Gas hydrates

Taking the heat out the burning ice debate
June 2015

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Compiled by the A.T. Kearney Energy Transition Institute

Acknowledgements

A.T. Kearney Energy Transition Institute wishes to acknowledge Ray Boswell, Technology Manager, Natural Gas Technologies, U.S. DoE / National Energy Technology Laboratory and Robert L. Kleinberg, Schlumberger Fellow, Schlumberger Doll Research for their detailed review of this FactBook. The Institute also wishes to thank the authors of this FactBook for their contribution: Benoit Decourt, Romain Debarre, and Sylvain Alias.

About the FactBook – Gas Hydrates

The role gas hydrates may play as an energy resource is a controversial, polarizing subject. Therefore, a fact-based report has been developed by the A.T. Kearney Energy Transition Institute, presenting: key concepts; the status of exploration and production technologies; the status of research, development and demonstration (R,D&D); and the environmental and safety challenges associated with the potential exploitation of this resource. This publication aims at providing stakeholders with a balanced, unbiased assessment of gas hydrates and the tools to understand them properly.

The Institute performed a literature review and engaged experts in the gas-hydrate field. The Institute also analyzed patents from 50 offices worldwide, using the Thomson Derwent World Patents Index (DWPI) database, and conducted a survey of gas-hydrate stakeholders to present the state of R,D&D and a faithful picture of current thinking among academics and industry players involved in the field. Outcomes of the DWPI analysis and the results from the survey are available in separate documents referred to as Appendix A and Appendix B.

About the A.T. Kearney Energy Transition Institute

The A.T. Kearney Energy Transition Institute is a nonprofit organization. It provides leading insights on global trends in energy transition, technologies, and strategic implications for private sector businesses and public sector institutions. The Institute is dedicated to combining objective technological insights with economical perspectives to define the consequences and opportunities for decision makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

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Once considered a threat to flow assurance and drilling operations, gas hydrates – mainly methane trapped in ice crystals – are now envisioned as a potential source of energy

Natural gas has become a major source of energy over the past decade, thanks to its abundance, versatility and low carbon content, relative to other hydrocarbons. Most long range forecasts expect its share of the primary energy mix to continue to rise. Today, natural gas is recovered from conventional reservoirs – in isolation or dissolved in oil as well – and from unconventional reservoirs, in which buoyancy forces are insufficient to make the gas flow, and intervention is required to produce hydrocarbons to the surface. But natural gas can also be found in gas-hydrate accumulations.

Gas hydrate is a chemical compound resembling ice, in which water molecules form a solid lattice around methane molecules. Gas and water are not bound together, however, water-ice acts as a cage-like crystalline lattice that traps gas molecules. Although methane is not the only type of gas than can be trapped in this way, it is by far the most common in nature. As a result, the terms “gas hydrate” and “methane hydrate” are often used interchangeably.

The conditions necessary for gas hydrates to form and remain stable are a low enough temperature and a sufficiently high pressure, a region known as the gas hydrate stability zone (GHSZ). In addition to pressure and temperature, there needs to be a sufficient quantity of gas. Globally, gas hydrates can be found in many continental-margin settings and in onshore or subsea permafrost.

The amount of gas in a natural gas reservoir depends on the fraction of rock volume occupied by gas, and the density of gas in that fractional volume. In conventional reservoirs, the *in situ* density of gas depends on temperature and pressure. When the gas is in the form of gas hydrates, its density is fixed at 164 times the density of methane gas at standard pressure and temperature conditions, and does not change with depth. Since most conventional gas reservoirs exploited are at great depths, gas-hydrate density *in situ* is lower than the gas density of most conventional gas accumulations.

Historically, gas hydrates have mostly been viewed as a threat to oil and gas operations. This is primarily because of the risk of gas hydrates forming in oil and gas flow lines, given suitable temperature and pressure conditions, and causing blockages. Gas-hydrate accumulations can also present a hazard in deep-water drilling and production of conventional reservoirs. As a result, research has been primarily focused on preventing the formation of gas hydrates in pipelines and predicting when and where they form in order to avoid them when drilling. It is only relatively recently in the history of the oil and gas industry – since the 1970s – that naturally occurring gas-hydrate accumulations started to be envisioned as a potential source of energy. For this reason, most technologies associated with the recovery of gas hydrates are still at an early stage of development. One should note that researchers are investigating the controlled formation of hydrates for use in industrial applications such as gas transport, carbon capture and storage, and water desalination.

Gas-hydrate exploration is focused on high-concentration accumulations in sand-rich sediments, which may be recoverable with small adjustments to conventional technologies

As in conventional oil and gas exploration, gas-hydrate resource evaluation requires the identification of a trap in which gas hydrates could form and remain stable in sufficient concentrations. Due to the properties of gas hydrates, this primarily means identifying: suitable pressure and temperature conditions; the presence of gas sources; and the existence of migration pathways and of suitable reservoir rocks.

Methane hydrates hosted in sand-dominated or other coarse-grained sediments are the only type of gas-hydrate resource that is likely to be recoverable in the near term. This is primarily because of the high permeability and porosity of these formation, which enable high concentrations of gas hydrates to form and facilitate recovery. By contrast, both academics and corporate players have lost interest in producing from gas-hydrate resources in disseminated, low concentration clay-dominated sediments, or from sparse, small and randomly occurring seafloor mounds. These resources would require wholly different approaches to production and are as different to sand-hosted hydrates as shale gas is to conventional gas.

Until recently, gas-hydrates resource evaluation mainly took the form of global gas-in-place assessments. While such assessments have decreased substantially from early estimates, they continue to vary by several orders of magnitude, and even the most conservative assumptions indicate enormous gas-hydrate potential. In addition, there is now less emphasis on global gas-in-place assessments. Indeed, most experts suggest that the results of these studies should be considered an upper limit to the resource endowment and that attention should focus on sand-rich sediments, which early global assessments often neglected. According an IIASA/HEI study, gas-in-place hosted in sand-rich sediments could amount to around 1,200 tcm globally. For the purposes of comparison, the International Energy Agency estimates total technically recoverable natural-gas resources, excluding methane hydrates, amount to around 855 tcm.

Contrary to what is commonly believed, exploration is not a major hurdle in the development of gas-hydrate resources. Thanks to a better understanding of the properties of gas hydrates and their response to seismic or electromagnetic signals (made possible largely by additional field data from drilling campaigns), conventional technologies with minor adjustments have proved effective in identifying and characterizing gas hydrates deposits. But a fall in exploration costs could help encourage the commercial development of gas hydrates. This could be achieved by adapting technologies to the properties of gas hydrates. For example, gas-hydrate deposits are buried at shallower depths than conventional gas reservoirs, which should enable the use of lighter drilling equipment and smaller drilling vessels, although it would also be necessary to improve the resolution of images that are typically available from shallow sediments.

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Despite successful production tests, gas-hydrate production faces important operational challenges and remains subject to long-duration production tests

The first step in producing gas from gas-hydrate accumulations is to destabilize the hydrate compound *in situ*, i.e. to move gas hydrates out of their stability zone. Three main dissociation techniques have been explored and tested during field production trials: (i) depressurization, (ii) thermal stimulation and (iii) CO2-CH4 exchange. Chemical inhibitors could also be used but are unlikely to provide a stand-alone dissociation solution. These techniques are not mutually exclusive and are likely to be combined over the production cycle.

Depressurization stands out as the most efficient dissociation technique for gas hydrates in sand-rich reservoirs. It has the potential to achieve high recovery rates, in the range of 50-80%, while being less energy-intensive than thermal stimulation. CO2-CH4 exchange is an elegant solution that would mitigate concerns about reservoir stability, while improving the carbon balance of hydrate production. However, this technique is impaired by limitations to the exchange rate. In addition, it cannot achieve the same permeability characteristics as depressurization, and its use is restricted by the availability and cost of CO2. As a result, despite a successful “proof-of-concept” during the Ignik Sikumi field trial, CO2-CH4 exchange has lost momentum. It is widely considered a long-term option, subject to the emergence of a CO2 market and to the need to mitigate concerns over geomechanical stability.

Dissociation of the hydrate structure is not the only challenge in gas-hydrate production. The recovery phase also raises several issues. These include: (i) water production and, in some cases, subsequent water treatment and disposal, (ii) stimulation or artificial lift requirements, (iii) flow-assurance issues arising from secondary hydrate formation, (iv) sand production, and (v) harsh operating environments (offshore or Artic), far from end-consumers. These issues are familiar to the oil and gas industry, but their convergence creates a unique challenge that may threaten the economic viability of gas-hydrate recovery. Another threat relates to uncertainties concerning geomechanical stability and subsidence arising from prolonged gas-hydrate production. This underscores the need for long-duration production tests.

In general, the production of gas hydrates is at a less advanced stage than exploration. Production tests, which have occurred since 2002 (onshore in the Canadian and U.S. Arctic, and more recently offshore Japan) have proved the concept, achieving an important milestone in gas-hydrate development. The next prerequisite is indisputably a long-duration production test, lasting between six and 12 months. Such a test would enhance the understanding of geomechanical stability, and would allow the calibration of numerical reservoir simulators, and better assess recovery rates and production profiles. The latter remain highly uncertain. Important unknowns include: well-spacing requirements; the lag time between the start of the dissociation procedure and the start of production; and time to and length of plateau production. For these reasons, economic assessments remain highly speculative. Japan is planning to conduct a mid-to-long-term production campaign in the next few years, although the start date and the duration have not yet been announced.

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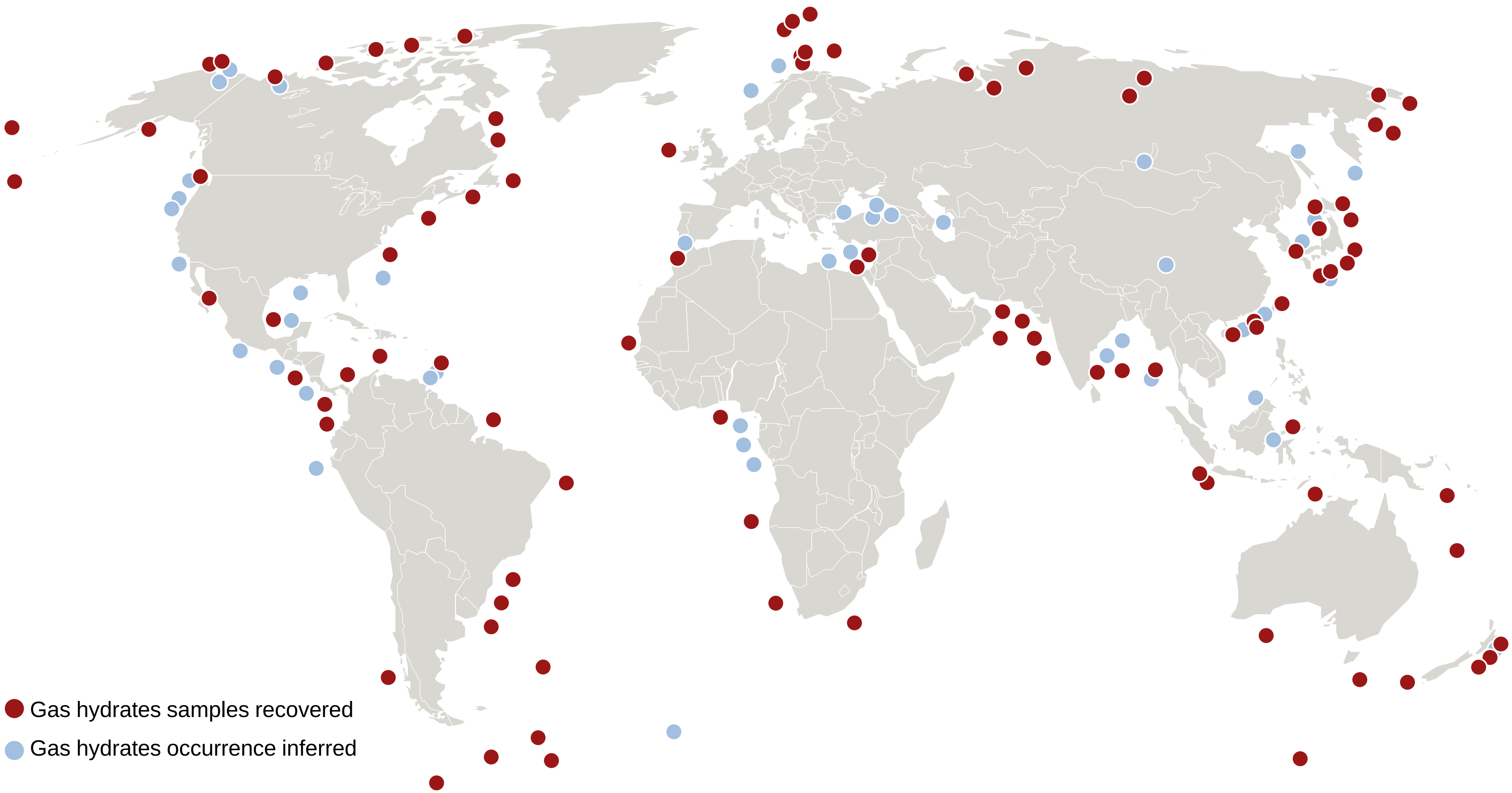
Gas hydrates have been recovered or inferred in many parts of the world

Global occurrence of gas hydrates



Source: Redrawn from USGS (2013), “Database of Worldwide Gas Hydrates” (link), and Kvenvolden and Lorenson (2001), “The Global Occurrence of Natural Gas Hydrate”

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Aside from concerns about sediment instability, gas-hydrate recovery should not face any major environmental impediment and should be viewed separately from natural gas-hydrate dissociation issues

Environmental concerns about gas-hydrate dissociation stem from the enormous assumed size of the resource and the global warming potential of methane. Like CO_2, methane is a potent greenhouse gas (GHG). However, according to the Intergovernmental Panel on Climate Change, an equivalent quantity of methane would entail 84 and 28 more radiative forcings than CO_2 over 20- and 100-year horizons, respectively. The change over time is due to methane being short-lived in the atmosphere – it is converted into CO_2 over decadal timescales.

