2009) and at the Eastern Siberian Shelf (SHAKHOVA et al., 2010) and the modeling results for the Svalbard slope (REAGAN and MORIDIS, 2008). We will critical discuss the significance of these observation and their relation to sub-surface hydrate dissociation along the lines of the recent Science News Focus (KERR, 2010).

Observations on gas release in the terrestrial realm (Scott Dallimore, Smilkov, K. D. Walters)

Free gas release within hydrate stability zone is observed at several sites around the globe. Possible reasons: Local heat injection from below, local salinity increase due to hydrate formation, sluggish kinetics of hydrate formation.

3. Hydrate dissociation induced by future global warming

Potential author: David Archer

Here, we will present modeling studies on future hydrate dissociation induced by global warming (ARCHER and BUFFETT, 2005; ARCHER et al., 2008; FYKE and WEAVER, 2006). David Archer could cover the marine hydrates while Scott could address the permafrost hydrates. Magnitudes, timing, unknowns, etc. will be presented and critical discussed.

4. Consequences of gas hydrate dissociation

Potential authors: Klaus Wallmann Christian Berndt, Arne Biastock, Klaus Wallmann, Tina Treude, W. Xu, Richard Kerr

Here, we will follow the fate of methane being released from gas hydrates considering that methane may be trapped as free gas in the sub-surface, will be microbially oxidized within surface sediments and in the overlying bottom water, and may escape into the atmosphere. The associated consequences including slope failure (refer to chapter 3), oxygen depletion and acidification of oceanic bottom water, and amplification of global warming will be presented and critically assessed.

5. Conclusions

Potential authors: Klaus Wallmann All contributing authors

Finally we will present the most likely magnitude, timing, and consequences of future gas hydrate dissociation under different climate change scenarios. We will list the unknowns and will try to define the uncertainties.

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Writing process: Concepts of each sub-chapter by Klaus, terrestrial component by Scott, future hydrate melting in the ocean by Dave Archer. Subsequently, addition authors will be contacted and ask to add figures and text and review the contents of the chapter

VOLUME 2, CHAPTER 1
World Energy Outlook and Methane Hydrate as a Possible Energy Source

Chapter Lead: Anne Solgard

Alternative futures for methane hydrates and the global energy system

As provided by Forum for the Future

The following is a proposed outline in note form of Forum for the Future's contribution to Chapter One. More content is provided for some sections so that reviewers can see the level of detail, format and style envisaged for the final document.

1. Introduction and background

Objectives of this exercise – to explore the role that methane hydrates might have in future energy systems, explicitly acknowledging uncertainty around critical social, economic and political contextual factors.

Introduction to scenarios – possible futures, rather than predictions

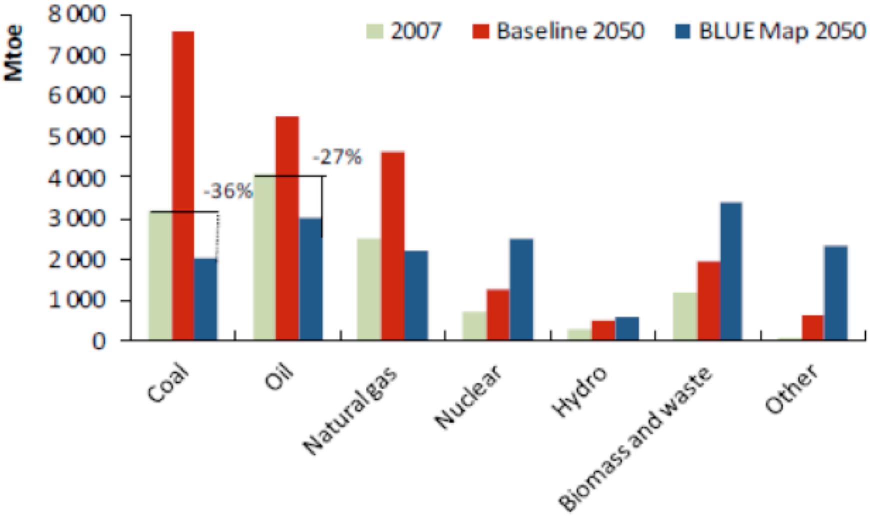
Process – based on Climate Futures, desk research and conversations with experts (tbd)

2. The "expected" energy future

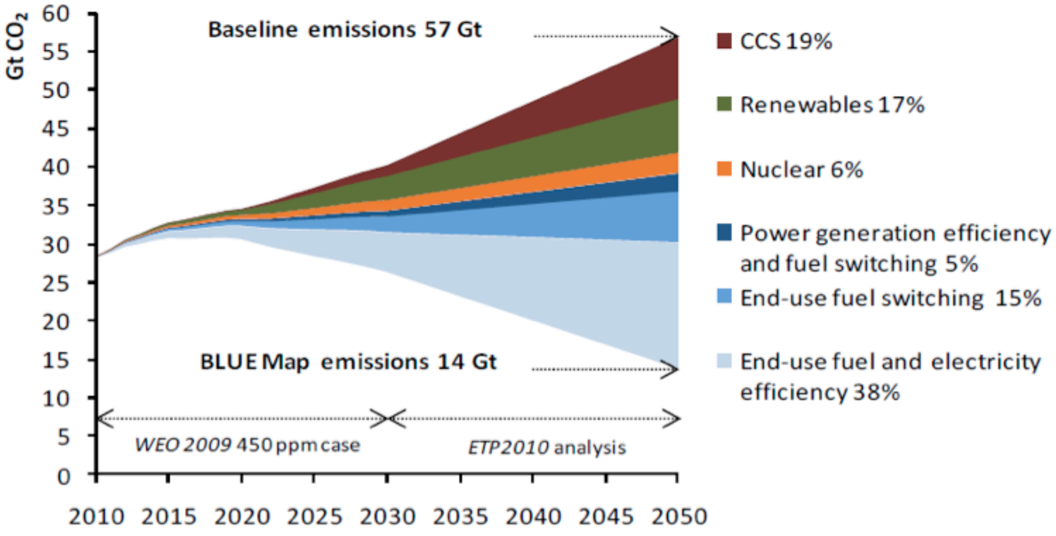
The mainstream 'expected' energy future (as presented by IEA) shows significant increases in fossil fuel use, including natural gas. The 'BLUE Map 2050' scenarios, are designed to give a 50% chance of avoiding 'dangerous' climate change. Neither of these scenarios appears to incorporate current developments in shale gas or methane hydrates, nor do they reflect key uncertainties in significant factors that will affect our energy future.

“Expected” energy future

Based on IEA 2010 ETP scenarios



- Baseline scenario assumptions
- Baseline scenario – comments on fuel mix
- BLUE Map scenario assumptions & target
- BLUE Map scenario – comments on fuel mix & emission reduction tactics



3. Exploring future possibilities

There follows an overview of selected megatrends that will affect how the world's energy future develops.

Globalisation

Globalisation is the process of cultural, economic and political integration across nations and regions. It has proceeded more or less continously since the Industrial Revolution, with a short hiatus in the first half of the Twentieth century. Global trade volume is a reasonable indicator of economic globalisation and has grown rapidly since the second world war, roughly matching the rate of GDP growth, and in 2009 was more than 200 times greater than in 1948. Political globalisation has developed less moothly, but the post-war period shows the successive founding of international governance institutions and signing of international treaties.

Future rates of globalisation are by no means guaranteed. In 2008 oil prices peaked at US$145 per barrel, and a sustained period of oil prices at that level would challenge the viability of global shipping and aviation, industries that underpin global trade. A peak in global oil production, which could happen as early as 2020 according to the International Energy Agency's Chief Economist, would lead to prolonged price hikes and volatility. Political ties could also weaken if international institutions fail to deal adequately with a range of challenges such as climate change or trade reform, and this could systematically undermine the quality of global governance.

Implications: [this could all go into risk and opportunity, later]
The future of globalisation could have an impact on the global consistency of regulatory frameworks that directly (for example, environmental regulations) or indirectly (for example, mediation of national boundary conflicts) affect methane hydrate extraction.

Political insecurity could increase if globalisation falters, threatening strategic assets including methane hydrates operations.

Failure to reach a climate change agreement could lead to the continued exploitation of fossil fuels such as coal and oil, rather than favouring lower-carbon fossil fuels such as natural gas and methane hydrates.

A more protectionist trade environment may mean that nations are less willing or able to rely on importing energy and so more likely to exploit indigenous energy assets, whatever the impact on climate change, and this could include methane hydrates.

Dealing with climate change

Climate data demonstrate the effects of greenhouse gas emissions on the climate system and environment: greater intensity and frequency of storms; more widespread drought; more and hotter heatwaves; biodiversity loss; sea level rise and ocean acidification; and so on. These are likely to intensify in the coming decades and become an ever-clearer human and natural disaster. Efforts to adapt to and avert the most damaging aspects of a climate changing world are likely to take centre stage, but the nature of the response is still highly uncertain.

The Copenhagen Accord, drafted at the Copenhagen Climate Change conference in December 2009 and signed by 114 countries, though not legally binding, formally recognises “the scientific view that the increase in global temperature should be less than two degrees Celsius”. Scientific consensus suggests that for a 50% chance of achieving this, this atmospheric carbon dioxide should be limited to 450ppm. There is no global deal currently in place that will deliver cuts at the scale required. However, many countries have committed unilaterally to absolute emissions reductions (for example, the European Union) or relative reductions (such as India and China). Many businesses have made similar commitments: for example, Walmart aims to cut emissions by a fifth by 2012 and Vodafone has committed to halving its emissions by 2020.

[The future response to climate change is highly uncertain and could follow three broad pathways each of which would have a significantly different impact on the exploitation of methane hydrates. This is explored in the scenarios below] [The following three paragraphs are too long and may be moved into the scenarios]

Three broad pathways seem to lie ahead in dealing with climate change. One broad pathway is through technological innovation and end-of-pipe solutions. With the right conditions for investment and diffusion, low carbon technology breakthroughs – highly efficient solar energy capture or energy storage, for example – could take place and have an impact on global emissions. If carbon capture and storage is proven to work at scale, fossil fuel use – including the exploitation of methane gas hydrates – would be able to continue. Moreover, if geo-engineering solutions (such as ocean seeding, albedo adjustment or atmospheric carbon scrubbing) are implemented, it may even be possible to ‘solve’ climate change technologically, with few structural changes in the economy – other environmental limits of notwithstanding (!). Such a route would probably be driven in part by a carbon price, but not an excessively high one, nor necessarily globally implemented, but is of course very dependent on the right R&D uncovering the right answers.