Since gas hydrates are only stable under high pressures and at low temperatures, there have been concerns that climate change could result in gas-hydrate dissociation and the release of methane into the atmosphere. The response of gas hydrates to climate change has only been investigated recently. Modelling in this field is in its infancy and faces major uncertainties. Nevertheless, it is generally agreed that gas-hydrate dissociation is likely to be a regional phenomenon, rather than a global one, and more likely to occur in subsea permafrost and upper continental shelves than in deep-water reservoirs, which make up the majority of gas hydrates. Indeed, the later are relatively well insulated from climate change because of the slow propagation of warming and the long ventilation time of the ocean. Moreover, the release of methane from gas-hydrate dissociation should be chronic rather than explosive, as was once assumed; and emissions to the atmosphere caused by hydrate dissociation should be in the form of CO_2 because of the oxidation of methane in the water column.

Notwithstanding the risk of natural gas-hydrate dissociation, it is important to draw a distinction between this issue and hazards arising from gas-hydrate resource exploitation. Producing gas hydrates cannot be a solution for mitigating the climatic hazards of the natural melting of gas hydrates. Conversely, there are few concerns regarding methane emissions caused by gas-hydrate production. Indeed, gas hydrates are stable by nature: unlike in other types of gas reservoir, if stimulation stops, hydrates will reform and gas will be trapped again in ice, instead of escaping. Nevertheless, in some cases, gas may escape out the wellhead after cementing and, as a result, monitoring will be necessary. Most stakeholders rank the geomechanical instability of reservoirs and subsidence issue as the most important challenges, not only from an environmental perspective, but also for safety.

Even if safety and environmental challenges can be overcome, gas hydrates as a resource are likely to face social-acceptance issues. Engaging stakeholders will therefore be vital in avoiding misplaced and harmful perceptions.

Developing gas hydrates might be viable, but further R,D&D is necessary to assess the economics of gas-hydrate production, and to address environmental and safety concerns

In the absence of long-duration production trials, assessments of the economics of gas-hydrate production remain highly speculative. Important parameters such as well spacing, production profiles and expected recovery rates remain uncertain, since models have not been calibrated with these characteristics.

Nevertheless, it is largely agreed that, using current technologies, gas hydrates are likely to be more expensive to recover than most other gas resources. In most cases, gas-hydrate recovery is expected to require more wells per unit of space. Gas-hydrate recovery would also exhibit a higher water-to-gas ratio, which may require special facilities and oversized flow lines. In addition, it involves dissociation operations (*e.g.* using compressors) and requires artificial-lift infrastructure and cutting-edge monitoring and control instruments. As well as exploration and production costs, gas-hydrate economics may also be affected in some regions by high transport costs: resources can be located far from markets, in harsh marine or permafrost environments, and face the usual “stranded gas” issue.

Therefore, the business case for gas hydrates would be improved in locations where synergies with conventional oil and gas operations could be leveraged. In addition, deposits in permafrost environments would typically be cheaper to exploit than marine accumulations, because operations would be based on land. Gas prices and consumers’ willingness to pay a premium for domestic resources will also be crucial parameters in making gas hydrates economically viable: if gas hydrates seem very unlikely to be competitive in gas-rich regions, energy independence and energy security concerns could help to make the case for gas-hydrate developments.

Asia is at the forefront of this new gas frontier. Unlike in North America, especially Canada, where R,D&D programs lost momentum following the shale-gas boom and the resulting fall in gas prices, R,D&D focused on gas hydrates has increased in intensity in Asia. This is reflected in the launch of exploratory campaigns in China, Korea and India, as well as in the number of patents filled in the region. China has, for instance, become the first patent-filing country for gas-hydrate upstream technologies, and a successful test offshore Japan has helped energize gas-hydrate stakeholders.

Developing gas hydrates is not the hair-brained idea of a few researchers. But R,D&D is still necessary to assess whether this resource can become commercially viable on a large scale and have a revolutionary impact on the energy sector.

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1. Introduction to gas hydrates

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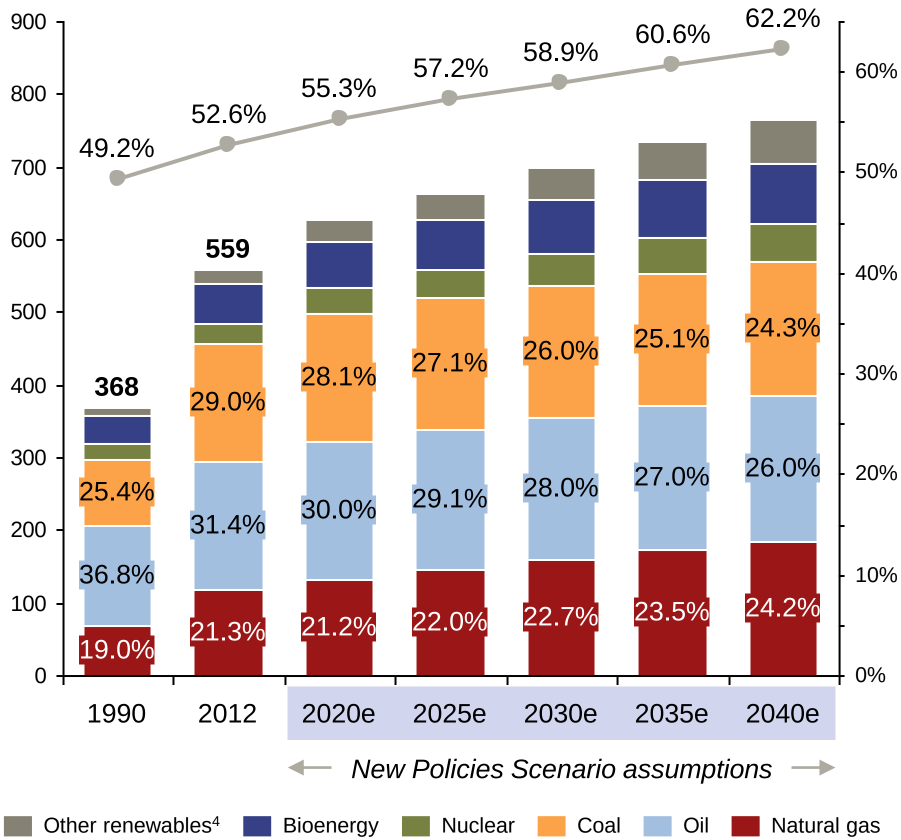
Natural gas's role in the global energy mix is growing and is expanding worldwide

Total world primary energy demand[1]

Exajoules (EJ), IEA 4DS scenario for the forecast[2]



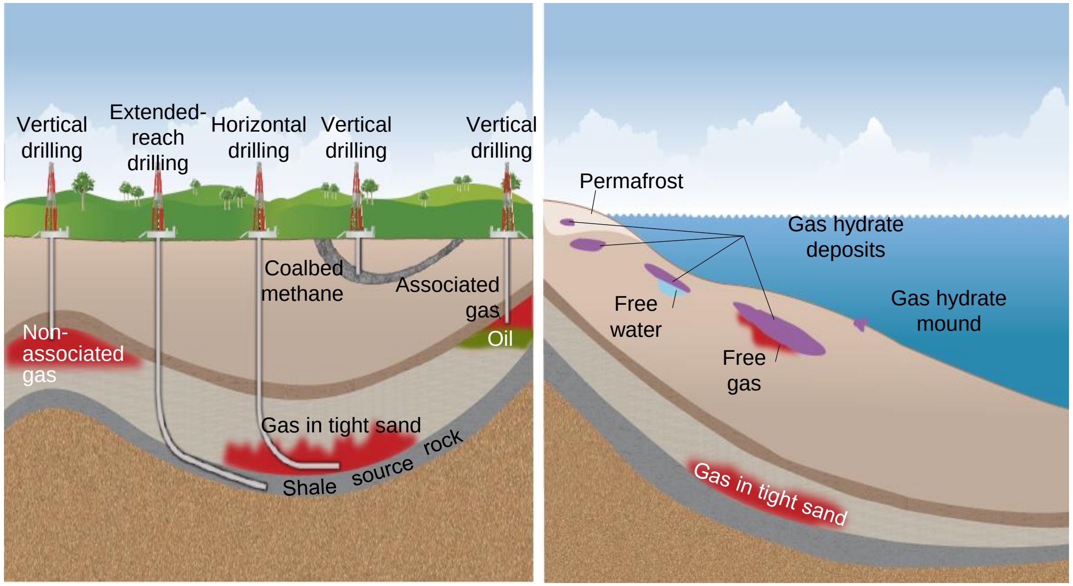
- **Having long been overlooked as an energy source, natural gas has become a crucial part of the energy mix**, mainly because of its abundance and its low carbon content relative to other fossil fuels.
- **Natural gas use increased at an average annual growth rate of 2.5%** between 1990 and 2012, and, as of 2014, accounted for more than 20% of the global primary energy mix. Thanks to its versatility, natural gas plays a major role in all end-use sectors except for transport.
- **Growth in natural gas consumption is expected to continue, albeit at a slower pace**. The International Energy Agency's reference scenario[2] assumes an average annual growth rate of 1.6% between 2012 and 2040 – with gas demand rising as high as 5.4 tcm. This means demand for natural gas should grow more quickly than demand for other fossil fuels. According to the Reference Case of the Organization of the Petroleum Exporting Countries, natural gas would account for a higher share than oil by 2040.
- **Finally, natural gas demand growth is likely to be driven by emerging economies**. Non-OECD countries[3] account for 79% of the incremental gas demand expected by the IEA.

1. For more information, please refer to A.T. Kearney Energy Transition Institute FactBook: "Introduction to Natural Gas"; 2. The New Policies Scenario is the IEA's reference scenario. It assumes recent government policy commitments will be implemented even if they have not yet been ratified; 3. OECD stands for Organisation for Economic Co-operation and Development; 4. Other renewables include hydro, geothermal, solar photovoltaic, concentrating solar power, wind and marine energy.

Source: International Energy Agency (2014), "World Energy Outlook 2014"; Organization of the Petroleum Exporting Countries (2014), "World Oil Outlook"

Natural gas can accumulate in various geological settings

Schematic geology natural gas resources[1]



Caution: figure is not drawn to scale

- **Natural gas resources are usually classified according to the properties of the reservoir in which they are trapped.**
- **Resources are referred to as conventional** when accumulated in a reservoir whose permeability characteristics permit natural gas to flow readily into a wellbore; **and as unconventional** when the reservoir and fluid characteristics do not allow gas to flow to the wellbore, hence requiring intervention.
- **There are four main types of unconventional natural gas reservoirs:** shale, tight, coalbed (CBM) and gas hydrates. Shale, tight and CBM reservoirs started to be exploited on a commercial scale over the past decade and supplied 266, 215 and 71 bcm of gas in 2013, respectively[1]. But gas from hydrate reservoirs has not been produced except in scientific programs[2].

1. For more information, please refer to A.T. Kearney Energy Transition Institute FactBook: "Introduction to Natural Gas"; 2. Gas hydrates may have been produced from Russia's Messoyakha field, which lies underneath a gas-hydrate accumulation, because of depressurization caused by conventional gas production. However, many people dispute this theory.

Source: A.T. Kearney Energy Transition Institute analysis; EIA (2010), "Schematic Geology of Natural Gas Resources"; IEA (2013), "Resources to Reserves 2013"

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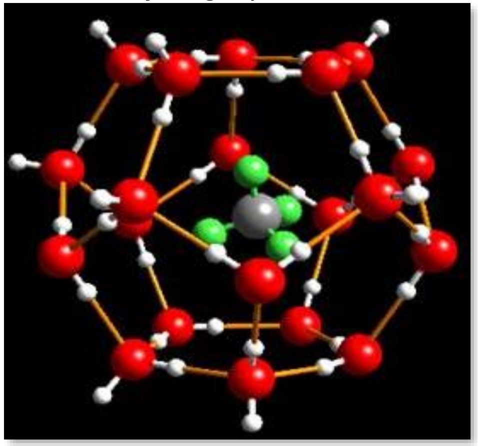
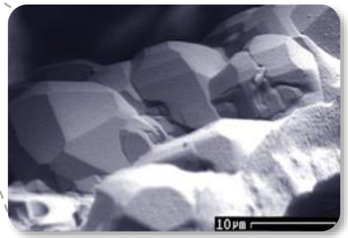
Methane hydrate is a chemical compound in which molecules of water-ice form a solid lattice around a molecule of methane

Methane hydrates, also known as burning ice, fiery ice or ice fire

Methane [CH_4] (green for hydrogen and grey for carbon) is the guest molecule in a cage formed by water [H_2O] molecules (red for oxygen and white for hydrogen)[1].