A second potential pathway is through a global policy regime that establishes a carbon price high enough to lead to the restructuring of economies: a shift to closed-loop production, more localised activity, product-to-service shift and so on. In contrast to the first pathway, this would directly and very noticeably affect people’s lifestyles. The costs of the transition would be such that – unlike with the first pathway – no country or region would be likely to ‘go it alone’ and therefore the world would need to sign up more or less en masse to such a regime. As noted above, the immediate prospects of this are slight.

A third pathway is more focused on energy security and adaptation than mitigation. In this possible future, a prolonged failure to agree a coherent international response to climate change leads to a systematic undermining of global governance and, as countries begin to compete more for limited resources, trade barriers go up and international cooperation go down. The incentives to reduce GHG would be undermined in such an environment, and the focus of investment would shift to adapting to a climate changing world: a case of battening down the hatches. This pathway would probably lead fairly quickly to human and environmental catastrophe, but there is a chance that this could be averted through geo-engineering.

Resource availability

Key points:

Water, land/soil, timber, many minerals including ‘rare earth elements’, driven by growth in consumption and systematic depletion. Will drive innovation and collaboration as well as conflict and poverty.

Technology progress

Key points:

The confluence of nanotech, biotech, ICT and so on raises as many questions as it answers. Risk of human/health/environmental problems. Risk of anti-technology backlash (eg GM in Europe). Risk that governance systems aren’t developed quickly enough to match speed of technology development.

Demographic change

Key points:

Huge growth of populations in Africa and India, stabilization in China and stagnation in Europe, Russia and Japan. Dependency ratio will be lowest in Africa in 20 years’ time – an opportunity for political and economic progress. By 2030 discussions about population may focus on imminent population stabilisation and decline and the socio-economic impacts of that.

New economies and markets

Key points:

China could be the world’s largest economy by 2030. The World Bank estimates that the global middle class is likely to grow from 430 million in 2000 to 1.15 billion in 2030. Rates of consumption affected. African economic miracle with 10% + growth in some countries. Poverty however still a huge issue.

Possibility of new measures of economic progress that deal with the growth paradox – already being investigated eg Bhutan, France.

New markets: carbon market, potential for biodiversity market eg the Yasuni rainforest agreement between Ecuador and the UN.

Shocks and surprises

Key points:

Greater potential for disruption and surprise as systems become more connected and more complex. Economic system has little redundancy and is over-dependent on certain commodoties, technologies and so on. This will increase volatility and potential for shocks and surprises. Volatile markets, terrorism, nuclear proliferation, epidemic – likely to see some of this in next 20 years.

Extreme networks

Key points:

We are moving towards total connectivity – already 70% of the planet has a mobile phone. Changes culture, society, politics. Media more aggressive, pervasive and difficult to control. Influence over civil society and NGO action. Increasing transparency e.g. of supply chains.

Feeding the world

Key points:

Food security will be a predominant issues over the next to three decades. UN projects global food demand increasing by 50% by 2030. This affects land use, technology, politics and energy. Could lead to instability, changes in global trade regime and so on.

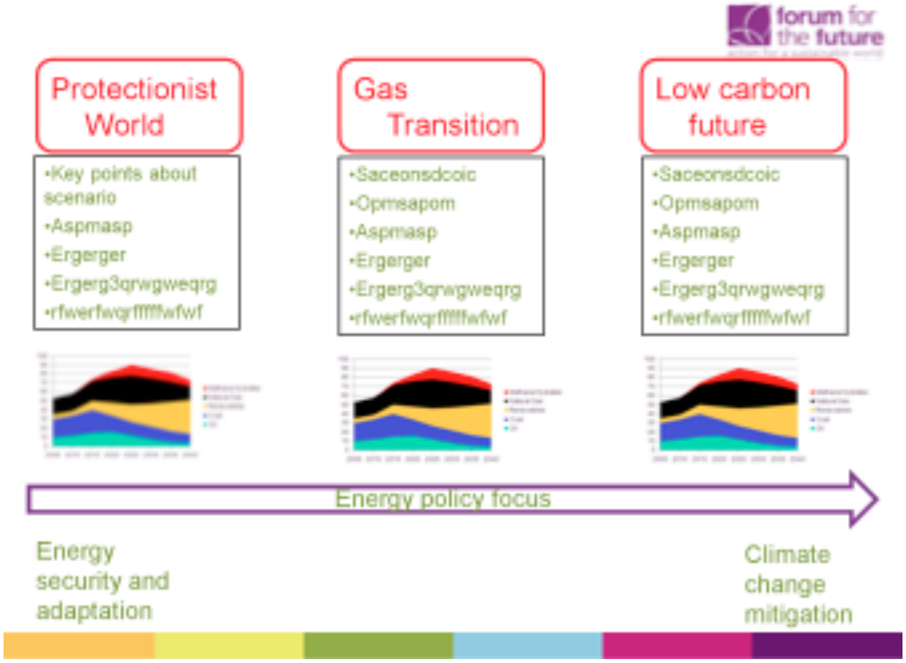
Energy transition

Key points:

Energy security an additional key issue for the next 20 – 30 years. Many people have poor access to energy. Supply may falter even in developed economies. Oil supplies likely to peak soon. Strong connection to pressure to decarbonise.

4. Three futures for methane hydrates

Summary graphic [hypothetical example] of the three proposed scenarios.



Protectionist World

- Key points about scenario
- Aspmasp
- Ergerger
- Ergerg3qrwgweqrg
- rfwerfwqrffffwfwf

Gas Transition

- Saceonsdcoic
- Opmsapom
- Aspmasp
- Ergerger
- Ergerg3qrwgweqrg
- rfwerfwqrffffwfwf

Low carbon future

- Saceonsdcoic
- Opmsapom
- Aspmasp
- Ergerger
- Ergerg3qrwgweqrg
- rfwerfwqrffffwfwf

Energy policy focus

Energy security and adaptation

Climate change mitigation

Scenario 1: A low carbon future

Proposed structure as follows:

a) Summary

This is a relatively low consumption, decentralised world with a strong focus on efficiency, renewables and demand management, driven by a high carbon price. Commercial globalisation has faltered but trade in services and information is strong, and global civil society is prospering. The carbon price drove heavy investment in large scale renewables and development of new fossil fuel sources slowed substantially. Methane hydrates are too high carbon to be widely exploited, though are mined at a relatively small scale by some countries willing to pay a substantial premium for energy security. Greenhouse gas emissions have been declining for a decade and attention has shifted to restoring the biosphere and sustainable food production.

b) An illustrative graph showing the energy mix over time according to this scenario

c) Information about the energy mix and system in this scenario

d) Information about the carbon regime in this scenario

e) An exploration of the role of methane hydrates in this scenario

f) Background information about other environmental issues such as water, resource use etc

g) Background information about associated social and political factors (economy, governance, geopolitics, civil society and so on)

h) [possible] brief vignette to bring the scenario to life

Scenario 2: Gas transition

Early draft content as follows. Please note, this content is provisional and yet to be tested in conversation with experts. Feedback on plausibility is very welcome.

a) Summary

This is a high consumption, globalised world where methane hydrates have an important role as a transition energy source, as the world moves gradually away from fossil fuels and towards a low carbon economy. Natural gas dominates the global fuel mix and greenhouse gas emissions have finally peaked. Climate change is starting to feel 'solved' as a mitigation issue; climate adaptation, food security and ecosystem collapse are becoming more pressing concerns. Methane hydrates are exploited on every continent and the incorporation of CCS points to a long term future for the industry.

b) An illustrative graph showing the energy mix over time according to this scenario

c) Energy mix and system

Natural gas is the world's most important energy source due to widespread fuel switching from coal, and it underpins electricity generation, transport and heating in most countries. Although conventional sources still produce significant quantities, unconventional sources such as shale gas and gas hydrates are strongly in the ascendant and supply the shortfall as conventional gas production dwindles.

Renewables are a significant source but remain dwarfed by gas. Energy systems are mostly centralised and depend on large power stations. Land transport in most rich countries is electrified, although some exceptions such as Scandinavia use hydrogen instead – which is mostly obtained via plasma pyrolysis of natural gas. India and many other middle-income countries use a cost-effective blend of hydrogen and natural gas for transport. Biofuels and petrol are dominant in lower-income countries.

d) Carbon regime

The response to climate change focuses on mitigation and is framed by agreements on carbon pricing and offset mechanisms that vary by geography. Transition to affordable low carbon energy sources is the focus; the first phase of this has been a switch to a gas economy in many parts of the world.

Carbon capture and storage is underway in many countries and has started to sequester significant amounts of carbon on a global scale. A combination of approaches is deployed. In many areas carbon dioxide is sequestered in disused gas fields, including methane hydrates fields. Another solution involves using carbon dioxide to produce synthetic limestone for building materials. The commercial success of these techniques is having the unintended consequence of delaying the transition to renewable energy sources.

e) The role of methane hydrates

The global push for gas means that energy infrastructure, skills and the political culture favour the exploitation of methane hydrates. The industry grew rapidly from a tiny base in the early 2020s and is now booming as so many countries have local resources that they want to develop. Japan has the most highly developed industry, but there are significant operations in the US, India, China, Brazil, South Africa and the UK. Former oil and gas majors dominate the industry as they were able to transfer drilling expertise and equipment. CCS is incorporated into the drilling process in many instances to hedge against future rises in the carbon price, and methane hydrates are beginning to be thought about as a long-term energy source rather than a bridging fuel. The signs are that this industry is likely to grow for many decades.

f) Natural systems and resources

Natural systems are under tremendous strain and close to collapse in many parts of the world. The global fish catch has plummeted and soil degradation is reducing yields across the globe despite the widespread deployment of biotechnology. Natural forest has largely been replaced by timber plantations or farms.

Resource use is very high, particularly of water and arable land as the world strains to feed itself.

Ecosystem services are starting to fail unexpectedly across the world – such as sudden catastrophic crashes in pollinator populations. The production of many minerals has peaked and reuse and recycling is necessarily at very high levels. Most industries aspire to closed-loop or synergistic processes. CCS cement is the poster child for turning waste into a useful resource.

g) Socio-political context

The world is globalised and multi-polar. International trade is strong, though increasingly expensive. Global agreements take a very long time to happen and as a result there are more bilateral and regional agreements. The US, China, India and Brazil are the most influential countries. Intellectual Property remains the dominant model for knowledge sharing; the commercial interests of big business are centre-stage and global commons are generally managed in their favour.