Electron microscope image of gas hydrate

- **Methane hydrate is technically a naturally occurring clathrate** (*i.e.* a chemical compound in which molecules of one material - 'the host' - form a solid lattice that encloses molecules of another material - 'the guest'), where the host is water ice, and the guest is methane. Methane and water are not bound together; water-ice acts as a cage-like crystalline lattice, trapping a methane molecule (see picture).
- **Three types of hydrate structures exist commonly in nature:** structure I, structure II and structure H. These structures vary according to the number and size of water cages where gas can be enclosed. For this reason, they have different shapes. Structure I, which can host small-diameter molecules such as methane, is the most common naturally occurring form of hydrate structure[2].
- **Methane hydrate is the most common type of gas hydrate in nature.** Therefore, "gas hydrate" and "methane hydrate" tend to be used interchangeably in the literature. Nevertheless, other guest molecules could be trapped instead, such as carbon dioxide (CO_2), nitrogen (N_2), hydrogen sulfide (H_2S) or ethane.
- Physically, gas hydrates resemble ice. However, when exposed to conditions other than those under which it is stable[3], the crystalline lattice turns to liquid water, and the enclosed gas molecule is released.

1. This represents 2 of the 8 parts of the typical Structure I gas-hydrate molecule; 2. For more information on structure, please refer to Appendix 1; 3. For more information on methane-hydrate stability conditions, please refer to slide 14.

Source: USGS (2014), "Gas Hydrates Primer"; Birchwood et al. (2010), "Developments in Gas Hydrates" in Schlumberger Oilfield Review, Vol.22 Issue.1

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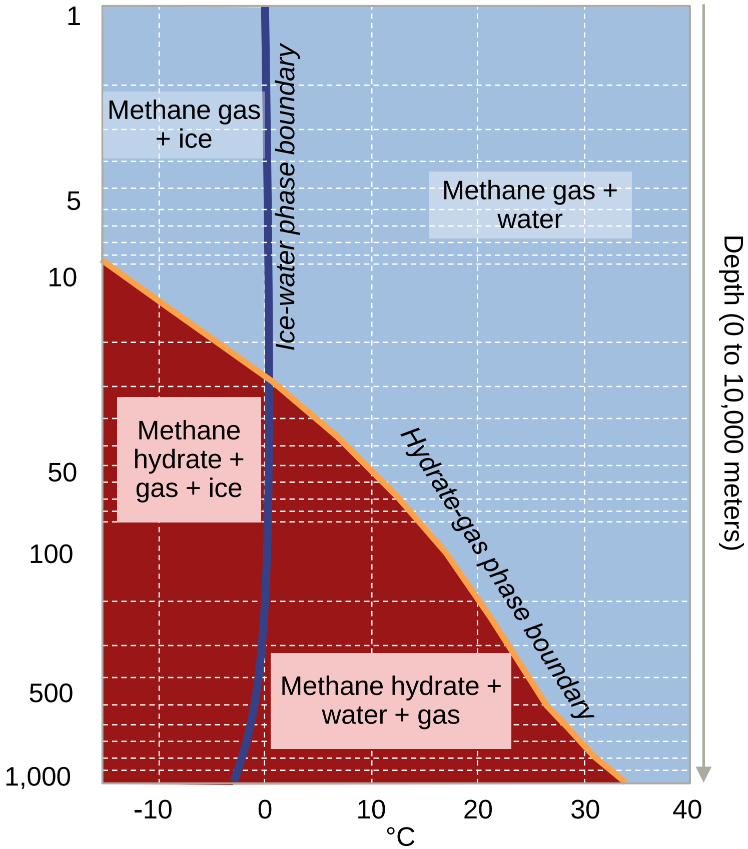
Methane hydrates require high pressures or low temperatures and sufficient quantities of methane to form and remain stable

Phase diagram of methane hydrate

Pressure in atm[1] (log scale), Temperature in °C



How to read this graph

- The red line shows the hydrate-gas phase boundary *i.e.* the pressure and temperature combination below which methane gas in sufficient quantity can be trapped in the water-ice lattice. Above this line, hydrates would dissociate and release methane gas from their water cages.
- In nature, this line varies according to the sediment's lithology and the surrounding chemical environment (*e.g.* salinity of water or presence of non-hydrocarbon gases).
- The blue line shows the ice-water phase boundary. To the left of this line, free water is in ice form; to the right of the line, free water remains liquid.

- **The most critical conditions required for methane hydrates to form are a sufficiently low temperature and a sufficiently high pressure.** Above the hydrate-gas phase boundary, temperatures are too high and pressure too low for methane hydrates to form. This explains the production techniques that have been investigated to produce and dissociate methane and water[2].
- **Other factors can play an important role in hydrate stability, notably the type of sediment, the salinity of pore water** within sediments, the presence of other hydrocarbon gases such as methane, or the presence of non-hydrocarbon gases such as CO_2. For instance, in saline environments, methane hydrates will require a lower temperature to form, shifting the phase-boundary with gas to the left.
- Globally, methane hydrates can be found in many continental margin settings and in onshore or subsea[3] permafrost.

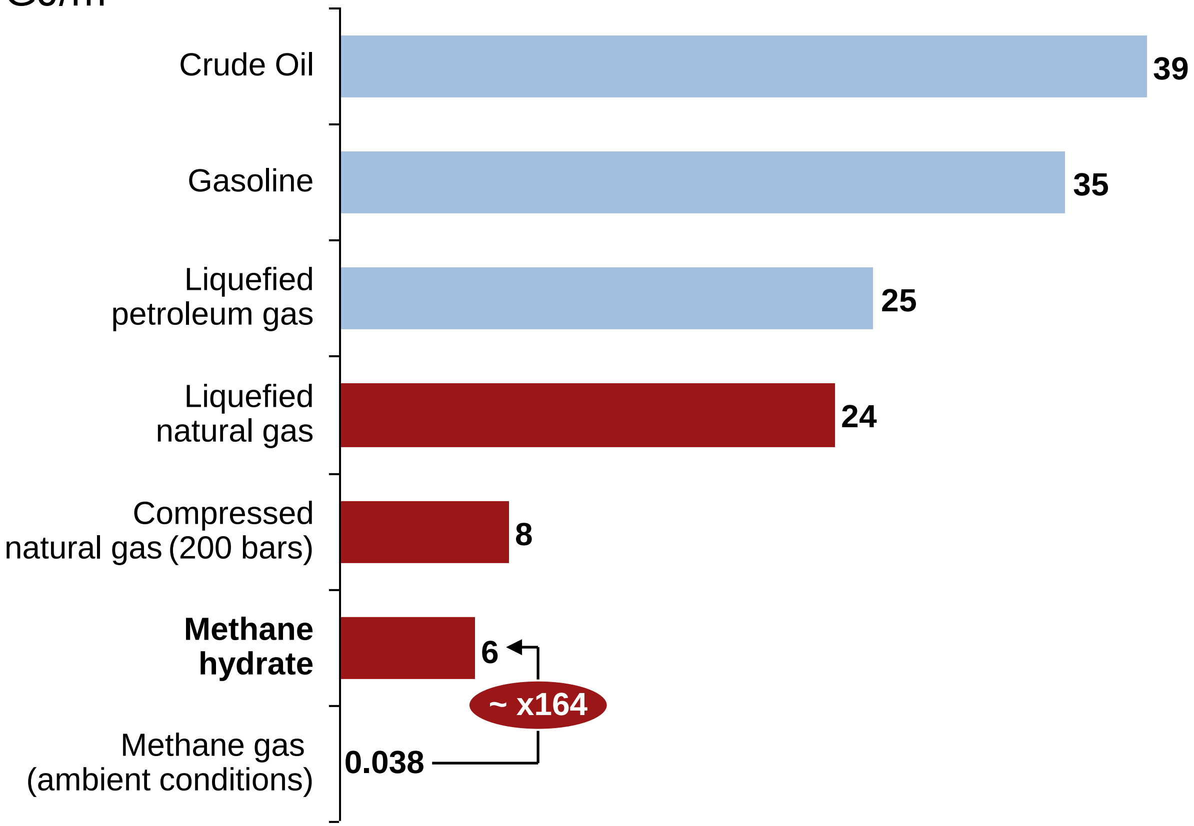
1. 1 atm = 01325 bar. Since pressure increases with depth below the surface of the ground or the ocean, pressure increases from top to bottom; 2. For more information, please refer to Section 3; 3. Subsea permafrost is offshore permafrost that was flooded by rising sea levels during the past ~15,000 years.

Source: A.T. Kearney Energy Transition Institute analysis; Birchwood et al. (2010), "Developments in Gas Hydrates" in Schlumberger Oilfield Review, Vol.22 Issue.1; Boswell et al. (2014), "Methane Hydrates"

Methane hydrates benefit from a high energy density relative to methane gas at standard pressure and temperature conditions

Volumetric energy density of chemical fuels[1]

GJ/m³



- **Methane hydrate is a dense form of natural gas.** When dissociated at standard pressure and temperature conditions[2], it will typically expand 164 times (*i.e.* a cubic meter of methane hydrate will release the equivalent of 164 cubic meters of methane gas)[3]. As a rule of thumb, the energy content of methane hydrates is 80% of that of natural gas compressed to 200 bars and around one-sixth of that of crude oil.
- **The volumetric energy density of gas hydrates is one of the drivers** behind interest in naturally occurring methane hydrates as an energy source, but also in using the principle of methane hydrate in industrial applications[4] (*e.g.* using hydrates to store and transport natural gas).

1. Figures are based on fuels' higher heating value (HHV); 2. 1atm (i.e. ~1 bar) and 0°C; 3. This figure depends on the hydrate's structure (type I, II or H) and on the level of occupancy of the hydrate's cage by methane molecules. This can range from 150 to 180; 4For more information on industrial applications, please refer to slide 20.

Source: A.T. Kearney Energy Transition Institute analysis based on U.S. DoE (2015); Birchwood et al. (2010), "Developments in Gas Hydrates" in Schlumberger Oilfield Review, Vol.22 Issue.1; Thakur and Rajput (2011), "Exploration of Gas Hydrates"

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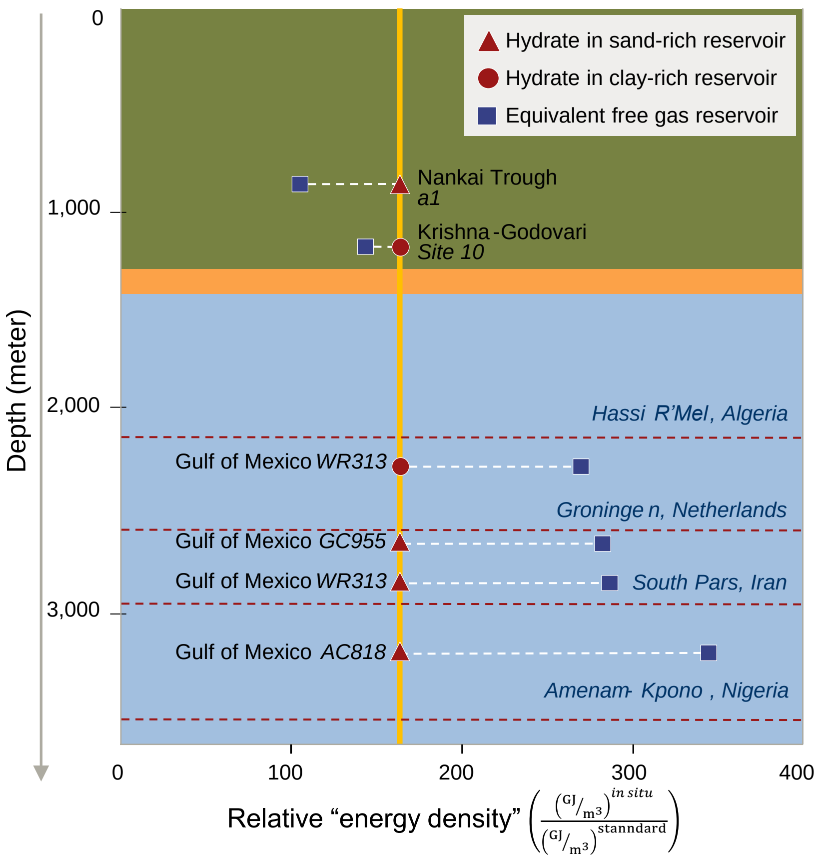
Methane hydrates' energy density *in situ* is lower than that of conventional natural gas resources in deep-reservoir conditions

Comparison of methane hydrate and free gas energy density[1]

Energy density *vs.* depth (in meters)[2]



How to read this graph

- The energy density of gas hydrates (vertical orange line), shown here as 164:1, barely changes with depth. The energy density of free gas accumulations varies with depth in a complex manner (it is influenced by temperature, pressure and sediment lithology). Approximate depths of existing gas hydrate accumulations are indicated along the gas-hydrate line, with the energy densities of hypothetical, free-gas accumulations at the same depths indicated by black squares. The dashed dark blue lines provide examples of the main reservoir depths of large conventional gas fields around the world.

- **Unlike conventional hydrocarbons, the density of methane hydrates does not vary significantly with pressure conditions.**
- **Therefore, the relative conventional gas and gas-hydrates formation volume factor varies, depending on reservoir conditions.** At shallow depths, gas hydrates are typically denser than free gas and less energy dense at great depth. Density is similar at moderate depths.
- **However, most conventional gas reservoirs exploited are at relatively great depths[3].** As a consequence, and contrary to common belief, the energy density of gas hydrates *in situ* is lower than that of conventional gas accumulations. This has important consequences for the economic viability of recovering methane hydrates (*e.g.* it is likely to require more wells).