Global civil society is mostly concerned with competing issues around food security and biodiversity as the world's population continues to grow.

h) [possible] brief vignette to bring the scenario to life

Scenario 3: Protectionist world

Proposed structure as follows:

a) Scenario summary

This is an energy-hungry, competitive world, characterised by resource conflict, with few global agreements and no international carbon oversight. Coal is the dominant fuel and methane hydrates are a critical local energy resource for many countries. There is scarce international capital for investment and little sharing of technology and expertise, so drilling and distribution risks are magnified. Climate change discussions are regional and centre on adaptation and geoengineering.

b) An illustrative graph showing the energy mix over time according to this scenario

c) Information about the energy mix and system in this scenario

d) Information about the carbon regime in this scenario

e) An exploration of the role of methane hydrates in this scenario

f) Background information about other environmental issues such as water, resource use etc

g) Background information about associated social and political factors (economy, governance, geopolitics, civil society and so on)

h) [possible] brief vignette to bring the scenario to life

5. Conclusions for Futures Scenarios

This section will feature the risks and opportunities for the methane hydrates industry implied buy the scenarios, and identify some key decision points in the world's energy future.

VOLUME 2, CHAPTER 2
Hydrates as a Global Resource for Natural Gas

Chapter Lead: Tatsuo Saeki

2.1 Introduction … very short … 1 page (text only)
2.2 Definition and Priority (Occurrence type)
2.2.1 Definition: Resource or Reserve, International Definition … 2 pages (a few chart and text)
    Prof. Masuda's material etc. can be useful.
2.2.2 Priority (Occurrence type) … 4 pages. (incl. pictures)
    Tim's diagram can be useful.
    Next section is focused into explanations regarding 2 types.
2.3 Methodology and Examples / Exercise
2.3.1 Permafrost area (delta front/plain sand) … 10 pages (incl. many pictures)
    Example: Alaska (as ref., Mallik)
2.3.2 Deep-sea area (channel complex sand) … 15 pages (Incl. many pictures)
    Area: The Nankai Trough (MH21), GOM (DOE publication)
2.3.3 Other example … 5 pages (incl. some pictures)
    India

VOLUME 2, CHAPTER 3
Technologies for Development of Methane Hydrate Resources

Chapter Leads: Tim Collett, Ray Boswell, Scott Dallimore, Koji Yamamoto; Contributors, Fred Wright, John Thurmond, Espen Andersen, Steve Hancock, George Moridis, Masanori Kurihara, Yoshihiro Masuda, Brian Anderson, James Howard

1. Introduction

This section is an overview about technologies for resource extraction in general. How the nature of the occurrence guides the approach. Prior work (thinking of hydrates as very shallow and permanently solid) had investigated mining. Recent work indicates that much is relatively deep and that the hydrate can be dissociated in situ – enabling use of well-based approaches. Scientists have utilized known, well-characterized arctic accumulations to test this approach, guided by numerical simulation, while at the same time exploring in the marine environment to determine the abundance of that subset of total hydrate occurrence that might be amenable to this approach. Results to date in both efforts are promising, but it is clear that gas extraction from hydrates faces numerous challenges -- environmental, technological, and economic. And technology will also continue to improve and help further mitigate those challenges.

2. Drilling a Gas Hydrates Well

This section will provide a description of what a typical gas hydrate well will look like. Arctic setting first, utilizing the design of the Mallik 2008 test as an example. Thrust of the theme is that it looks a lot like other hydrocarbon wells, and utilizing all existing and known/tested technologies. Utilize Hancock's OTC paper as well.

Probably introduce the concept of the horizontal wells here.

A description of the technical drilling challenges, so in the arctic, this will include permafrost protection, subsidence, gas control, release, seal integrity…

In the marine setting, we can state that drilling will be from certain types of ships and vessels, no different from those that would drill other shallow deepwater wells. Describe initial wells may be off existing platforms, and not standalone ventures. Describe the drilling hazards that will need to be considered (again no different from those facing deeper wells), including shallow water flows, gas, overpressure, temperature control and well control issues.

3. Producing a Gas Hydrate Well

This will describe the general challenge of achieving optimal flow rates and recovery efficiencies and meeting economic criteria? Not sure how or where to discuss the nature of these criteria, and how they might relate to various national priorities, policies, goals, etc…

3.1 Completions:

Probably extend this to completion as well, and talk about issues related to open hole completions in shallow horizontal wells?, sand control, dealing with produced solids, avoiding water, dealing with water

3.2 Disassociation Techniques:

Conventional and novel, a graphic of the four approaches and a general description of how each might work. Show them in relation to stability diagrams and the shifting of the Stability curve?

Pressure reduction first, describe general approach (downhole pumps), findings in the field, and recent finding in numerical simulation. Discuss challenges (I believe this would deal primarily with the issues of thermodynamics of achieving, controlling, and sustaining dissociation without ice formation? – many of the broader challenges are described in the following section)

Temperature stimulation second, various potential approaches and findings in the field and in modeling.

Chemical processes

CO2-CH4 Exchange third, challenges and approaches (call-out box on molecular modeling)? Use *Farrell et al,* FITI as model for this section.

3.3 Stimulation Techniques:

Discuss how the goal of achieving long-term production at commercial rates will likely require augmentation to principal production approach, both at start up and periodically during well life. How these details will be driven by site-specific conditions, events, etc.

Temperature maintenance in new well-bore (call-out box on Endothermy?) and role for temperature control there, including various approaches (fluid injection and radiative heat sources).

Chemical stimulation – methanol etc injection.

Mechanical stimulation – i.e. well fracturing.

3.4 Managing and monitoring a GH well:

Describe likely 20+ year well life, and discuss likely strategies for Managing water (and sand) as a by-product, monitoring and mitigating issues of subsidence, monitoring dissociation progression, flow assurance issues. Discuss plans for monitoring environmental impacts (water, gas, subsidence) during testing phases.

4. Potential for extending production beyond sand-hosted reservoirs

Note the presence of GH in vent-chimneys, show some images of their structure, geometry, nature. Describe how they may be attractive options in certain locales, but that they will likely require approaches other than depressurization or exchange. Discuss any possible approaches, particularly thermal stimulation? (call out box on volume expansion issues)?

5. Timeframe for methane gas hydrate development

Example from conventional oil and gas industry (this would be a description of timeframes related to R&D and technology "penetration" as exhibited by coal-bed methane and-or shale gas? Regional/national factors (a discussion of how timeframe will not be solely based on economics, but also on other geo-political factors?

6. Future trends in R&D and investment considerations

Discuss future production testing plans and likely requirements/scenarios for incorporation of GH production technology by industry

1.6 Environmental Impacts based on production scenarios

1.1.1 Evaluation of impacts based on physical settings of targets

(1) Marine settings

(2) Permafrost settings

(3) Contrast with examples of shallow gas production

1.1.2 Impacts and footprint management

1.1.3 Impacts to methane-based ecosystems

(1) Flux reduction affecting ecosystems

1.1.4 Atmospheric/hydrospheric methane leakage

(1) Thermodynamic constraints that prevent large volume release

(2) Explanation of risks related to possible marine leakage

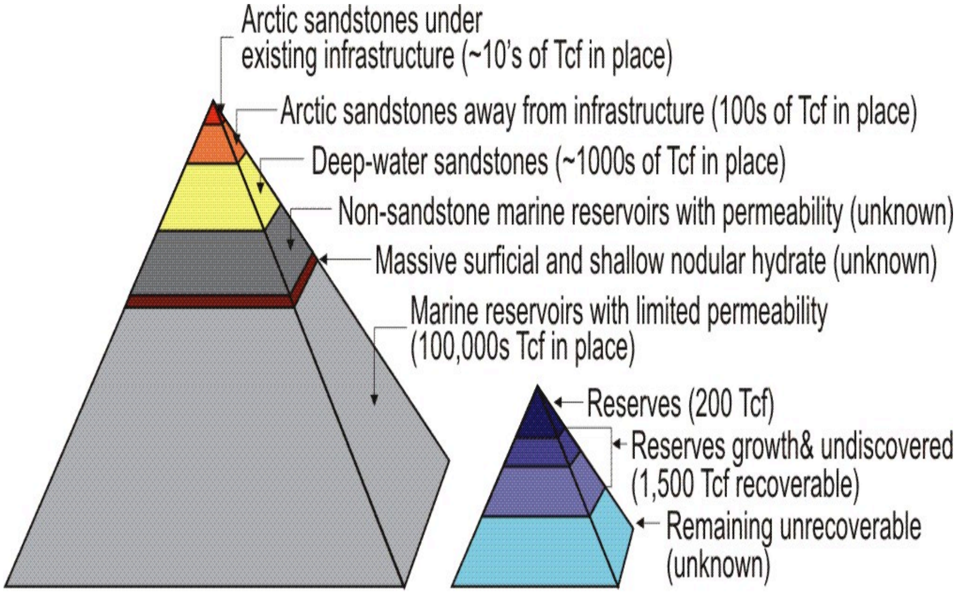
1.1.5 Production induced sediment movement and slope failures

(1) Affects to well stability

(2) Surface interactions

1.1.6 Water handling

1.8 Conclusions



Arctic	**Gas hydrate habit and reservoir setting**	**Site survey & foundation considerations**	**Drilling**	**Completion**	**Production**	**Field Response**
Sand host sediments	Known deposits (ANS, Mallik, Siberia?) largely occur as pore space occurrences in unconsolidated sediments. Rare macroscopic forms of hydrate in excess of pore space	Shallow permafrost issues similar to conventional	Similar drilling practice to conventional with attention to mud properties and temperature. Note: many thousands of penetrations in NAS	Operational issues associated with unconsolidated sediments and mobility of dissociated sand. Proven engineering solutions like sand control measures widely available	Loss of sediment strength and consolidation induced by gh dissociation may affect near well bore conditions Water production rates unknown.	Producing interval is likely to be >600 m depth and beneath competent permafrost interval.
Fine grained host sediments	No current observations worldwide					