1. Energy density compares the energy stored within one volume of methane-hydrate in-situ with the energy stored in the same volume of methane-gas at standard pressure and temperature; 2. In WR313, Gas-hydrate deposits primary occurred in sand. Nevertheless, as shown this diagram, secondary fracture-dominated deposits were found at lower depths; 3. One of the main reason for deep gas exploitation is that it is more energy dense.

Source: A.T. Kearney Energy Transition Institute analysis; 1modified from Boswell and Collett (2010), "Current perspectives on gas hydrate resources"

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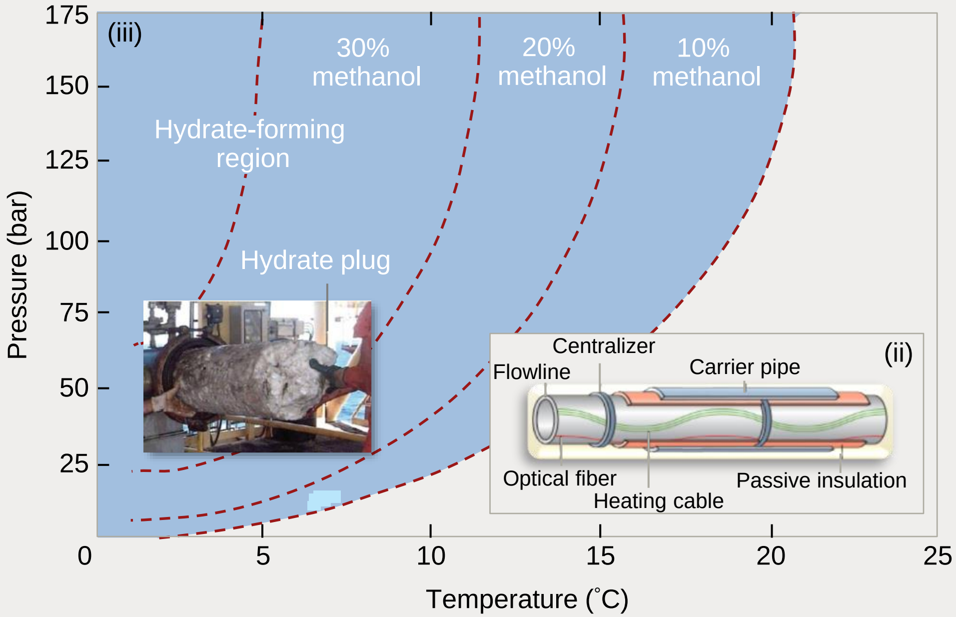
Industry interest in gas hydrates has, for a long time, been confined to preventing the formation of gas hydrates in oil and gas flowlines

Pressure and temperature conditions of fluids in a subsea pipeline



During their path from a deep-water well to the platform and central processing facility, the fluids in a pipeline are subject to temperature and pressure changes. Within the shaded area, it is possible for gas hydrates to form inside and plug the pipeline. Adding chemical inhibitors such as methanol can shift the stability zone to colder temperatures, preventing the formation of hydrate plugs.

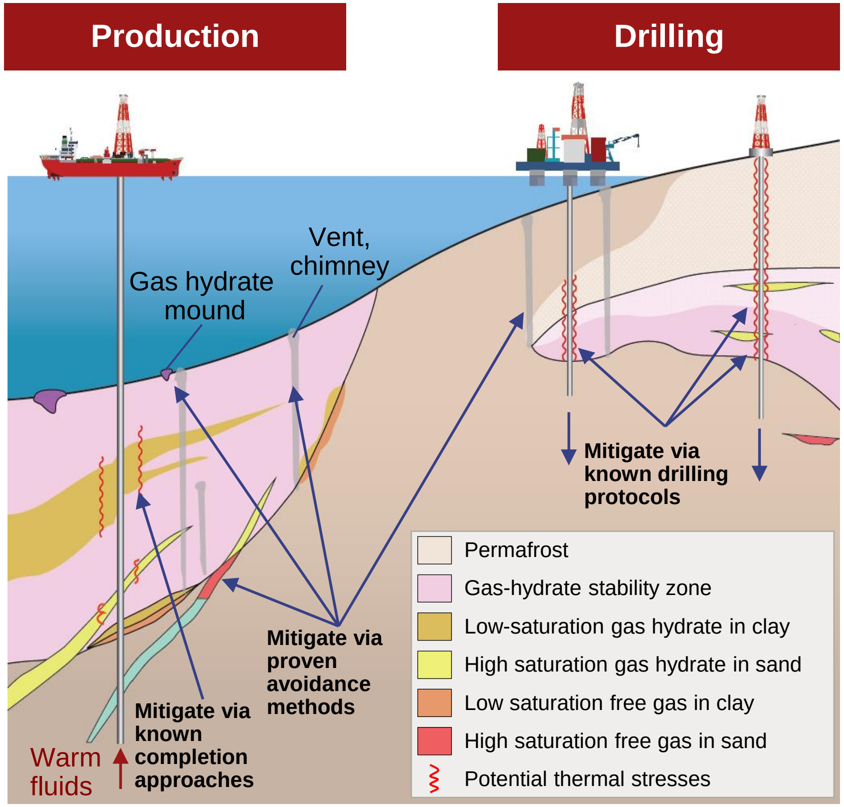
- **Flow assurance** *i.e.* maintaining oil and gas flow in pipelines or facilities, **was, for a long time, the primary driver of gas-hydrate research**.
- **Gas hydrates can form in the presence of water and gas under operating conditions characterized by high pressure and low temperature**, notably in transmission lines. The unexpected formation of hydrate accumulations can result in production losses, affecting the economics, and it can pose grave safety risks for installations and personnel.
- **As offshore operations have moved into deeper and deeper waters, higher pressures and lower temperatures have made gas-hydrate control a necessity**[1].
- **Three traditional approaches have been used in order to mitigate hydrate accumulation**: (i) water removal from the gas mixture, (ii) temperature control in critical zones, and (iii) the addition of inhibitors. The latter consists of adding chemical additives to prevent hydrate formation. Both for economic and environment reasons, low-dosage hydrate inhibitors such as kinetic hydrate inhibitors[2] and anti-agglomerants[3] are now preferred to thermodynamic inhibitors, which were in use previously[4].

1. Picture credit: Koh et al. (2011), "Fundamentals and Applications of Gas Hydrates"; 1. At ocean depths greater than 600m, operating temperatures can be around 4°C. At this temperature, less than 0.7 MPa is needed to stabilize hydrates, far less than typical pipeline operating pressures; 2. Kinetic hydrate inhibitors affect the induction time and slow down the formation of hydrates; 3. Anti-agglomerants prevent hydrate crystals from sticking together and/or depositing on the pipe walls; 4. Thermodynamic inhibitors lower hydrate formation temperature.

Source: Amin et al. (2005) "Subsea Development from Pore to Process" in Schlumberger Oilfield Review, Vol.17 Issue.1; Koh et al. (2011), "Fundamentals and Applications of Gas Hydrates"

Oil and gas companies monitor gas-hydrate accumulations during conventional hydrocarbon exploration and production in order to avoid hazards

Mitigation efforts required by the presence of gas-hydrates deposits



Caution: figure is not drawn to scale

- **In addition to concerns about flow assurance, the oil and gas industry has regarded gas-hydrates as a hazard when exploring or producing hydrocarbons from conventional reservoirs**. Indeed, gas-hydrate stability zones in deep-water marine settings or in permafrost are typically found at shallower depths than conventional oil and gas. As a result, it is possible to encounter gas-hydrate deposits when drilling for conventional resources, especially offshore and in deep waters.
- **There are two main hazards associated with drilling through gas-hydrate deposits**: (i) it can cause a **well-control problem,** if gas hydrates decompose, release gas and cause a gas kick; (ii) the **circulation of warm drilling fluid through gas-hydrate-rich sediments or heat released during cementing can result in gas-hydrate dissociation**, jeopardizing geomechanical stability and threatening the safety of the operation[1]. The most significant hazard, however, occurs during production: the flow of hot fluids from deeply buried conventional reservoirs through overlying gas-hydrate accumulations.
- In order to prevent these hazards, oil and gas companies can use inhibitor additives or special cements that minimize heat release during drilling operations. However, **most efforts to date have focused on predicting where potential gas-hydrates deposits are likely to have formed, in order to avoid them when drilling**. This has led to important scientific advances in gas-hydrate detection, which have also proved useful when trying to extract methane from gas-hydrate accumulations.

1. e.g. an anchor problem for floating rigs, a foundation problem for any bottom-supported facility.

Source: Collett et al. (2000), "Growing interest in gas hydrates" in Schlumberger Oilfield Review, Vol.12 Issue. 2; Consortium for Ocean Leadership (2013), "Marine Methane Hydrate Field research Plan"; Boswell et al. (2011), "Geohazards Associated with Naturally-occurring gas hydrate"

Gas hydrates were only envisioned as a potential source of energy after the 1970s

1810

1810
Humphrey Davy discovered first example of chlorine hydrate in his laboratory

1888
First documented identification of hydro-carbon hydrates

1934
Gas hydrates identified as responsible for causing pipeline blockage in Kazakhstan

1963
Hydrates are encountered in Western Siberia's Messoyakha field

1971
First production of gas attributed to decomposition of hydrate layer in Messoyakha gas field

1972
Early industry tests of the commercial potential of gas hydrates in Alaska

1980

1980
Hydrates identified offshore Japan

1985
Hydrates identified offshore India

1990

1995
Core sampling offshore South Carolina

Mid-1990s
First estimate of hydrate resources offshore Japan

1998-1999
First discovery of concentrated gas hydrate in marine sand reservoirs at Nankai Trough

1999/2000
Drilling of core and downhole logging holes in Nankai Trough

2000

2000
U.S. Congress passes Methane Hydrates Research and Development Act

2000
Creation of the Research Consortium for Methane Hydrates

2002
Arctic Mallik Project: first experimental production tests in Northern Canada (thermal stimulation)

2006
First expedition of the India National Gas Hydrate Program

2007
First large-scale methane hydrate exploration and drilling expedition Korea's East Sea

2007
Marine gas hydrates recovered and cored in the South China Sea

2007-2008
Arctic Mallik Project
First production through depressurization

2010

2012
Alaska North Slope
First production trough CO_2 injection

2013
Nankai Trough Project:
first production of marine methane hydrates through depressurization

2013
China's second major gas hydrate expedition in the south China sea

2014

Note: This list is not exhaustive. More information on historical gas-hydrate projects can be found in Appendix 4 to 8.
Source: Consortium for Ocean Leadership (2013), "Marine Methane Hydrate Field research Plan"; Collett et al. (2000), "Growing Interest in Gas Hydrate" in Schlumberger Oilfield Review, Vol.12 Issue. 2

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Research and development is also considering the formation of hydrates in a controlled manner, authorizing industrial application of gas hydrates

Potential industrial applications for hydrates

Maturity (+ to -)

1 Natural gas transportation[1]

- Transporting natural gas in the form of hydrates is an attractive concept because of the high energy density of hydrates at ambient conditions, and their stable, and therefore safe nature under certain pressure and temperature conditions. As a result, solid gas transport in the form of hydrates is under consideration as an alternative to compressed natural gas or liquefied natural gas for flexible, long-distance transportation. Mitsui Engineering & Shipbuilding and Chugoku Electric Power Company completed the first commercial overland transportation demonstration project in Japan in 2011.

2 CO_2 sequestration and disposal

- Injecting carbon dioxide (CO2) into deep marine sediments could enable CO2 storage in the form of solid hydrates, under specific temperature and pressure conditions. In addition, injecting CO2 into methane-hydrates formations can be used to destabilize gas-hydrate deposits and "exchange" CO2 for methane. ConocoPhillips and the U.S. DoE performed the first field trial to determine the feasibility of CO2-exchange technology in a gas-hydrate reservoir in Alaska in 2012.

3 Desalination

- In a saturated saline solution, the formation of hydrates causes the crystallization of salt, producing two solid phases: hydrate and salt. However, the low-temperature and high-pressure conditions necessary to bring the system within gas-hydrate stability zone tend to result in high costs, challenging the economic viability of this gas-hydrate application. A large number of studies have been conducted on this subject since the 1960s and R&D is focused on decreasing the costs of the separation.

4 CO_2 separation

- Using hydrates in carbon capture and storage (CCS) projects to separate CO2 from shifted syngas has been considered, notably in the integrated gasification combined-cycle process. It is viewed as a way of reducing the costs and energy requirements of capture processes, notably in combination with cryogenic condensation. In 1999, for instance, the U.S. DoE launched the first project to capture CO2 using hydrates, based on SIMTECHE process.