Marine

Marine	Gas hydrate habit and reservoir setting	Site survey & foundation considerations	Drilling	Completion	Production	Field Response
Sands **<250 from sea bed**	Known deposits (Nankai, GOM,??) largely occur as pore space occurrences in unconsolidated sediments.	Shallow foundation issues similar to conventional Shallow reservoir depth presents challenges to the design of surface conductor and casing strings	Similar drilling practice to conventional with attention to mud properties and temperature.	Operational issues associated with unconsolidated sediments and mobility of dissociated sand. Proven engineering solutions like sand control measures widely available	Loss of sediment strength and consolidation induced by gh dissociation may affect near well bore conditions Water production rates unknown.	Producing interval is close to sea floor. Surface casing may become integral part of responding reservoir…
Sands **>250 from sea bed**	Known deposits (Nankai, GOM,??) largely occur as pore space occurrences in unconsolidated sediments.					
Marine muds disseminated						
Marine muds fractured/ nodular					No known technology or worldwide experience to accommodate volume reduction and sediment mobility as it produces	
Cold vents and shallow gas hydrate outcrops		Non traditional extraction required will be destructive to sea floor communities and cause sea floor settlement	N/A	N/A	N/A	Non traditional extraction required will be destructive to sea floor communities and cause sea floor settlement

UNEP GLOBAL OUTLOOK ON METHANE GAS HYDRATES

APPENDIX 2: MEETING AGENDA AND PARTICIPANT LIST

Content Drafting Workshop

November 18-19, 2010, Tokyo, Japan

Meeting Agenda

WORKSHOP GOALS

1) To assemble a draft 0 of the content of the UNEP Global Outlook on Methane Gas Hydrates

2) To set the direction for the next phase of work leading to a draft 1 that will be subject to external peer review.

MATERIALS EXPECTED FOR MEETING

- It is clear that not all chapters have evolved or can evolve at the same pace. However, a minimum requirement for the meeting will be a detailed outline with identified contributors for each chapter.
- Any relevant visual material for use in the product: this includes graphs and charts or concepts for graphs and charts, high-resolution photos and videos

MEETING OVERVIEW

The first afternoon is to provide a progress report on the work done so far and to set the stage for the focused content organising and drafting to be done on day 2.

Day 1, Afternoon

- Review work done to date on the project as a whole and on specific chapters;
- Discuss Chapter organisation and any issues needing immediate attention
- Organise day 2

THURSDAY EVENING, NOVEMBER 18, 19:00 RECEPTION HOSTED BY JOGMEC

Day 2, Morning:

Chapter-based group work; initial chapter workgroups

Day 2, Afternoon

1. Chapter-based group work; remaining chapter workgroups
2. Plenary session: status of chapters; collection of content material; next steps for content production

Workgroups

As various participants are involved in more than one chapter, the group based work has been divided according to chapters. The afternoon of day 1 and most of day 2 is setup to ensure that all chapter groups get to meet together with all members. Group discussion leaders have been assigned to ensure a coordinated flow to each groups' deliberations. Group discussion leaders will be responsible to summarize the outcome of their respective groups in the final plenary session and the highlighting of any challenges.

CHAPTER TEAMS DAY 2

Volume 1: Natural Systems

GROUP 1 (Chap 1)	GROUP 2 (Chap 2)	GROUP 3 (Chap 3)	GROUP 4 (Chap 4)	GROUP 5 (Chap 5)
Boswell	**Waite***	**Rose***	**Treude**	**Wallmann**
Waite*	Boswell	Treude	Wallmann	Dallimore
Yamamoto	Yamamoto	Wallmann	JY Lee	Treude
Collett	Collett		S R Lee	JY Lee
S R Lee	S R Lee			

Volume 2: Human Systems

GROUP 6 (Chap 1, 4)	GROUP 7 (Chap 2)	GROUP 8 (Chap 3)
Beaudoin	**Dutta**	**Dallimore**
JY Lee	Saeki	Yamamoto
Beaulieu	Lall	Boswell
McKee	Andersen	Andersen
S R Lee	Tocher	Tocher
		Collett

Bold: Group discussion leader

**: will participate via Skype*

Although Group Leads are expected to be fixed for the 3 group break-out sessions, other group members are free to be mobile and provide support to the other groups active during a given break-out session. Volume 2 Chapter 5 is entirely dependent on the outcomes and content of the product as a whole. I will lead sidebar discussions on the development of this chapter but there will be no official focus on it at this stage.

SCHEDULE

Time / venue	**Agenda**	**Moderator**
Thursday, 18 November, 2010		
13:00 – 15:00	PLENARY SESSION 1: • Welcome • Project update; website, outreach • Open round of discussion • Organisational round related to groups and breakout sessions	Yannick Beaudoin, UNEP/GRID-Arendal Kenji Ohno, JOGMEC
15:00 – 17:00	GROUP BREAK OUT SESSION 1: • GROUP 3 • GROUP 6 • GROUP 7 • GROUP 8	
17:00 – 18:00	PLENARY SESSION 2: • Group Leads brief on progress; identify challenges • Organisation of day 2 • Open discussion round	Yannick Beaudoin, UNEP/GRID-Arendal
19:00	"ICEBREAKER" RECEPTION	
Friday, 19 November, 2010		
09:00 – 09:30	PLENARY SESSION 3: • Welcome	Yannick Beaudoin, UNEP/GRID-Arendal
09:30-11:30	GROUP BREAK OUT SESSION 2: • GROUP 1-2 • GROUP 5 • GROUP 7	
11:30 – 13:30	GROUP BREAK OUT SESSION 3: • GROUP 4 • GROUP 6 • GROUP 8 • GROUP 7	