1. More information on gas-hydrate transportation can be found in Appendix 2.

Source: Nogami et al. (2011), "World's First Demonstration Project of Natural Gas Hydrate (NGH) Land"; Giavarini and Hester (2011), "Gas Hydrates Immense Energy Potential and Environ-mental Challenges"; Surovtseva et al. (2011), "Design and operation of pilot plant for CO2 capture from IGCC flue gases by combined cryogenic and hydrate method"

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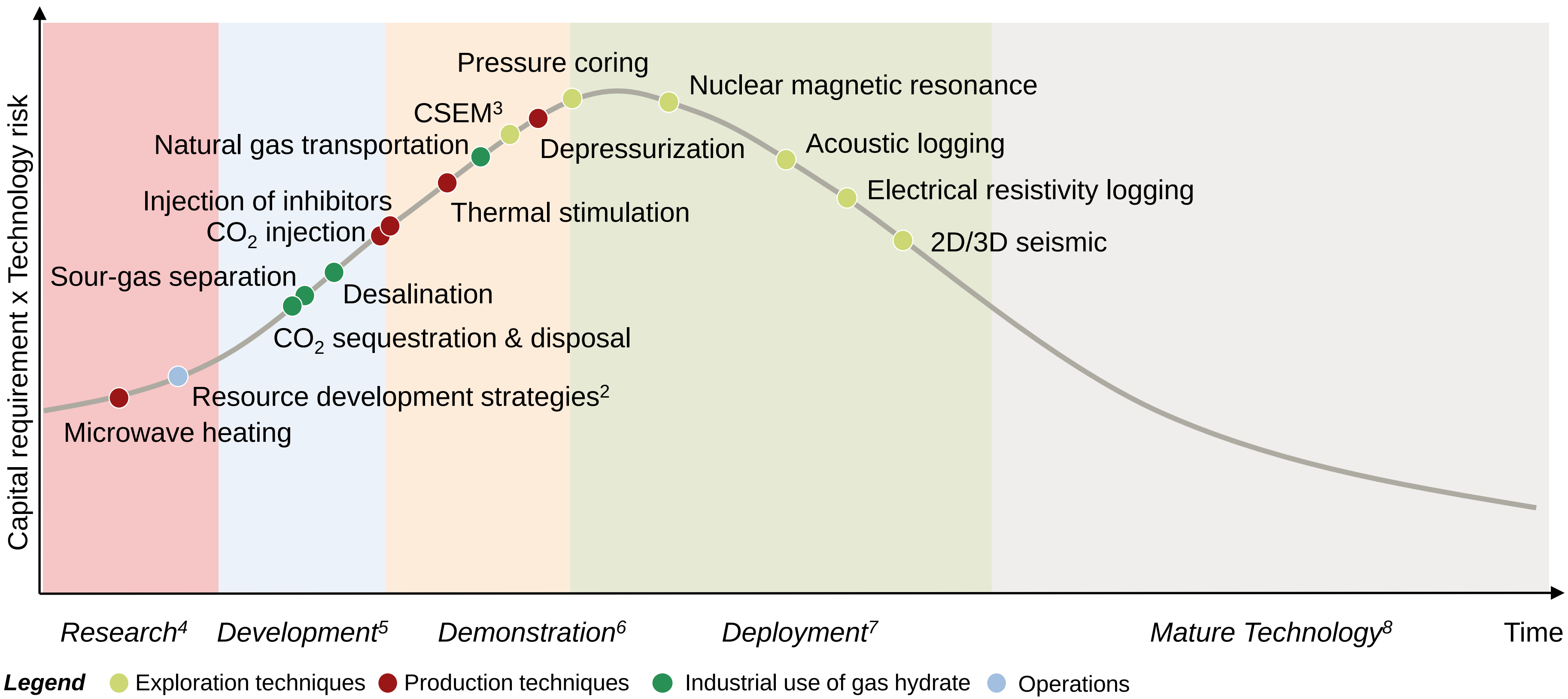
Gas-hydrate technologies remain at an early stage of development, despite the maturity of many of the individual exploration technologies being used

Technology maturity curve[1]



1. The maturity curve is based on responses from gas-hydrates experts to the Gas Hydrate Survey, in October 2014. Results have been slightly adjusted in light of qualitative interviews conducted by the A.T. Kearney Energy Transition Institute and academic reviews. While some technologies may be widely deployed in the conventional oil and gas industry, most are not mature in the context of gas hydrates. For example, while core recovery is common practice in the oil and gas industry, coring technologies had to be adapted to enable gas-hydrate coring, and none of the pressure corers have yet reached a commercial scale; 2. Addressing issues relating to operations, e.g. number and type of wells, and size of drilling vessels; 3. Controlled-Source Electromagnetic Methods; 4. Lab work / theoretical research; 5. Bench-scale; 6. Pilot-scale; 7. Proved commercial-scale process, with optimization work in progress; 8. Commercial-scale, widely deployed, with limited optimization potential.

Source: A.T. Kearney Energy Transition Institute analysis

2. Exploration and resource assessment

As with any hydrocarbon source, gas hydrate resource evaluation relies firstly on geological and geophysical surveys

Simplified "petroleum system approach" for gas-in-place hydrates resources evaluation

Determine the **Gas Hydrate Stability Zone** (GHSZ) based on present-day pressure and temperature conditions

Determine the **Gas Hydrate Occurrence Zone (GHOZ)**: ensure sufficient hydrate-forming gas was available[1] and able to migrate into the gas hydrate stability zone

Ensure there is the right **trap and lithology[2]** (type of sediments, presence of a seal, connection to migration pathways *etc.*)[3]

The assessment includes the presence or absence of these components, but should also incorporate a data confidence factor.

- Before any exploration wells are drilled, it is essential to determine where gas hydrates could form and remain stable, based on pressure and temperature conditions. The thickness and depth of this zone, known as the gas hydrate stability zone, will vary according to location (*e.g.* beneath the seafloor, or in permafrost). One must then ensure that enough gas was available and able to migrate into this zone. This is especially important since, unlike conventional oil and gas, once formed within the stability zone, gas hydrates will not migrate to a reservoir where they can accumulate further. Finally, as with any hydrocarbons, one must review the reservoir lithology, its connection to potential migration pathways for gas to accumulate and, generally, the presence of a trap[4].
- Depending on the definition, resource figures can refer to very different concepts. **Gas-in-place** (GIP) refers to all hydrocarbon volume in a given reservoir and is a function of geological condition: GIP = area (m^2) x thickness (m) x porosity (%) x saturation (%) x volumetric conversion factor. **Technically recoverable resources** (TRR) are a subset of GIP and add a recovery factor to take into account only the volume that could be produced based on existing technologies or advances in the foreseeable future. **Economically recoverable resources** (ERR) are a subset of TRR that would meet the investment criteria of a typical oil & gas company.

1. Gas availability is one of the main factors affecting the presence, quantity and distribution of hydrates. Gas availability depends on both the quantity of organic sources originally in place – bounded by the concentration of total organic carbon (TOC) – and on the presence of migration pathways; 2. Lithology is the description of rock composition and texture; 3. This last step gained favor relatively recently, largely due to high-concentration deposits in sand-rich sediments being considered as most-promising; 4. These steps, associated technologies and techniques, and results are detailed in the following slides.

Source: A.T. Kearney Energy Transition Institute analysis; Kleinberg (2009), "Exploration strategy for economically significant accumulations of marine gas hydrate"; Reichel and Gallagher (2014), "A Global Review of Gas Hydrate Resource Potential"

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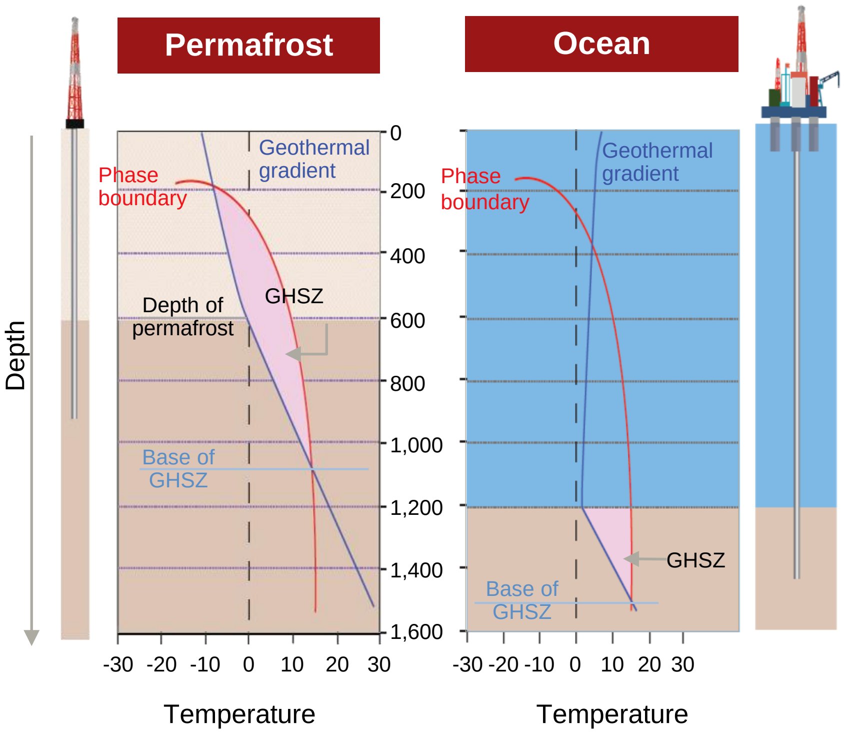
Gas hydrates stability zones can be found in many places and vary significantly in depth and thickness

Illustrative gas hydrate stability zones

Depth (m), temperature (ºc)



Caution: illustrative only. Conditions vary from place to place, depending on actual water temperature, salinity, thermal gradient *etc*.

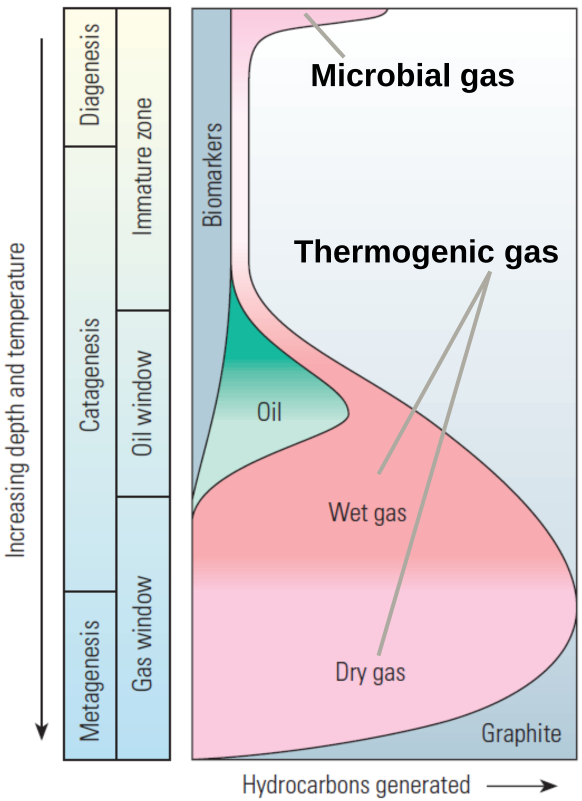
- **To determine where gas hydrates could form, one must first look at pressure and temperature conditions**. The latter differ depending whether hydrates are in a marine setting or in permafrost, and from place to place within the setting (*e.g.* salinity).
- **In marine settings**, pressure and temperature conditions that fall within the gas-hydrates phase boundary can typically be encountered in water depths below 300-600m[1]. However, in the ocean, gas hydrates cannot form since there is not enough gas[2]. Therefore, one must consider the seafloor as the top of the gas hydrate stability zone (GHSZ). Below the seafloor, temperatures gradually increase with depth. As hydrates cannot form above a certain temperature, this limits the depth of the GHSZ to a few hundred meters below the seafloor (typically 500-1,000m). Note that deeper water settings with a colder bottom water temperature and greater pressure will permit thicker gas hydrate stability zones.
- **In permafrost**, and unlike marine settings, temperature always increases with depth. However, the geothermal gradient[3] in the permafrost is higher than the average for earth and the increase is therefore quicker from the surface down to the base of the permafrost where it is at 0°C. Temperature and pressure conditions that meet GHSZ requirements can be found within the permafrost at depths typically below 100-300m, and up to hundreds of meters deep, as well as below the permafrost. Note that the thicker the permafrost, the deeper the base of the GHSZ.

1. Beneath the relatively warm, well-mixed surface layer, ocean water temperature declines rapidly down to depths of 200-1,000 meters. Then, it starts to decrease much more gradually towards the seafloor where it typically reaches temperature of 3-4°C; 2. For hydrates to form, gas concentration must be higher than its solubility in water, a condition that is not met in the ocean; 3. Geothermal gradient is the rate of increase in temperature per unit depth in the earth. Although the geothermal gradient varies from place to place, it averages 25 to 30 °C/km.

Source: A.T. Kearney Energy Transition Institute analysis; Giavarini and Hester (2011), "Gas Hydrates Immense Energy Potential and Environmental Challenges"

The availability of sufficient gas is a critical factor for the formation of gas hydrates, which limits the gas hydrate occurrence zone

Natural gas formation[1]



- **Given pressure and temperature conditions are met, gas availability is the most important factor controlling the formation, quantity and distribution of gas hydrates.** In most places that satisfy stability conditions, gas hydrates do not exist, because there is not sufficient gas supply. Hydrate-forming gas can originate from either microbial activity (diagenesis phase, forming microbial gas), or from high-temperature cracking of deep petroleum (catagenesis and metagenesis phases, forming thermogenic gas)[2].
- **Microbial gas[3] is thought to be the dominant source of hydrate-forming gas in marine settings.** Unlike thermogenic gas, microbial gas forms at relatively low depths and temperatures. In the absence of other sources of natural gas, it is largely correlated with the quantity of organic material in place, and is therefore limited by the total organic carbon distribution. In the ocean, the highest organic carbon distribution is found around the continental margin, where the continental shelf transitions to deep ocean. Thermogenic gas, meanwhile, is most common in conventional gas reservoirs. However, thermal cracking that produces thermogenic gas tends to occur at depths below the gas hydrate stability zone. The presence of methane produced in this way indicates the existence of migration pathways, since the gas needs to move upwards.
- **Gas delivery is essential[4].** It is believed that in deposits where *in situ* microbial gas is the only source of gas, the concentration would not be sufficient (just a few percent). Migration pathways (e.g. along fault and fracture) are therefore critical to allow sufficient accumulations of gas and affect the concentration and distribution of gas hydrates resources. Gas transport through the rock matrix typically produces high concentration accumulations at the base of the gas-hydrate stability zone, whereas fractures can allow gas transport higher in the stability zone[5].