13:30-14:30	LUNCH	
14:30 – 15:30	PLENARY SESSION 4: • Group Leads brief on progress; identify challenges • Prioritising of groups needing to meet in Break out session 4	Yannick Beaudoin, UNEP/GRID-Arendal
15:30-17:30	GROUP BREAK OUT SESSION 4	
17:30-18:30	PLENARY SESSION 4: • All group leads provide final commentary • Discussion on steps towards draft 1 • Fundraising update • Marketing and outreach: Key targets (e.g. Arctic Council; ICGH; Ministers of Energy; Company CEOs • Open round	Yannick Beaudoin, UNEP/GRID-Arendal

Participants

NAME	AFFILIATION	EMAIL
Tina Treude	IFM-GEOMAR (Germany)	ttreude@ifm-geomar.de
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Timothy Collett	US Geological Survey	tcollett@usgs.gov
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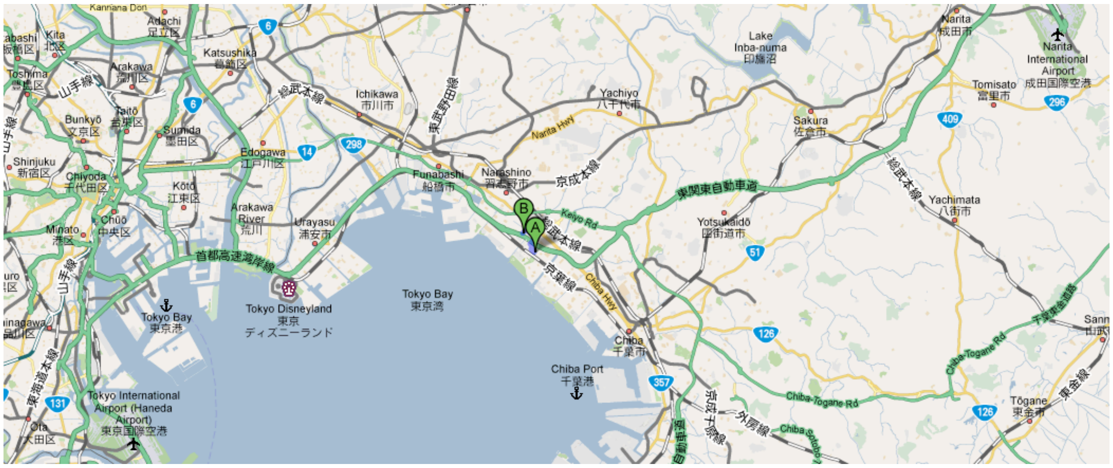
Tatsuo Saeki	JOGMEC (Japan)	saeki-tatsuo@jogmec.go.jp
Yannick Beaudoin	UNEP/GRID-Arendal	yannick.beaudoin@grida.no
Kelly Rose*	National Energy Technology Laboratory, US Dept of Energy	Kelly.Rose@NETL.DOE.GOV
William Waite*	US Geological Survey	wwaite@usgs.gov

: will participate via Skype

Logistical information

Makuhari Area



A = Hotel Springs Makuhari
B = JOGMEC TRC
Haneda Airport at the bottom left; Narita Airport at top right

Close up of Makuhari area

A = Hotel Springs Makuhari

B = JOGMEC TRC

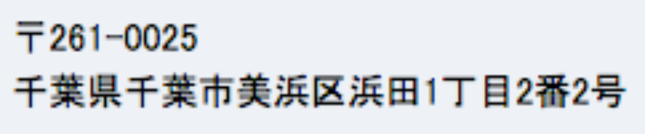
The blue line is a possible walking plan which would take about 20-25 mins.

Meeting Venue

The Technology and Research Center (TRC) at Makuhari is the synthesis of all technical departments involved in oil and gas development in JOGMEC. Developmental technology research for oil and natural gas, geological surveys, and evaluation of JOGMEC-related oil and gas E & P projects are chief responsibilities of the TRC.

If using a taxi to get to the TRC, it is recommend you print out and present the following address to the driver:

技術センター



〒261-0025
千葉県千葉市美浜区浜田1丁目2番2号

If commuting from the downtown area, you can use the subway system as per below and then use a taxi from the Kaihin Makuhari Station:

TRC complex

1-2-2, Hamada, Mihama-ku, Chiba-city, Chiba
261-0025 JAPAN

TEL : +81-43-276-9212
FAX : +81-43-276-4061

《Access from the station》
10 minutes. Drive by shuttle bus or taxi from:
—JR SOBU line "Makuhari Hongo" Station
—KEISEI-Chiba Line "Makuhari-Hongo" Station
—KEIYO Line "Kaihin-Makuhari" Station

Accommodation (for participants that opted for meeting coordinator to book)

Address
1-11
Hibino, Mihamaku, Chiba-shi. Chiba
TEL：043-296-3111
http://www.springs.co.jp/stay/english/index.html

GRID-Arendal

Teaterplassen 3
4836 Arendal
Norway

Visit the GRID-Arendal website at:
www.grida.no

Visit the UNEP Global Outlook on Methane Gas Hydrates project site at:
www.methane.gashydrates.org

Project Manager:
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