1. For more information about these concepts, refer to the A.T. Kearney Energy Transition Institute "Introduction to Natural Gas FactBook"; 2. It can also result from sedimentation, which causes pre-existing gas hydrate to decompose, or from old conventional gas traps that were converted to gas hydrates during glacial episodes in permafrost regions; 3. Also known as biogenic gas; 5. Gas hydrate concentration is usually greatest at the base of the GHSZ, because gas hydrate is self-trapping. Once it forms, it does not move, and it renders the rock impermeable to further gas flow. For more information, refer to Appendix 3.

Source: Tissot et al. (1974), "Influence of Nature and Diagenesis of Organic Matter in Formation of Petroleum"; Kleinberg (2009), "Exploration strategy for economically significant accumulations of marine gas hydrate"; Giavarini and Hester (2011), "Gas Hydrates Immense Energy Potential and Environmental Challenges"

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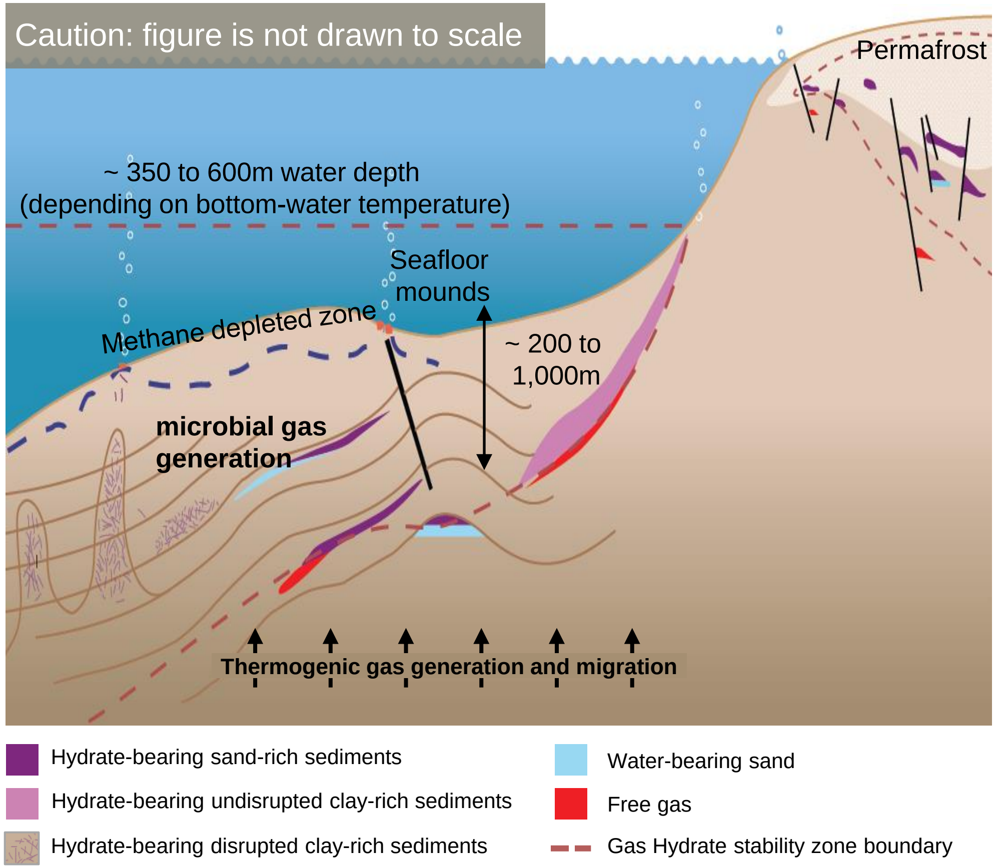
Gas hydrates can be found in different types of geological settings, with 98% of hydrate resources estimated offshore and 2% in permafrost

Schematic depiction of common gas hydrate geological environment



- When reservoir and pressure conditions are met and enough gas supply is available[1], several other factors will also affect gas hydrate formation, quantity and distribution: especially (1) the reservoir lithology[2]; (2) the source of gas-hydrate forming gas and migration pathways; and (3) the location.
- **Seafloor mounds and shallow deposits**. Theoretically, there is not enough microbial gas near the seafloor for gas hydrate to form. However, when migration pathways exist, thermogenic and microbial[3] gas may vent along fractures or faults from deeper locations in sufficient quantity to allow for gas hydrate formation. Gas hydrate can fill pore space, but also, when the flux is high enough, grow as massive chunks, lenses, and nodules. When the gas flux travels up to the seafloor, it can even result in seafloor accumulation, known as a "seafloor mound", which can extend several meters above the seafloor.
- **Deep accumulations**. At large depths, gas hydrates are not able to overcome the lithostatic pressure between the sediments and are usually restricted to filling pore space between the sediments, or filling fractures. The saturation and pore space occupancy will usually depend on the type of sediments. In clay or in fine silt, it will be mainly in a low saturation network of tiny fractures. In coarse-grained sediments, such as sand or coarse silt, it can accumulate in layers with high saturation[4].

1. Refer to previous slides for more information; 2. Lithology is the description of rock composition and texture; 3. Microbial gas is also known as biogenic gas; 4. Note that there are also rare occurrence where gas hydrates occur within consolidated host sediments (e.g. observed in Qilian Basin in China or in the Messoyakha field in Russia). There is a lack of data for this type of accumulation.

Source: Boswell et al. (2014), "Methane hydrates"; Max et al. (2013), "Natural Gas Hydrate - Arctic Ocean Deepwater Resource Potential"

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Permeability, saturation and the presence of mobile “fluid” will vary according to gas-hydrate bearing reservoir characteristics

Classification of gas-hydrate reservoir characteristics from Boswell ET AL.[1]

Types

Permeability (md): 0.5 – 0.1 – 0.0001

- **Massive mounds on the seafloor**
- **Sand-rich host sediments**
- **Clay-rich host sediments**
- **Consolidated host sediments**

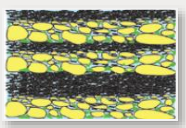
Gas hydrate saturation: 90% – 50% – 40% – 10% – 1%

Sub-types

Massively bedded (MB)

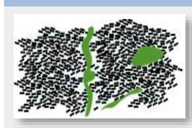
These types of accumulation have been found, for instance, in the Mallik project in Canada. Generally considered the easiest to produce.

Thinly inter-bedded (TB)



Sand layers are thinly inter-bedded with individual layers of muds. Since the latter are good conductors for the reservoir’s thermal energy, they may provide strong flow rate2.

Grain-displacing in disrupted, deformed sediments



Pervasive grain displacing forms such as veins, lenses and nodules. Can be found in strata-bound and chimney structures.

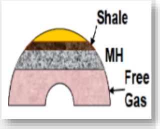
Pore-filling in undisrupted sediments

Includes disseminated pore filling gas hydrates at low concentration within largely undisrupted sediments.

Classes

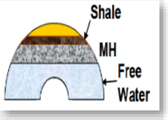
Class 1: reservoir underlain by free gas

This class is attractive, since it would allow simultaneous production of free gas. However, it seems not to be very common in nature[3]. It would usually occur at the base of the gas hydrate stability zone.



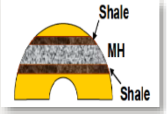
Class 2: reservoir underlain by free water

This class may be the most common production target[4]. Water would help depressurization, but raise water co-production challenges[5].



Class 3: confined reservoir

The reservoir is fully saturated with hydrates and “sandwiched” between impermeable layers such as shale layers. It has been the most studied class since its confined nature was fitted for experiments, but may not be ideal for commercial purposes.

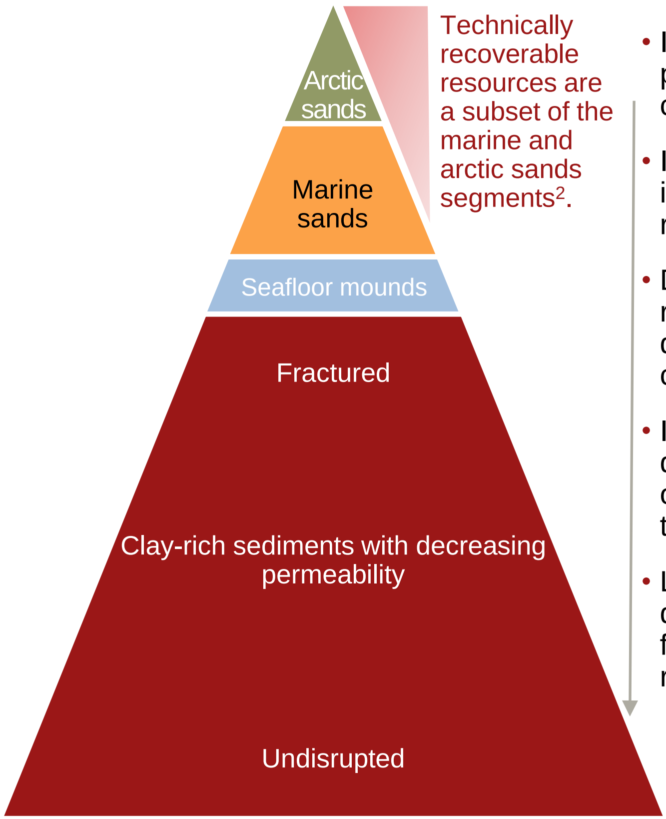


1. Gas hydrates are represented in green. Classes are for sand-rich host sediments only, since the others are less likely to be developed, limiting the need for categorization. Note that Boswell *et al* equally present a Class 4 setting, which describes locations where marine hydrates occur at low saturation (typically <10%) and are dispersed in unconfined coarse materials; 2. As demonstrated during Nankai production test; 3. This is because, contrary to what is commonly believed, gas hydrates do not constitute a very good seal and are likely to let gas escape; 4. This type of class can be found at the base, or within the gas hydrate stability zone; 5. For more information on water co-production challenges, refer to slide 44.

Source: Boswell et al. (2011), “Gas hydrate accumulation types and their application to numerical simulation”

High concentrations of gas hydrates hosted in sand-rich sediments stand out as the only technically recoverable resources in the near term

Gas hydrate: Gas-in-Place resources[1]



- Increasing production challenges
- Increasing in-place resources
- Decreasing reservoir quality and concentration
- Increasing dependence on technology
- Likely decreasing fractional recovery

- **High-concentration pore-filling gas hydrates hosted in sand-rich sediments**, whether beneath the seafloor on the ocean margin, or within and below the permafrost, **stand out as the only potential technically recoverable resources in the near term.** This is because these deposits exhibit high intrinsic permeability, allowing
  – Sufficient water and gas mobility for gas hydrates to accumulate at a high saturation level;
  – Pressure and/or temperature perturbations to spread into the sediment and achieve dissociation[2].
- **Other types of hydrate accumulations are unlikely to be developed in coming decades[3]**.
  – Clay- and silt-rich sediments exhibit low permeability and porosity resulting in low saturation (less than 10% in pore volume). They are the most prevalent type of deposits, but tend to be very disseminated.
  – Seafloor mounds can contain hydrates with high saturation. But, they are highly dependent on local migration pathways, which are usually hard to predict; and they are relatively small and disseminated.
- **Pore-filling gas-hydrate accumulations in sand sediments would also be less subject to geomechanical hazards** and subsidence effects than alternative reservoirs. As a rule of thumb, the deeper the reservoir, the better. However, other factors may offset the potentially higher mechanical stability advantages, including the concentration/saturation and the cost of drilling[4].

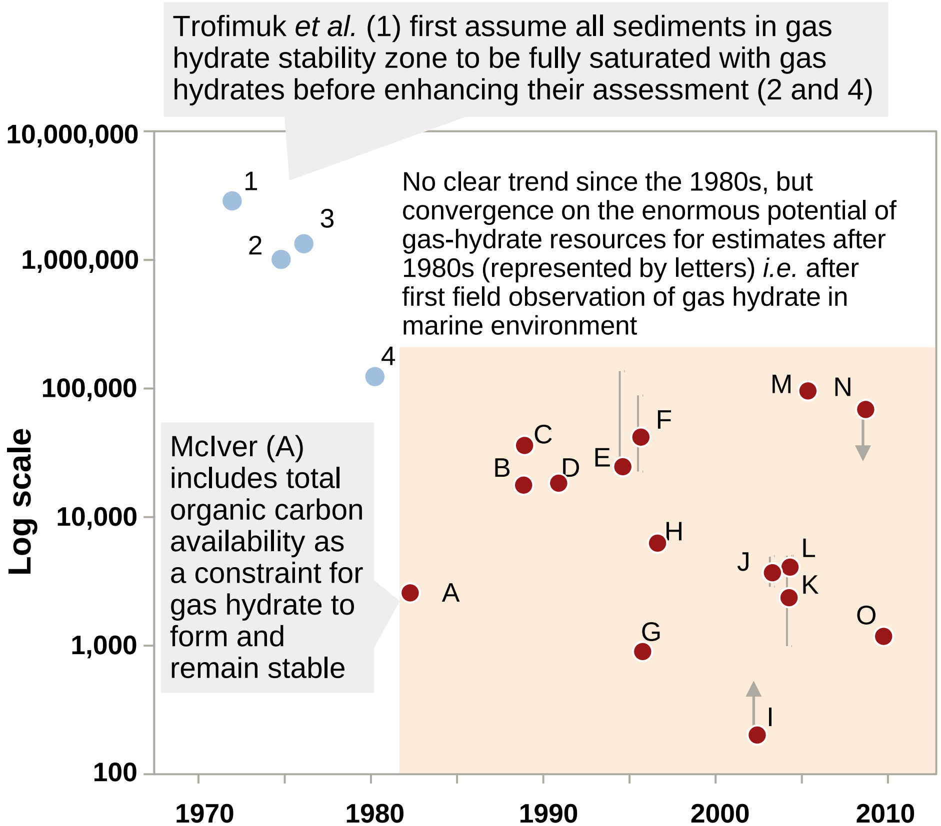
1. Consolidated host sediments are not shown by the author of the graph since they are believe to host negligible quantities of hydrates; 2. For more information, refer to Section 3; 3. Grain displacing, moderate-to-low concentration, veins and nodules concentrated in "chimney structures" and typically housed in clay-rich sediment still retain some marginal interest in some nations, despite the lack of a demonstrated (or even conceived) production approach. These deposits would require wholly different production approaches and would be as different from sand-hosted hydrates as shale gas is from conventional gas; 4. Deeper reservoir may indeed be less subject to geomechanical hazards than shallow reservoirs and should require less energy for gas hydrate dissociation.

Source: Boswell et al. (2014), “Methane hydrates”; Ruppel (2011), “Methane hydrates and the future of natural gas”

Global assessments of gas hydrate resources conducted over past decades range over several orders of magnitude

Global estimates OF gas hydrates resources

Gas-in-place estimates in tcm according to publication date



- **The vast energy resource potential expected to be housed in gas hydrates is one of the primary drivers for their exploration**. Gas hydrate resource estimates usually rely on top-down, gas-in-place assessment, primarily providing an upper-bound value of the gas-hydrate endowment.
- As a result of a better understanding of gas hydrate formation, new field data, and improvements in probabilistic modeling, estimates have decreased by an order of magnitude, compared to those prior to the 1980s. Since that time, no clear trend has emerged and estimates continue to range over several orders of magnitude. **Yet, even the most conservative assessment concludes that gas hydrates do host a very significant share of the earth's organic carbon.**
- **The viability of resource recovery depends less on the gross quantity of the resource than on its concentration.** Gas-hydrate-bearing sands were excluded from gas-in-place discussion in most cases (they were deemed to be negligible compared to other deposits). Since gas hydrates hosted in sand are now considered the most likely target deposit in the near-term (and tend to occur more frequently than initially thought), these days assessments of global gas-in-place often take second place to evaluation with an emphasis on high-concentration sand-hosted resources.

1. Trofimuk *et al.*; 2. Trofimuk *et al.*; 3. Cherskiy and Tsarev; 4. Trofimuk *et al.*; [A]McIver; [B]Kvenvolden; [C]Kvenvolden and Claypool; [D]MacDonald; [E]Gornitz and Fung; [F]Harvey and Huang; [G]Ginsburg and Soloviev; [H]Holbrook et al.; [I]Soloviev; [J]Milkov et al.; [K]Milkov; [L]Buffet and Archer; [M]Klauda and Sandler; [N]Wood and Jung; [O]archer *et al.*

Source: Boswell and Collett (2010), "Current perspectives on gas hydrate resources"; Kleinberg and Brewer (2001), "Probing Gas Hydrate Deposits"

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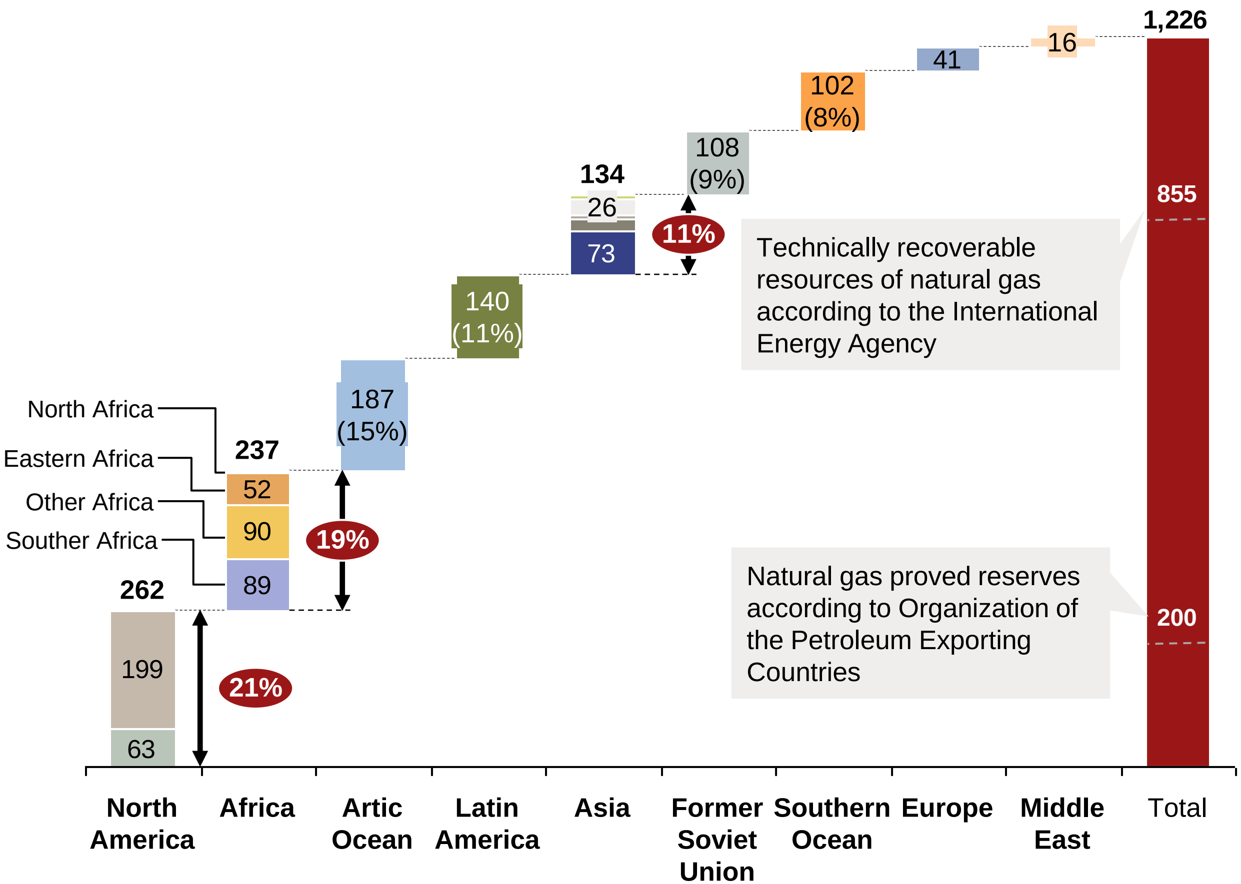
Highly promising gas hydrates in sand reservoirs are gaining attention and are today assessed through a petroleum system approach

Estimated Gas-in-place in Hydrate Bearing Sand

HEI and IIASA estimates[1], tcm



- Due to the growing consensus that high saturation gas-hydrate resources hosted in sand-rich sediments are the most amenable for exploration and production, **resource evaluation efforts have re-focused on sand-deposits**, using a petroleum system approach to evaluate the resource potential.
- For instance, as part of the Global Energy Assessment conducted by the IIASA[1], HEI reviewed gas-in-place assessment by incorporating likely sand-distribution models and **came up with a median estimate of 1,226 tcm**. These results are consistent with other studies and correspond to substantial resource potential.
- Despite the intrinsic uncertainty of these estimates, **evaluation at the global scale seems sufficient at this stage**, but would be best completed and refined by in-depth evaluation at the basin level, as performed on the U.S. Alaska North Slope or offshore Japan in Nankai Trough.

1. HEI for Hydrate Energy International; IIASA for International Institute for Applied Systems Analysis. For more information, refer to Appendix 9.

Source: Johnson (2011), “Global Resource Potential of Gas Hydrate – A New Calculation”; Organization of the Petroleum Exporting Countries (2014), “Annual Statistical Bulletin”; International Energy Agency (2013), “World Energy Outlook 2013”

Thick and highly-concentrated gas-hydrate deposits are relatively easy to recognize and characterize using conventional exploration techniques

Schematic of gas hydrate exploration process[1]

Simplified process for high concentration gas-hydrates sand-rich sediments

Geological survey

- Based on geological data, basins can be modelled to identify and evaluate prospective areas for gas-hydrates deposits based on pressure and temperature conditions, source gas generation, gas migration pathways and sediments lithology[2]. It is usually performed using petroleum system modelling software enriched with gas-hydrates functionalities, such as that developed by German SUGAR project for PetroMod software.

Geophysical survey

- Once prospective accumulations have been identified, remote-sensing techniques are used to detect and characterize prospects. This can be achieved by sending seismic signals (bottom simulating reflector), by seismic inversion[3], by conventional 2D or 3D seismic imagery or by acoustic data acquisition. Controlled source electromagnetic survey (CSEM) has also gained momentum offshore and proved effective in detecting gas hydrates.

Well drilling

- This phase consists of drilling an exploratory well to test prospective accumulations identified during basin modeling and validated by geophysical analysis. This requires employing a drilling rig (onshore rig in permafrost, or an offshore drillship for marine settings). Due to the costs of drilling rigs, only a few drilling campaigns have been carried out so far.

Logging

- To further confirm the presence and saturation of gas hydrates, direct measurements of formation can be performed (known as logging). Measurements including electrical resistivity, sonic wave velocity, nuclear magnetic resonance relaxation time or gamma-gamma density measurement will help assess the amount of gas hydrates present at any particular depth. Logging can be performed while drilling or by employing an electrical cable to lower tools into the borehole and transmit data (known as wireline).

Coring

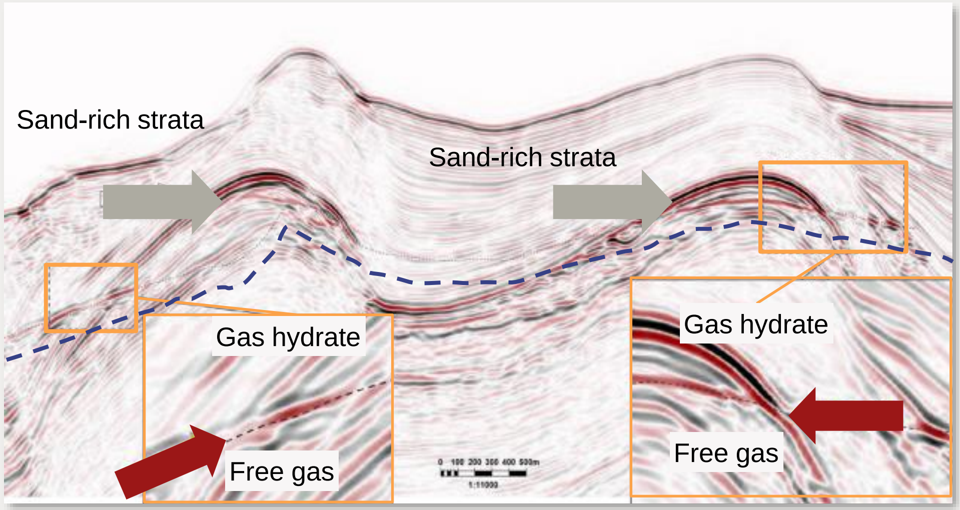
- Direct sampling, also known as coring, can be performed to observe directly the composition of gas hydrates (hydrate structure, source of hydrate-forming gas etc…) and surrounding sediments. For gas hydrates to remain stable outside their stability zone, coring needs to be performed using pressurized system.

1. Note that the process is not fully sequential. Logging can be performed while drilling, and geophysical survey can use data acquired during previous logging or drilling campaigns; 2. For more information on petroleum system approach, please refer to slides 22 to 26; 3. Seismic inversion consists in extracting quantitative information about reservoir rocks and fluid parameters from seismic data.

Source: Dai et al. (2008), "Exploration for gas hydrates in the deepwater, northern Gulf of Mexico: Part I. A seismic approach based on geologic model, inversion, and rock physics properties"; Kleinberg (2009), "Exploration strategy for economically significant accumulations of marine gas hydrate"

Bottom simulating reflector is useful to identify gas hydrate occurrence, but may be misleading

Example of BSR features in an offshore basin



Bottom simulating reflector / base of gas hydrate stability zone

The potentially strong acoustic impedance contrast between gas-hydrate bearing sediments and adjacent sediments that contain free gas or water can cause a high-amplitude reflection. The reflection depth depends on the temperature and pressure conditions conducive to hydrate stability. Typically, it runs parallel to the seafloor. Such interfaces are known as bottom-simulating reflectors (BSRs), and the seismic reflections they cause often cut across structural and stratigraphic reflections.

- **The seismic bottom simulating reflector (BSR) has long been considered as a definitive indicator of gas hydrate presence** and the search for BSRs has therefore driven many gas hydrate exploration campaigns. However, gas hydrates have been recovered in sites where BSR was absent, whereas some sites with a strong BSR have been found to contain few or no hydrates.
- **In fact, BSR indicates primarily the delineation between free gas and hydrate-bearing sediment**. It has been used for a long time by the oil and gas industry to avoid gas hydrates when drilling for conventional resources.
- **Interpretation may be misleading since** (i) a very small amount of free gas can produce a strong BSR and (ii) a continuous seismic reflector does not imply a continuous gas-saturated layer[1].
- **BSR remains, indisputably, very useful** to detect hydrates and identify the base of gas-hydrate stability zone, **but it is not an indicator of gas-hydrate concentration**. So it is certainly not sufficient to identify accumulations concentrated enough to become prospective targets of exploration campaigns.

Note: Picture credit: NETL (2014), “Gas Hydrate Assessment in the Northern Gulf of Mexico: Preliminary Results Reveal New Prospects”; 1. Otherwise said, it means that BSR is very sensitive to the occurrence of free gas and relatively insensitive to the abundance and concentration of gas hydrates.
Source: Kleinberg (2009), “Exploration strategy for economically significant accumulations of marine gas hydrate”; Boswell (2014), “Developments in Marine Gas Hydrate Exploration”; Birchwood et al. (2010), “Developments in Gas Hydrates” in Schlumberger Oilfield Review, Vol.22 Issue.1

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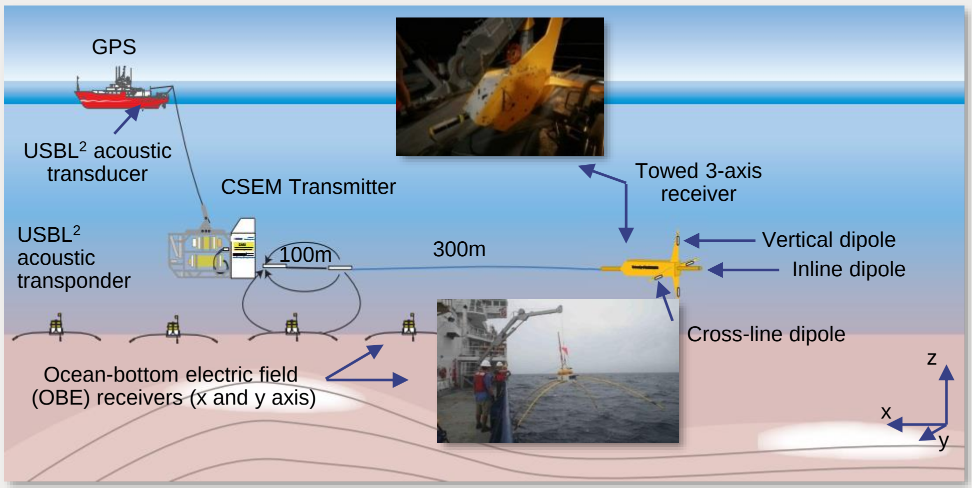
Geophysical surveys have gained momentum over the last decade and shown promising results

Marine electro-magnetic surveying of gas hydrates[1]



CSEM consists in deploying seafloor electric and magnetic field recorders and an electric dipole transmitter deep-towed above the seafloor (~50-100 meters) to detect resistivity variations. CSEM has been tested in different places including offshore Svalbard (Norway) by researchers from the University of Southampton, in the Black Sea (Romania) and on the Hikurangi Margin (New Zealand) in the framework of the German SUGAR project, and extensively in the Gulf of Mexico as part of the Joint Industry Project, as well as more recently in Japan, using in both cases a technology developed by the Scripps Institution of Oceanography.

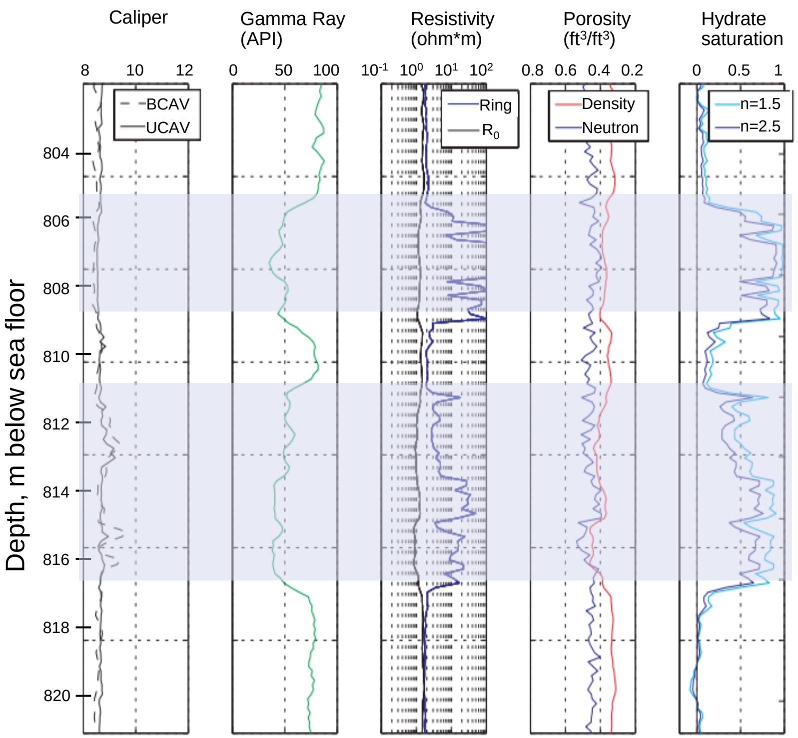
- **Geophysical surveys have proved useful for detecting and quantifying gas-hydrate deposits.** Current electromagnetic and conventional seismic technologies can detect increases in sediments' electrical resistivity and acoustic wave velocity induced by gas-hydrate presence, respectively.
- **Velocities are usually obtained by inversion of seismic data for acoustic impedance**[3]. As part of the Joint Industry Project, geophysicists managed to convert impedance data into gas-saturation estimates, successfully tested by drilling with a high success rate[4].
- **Controlled-source electromagnetic (CSEM) survey technologies have gained interest for gas-hydrate exploration**. Despite limited lateral and vertical resolution, some recent studies say CSEM may be a powerful tool in gas-hydrate exploration, if used in conjunction with seismic velocity, in order to discriminate between gas hydrates and free gas[5].
- **Together with other surveys** such as bottom-simulating reflector or hydro-acoustic detection to detect gas bubbles and flares, geophysical surveys have been enhanced to detect and characterize gas hydrate deposits effectively. However, logging remains essential for assessing the concentration of gas hydrates in more detail.

1. Schematic from NETL and picture courtesy from Scripps Institution of Oceanography; 2. USBL for ultra-short baseline; 3. The original reflectivity data is converted from an interface property to a rock property, known as impedance; 4. Among the 7 wells drilled, 4 out of 5 wells that were predicted to have hydrates at high saturations encountered saturation above 50% (WesternGeco); 5. Free gas is equally resistive as gas hydrates, but reduces seismic velocity. Conversely, while gas hydrates increase seismic velocity, free gas reduces it.

Source: Weitemeyer and Constable (2010), "Mapping Shallow geology and gas hydrate with marine CSEM surveys"; Dai et al. (2008), "Exploration for gas hydrates in the deepwater, northern Gulf of Mexico: Part I. A seismic approach based on geologic model, inversion, and rock physics properties"; Goswami et al. (2013), "CSEM Survey of a Methane Vent Site, Offshore West Svalbard"

Density log-derived porosity, electrical log, acoustic log and nuclear magnetic resonance measurements have proved successful in determining hydrate saturation

Well logs from hydrate well - Walker Ridge 313 Site, Gulf of Mexico



High resistivities are the clearest indications of gas hydrates depicted by pink shading. Estimated hydrate saturation range from 40% to more than 75%

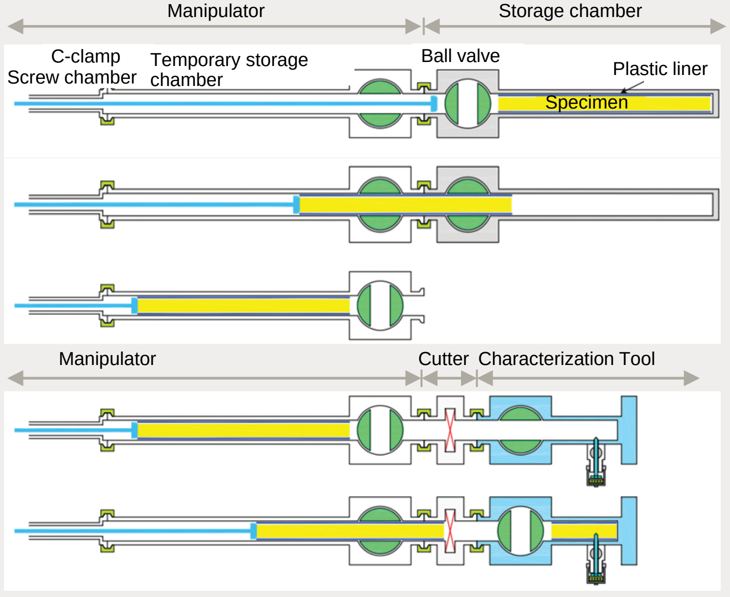
- **In order to validate geological and geophysical surveys, and to characterize the amount of hydrate, logging is essential**. As part of logging, gamma-gamma density measurement gives a measure of porosity, *i.e.* the volume fraction of the rock occupied by water and hydrates, but cannot distinguish water from hydrates. To distinguish water from gas hydrates, there are three main approaches: electrical resistivity, sound velocity and nuclear magnetic resonance.
- As underlined by electromagnetic surveying, gas hydrates and most solid minerals are good electrical insulators, whereas saltwater is a good conductor. **Therefore, resistivity provides a good indication of gas hydrates presence**, and can even provide an estimate of hydrate saturation when compared with porosity. However, this requires a good knowledge of the resistivity of pore water, which may not be straightforward[1].
- **Predicting gas-hydrate saturation can also be derived from sound velocity**. The latter varies depending on the acoustic properties and proportion of the sediments materials. However, it also varies according to their assembly. For gas hydrates, it depends greatly on where they are located in the sediments (*e.g.* pore-filling, as coating on grains) and models best fits when hydrate acts as a component of the grain matrix.
- **Finally, density log derived porosities can be combined with the nuclear magnetic resonance** (NMR) **approach**. NMR is based on the magnetic resonance of hydrogen nuclei[2]. It detects the pore water, and by subtracting gamma-ray measure of water plus hydrate, it allows the determination of the amount of gas hydrates present at any particular depth[3].

1. Pore water resistivity is usually not equal to that of seawater; 2. This is because typical pore-filling fluids such as water, oil or natural gas are rich in hydrogen; 3. NMR from solids disappears rapidly. NMR from liquids decays more slowly and is easily detected. Since hydrates are solid, the signal from them decays too rapidly to be detected.

Source: Birchwood et al. (2010), "Developments in Gas Hydrates" in Schlumberger Oilfield Review, Vol.22 Issue.1; Kleinberg and Brewer (2001), "Probing Gas Hydrate Deposits"; McConnell et al. (2009), Gulf of Mexico Gas Hydrate Joint Industry Project Leg II: Walker Ridge 313 Site Summary"

Pressure coring technologies have been refined and enriched to allow for extensive analysis of gas-hydrate samples under in situ conditions

Schematic pressure core manipulation



[1] The manipulator (MAN) couples with the storage chamber, and fluid pressures are equalized at the target pressure (p0) before opening the ball valve. [2] The MAN captures the core and transfers it to the temporary storage chamber. [3] Ball valves are closed, and the depressurized storage chamber is separated. [4] The selected characterization tool is coupled to the MAN and is pressurized to p0. [5] Ball valves are opened, and the core is pushed into the characterization tool; stand-alone characterization tools may be detached after retrieving the rest of the core and closing valves.

- **Gas hydrates dissociate outside their pressure and temperature stability zone, making sampling challenging**. And yet, performing measurements and tests on gas-hydrate samples is essential for a proper characterization. As a consequence, pressure coring technologies (PCT) have been developed in order to recover cores and preserve the samples under *in situ* pressure and temperature conditions at all times.
- Originally, PCT developed in the 1980s and 1990s were mainly about coring and core transfer. **Over the last decade, efforts have focused on handling, manipulation tools and characterization chambers** to measure mechanical, electrical, biological and hydraulic properties of gas hydrates under *in situ* pressure, temperature and stress conditions.
- Geotek has, for instance, developed a **Pressure Core Analysis and Transfer System** (PCATS) to ensure (i) coring transfer from a manipulator into a measurement chamber, (ii) core analysis providing simple geophysical data, (iii) core sub-sample and transfer into pressure chambers for transport, future analysis or storage; all of it gathered in a transportable, container-type system. GeorgiaTech also developed, with support of the DoE-Chevron Gulf of Mexico Gas Hydrates Joint Industry Project, the instrumented pressure testing chamber (IPTC), subsequently improved and completed with new testing and manipulation devices known as pressure core characterization tools (PCCT). These tools have been successfully used in Nankai Trough in 2012 to prepare the production test (70% recovery rate with good overall conditions, and effective transfer to cold room for PCCT analysis).

Source: Santamarina et al. (2012), "Pressure Core Characterization Tools for Hydrate-Bearing Sediments"; Yamamoto et al. (2012), "Pressure Core Sampling in the Eastern Nankai Trough"

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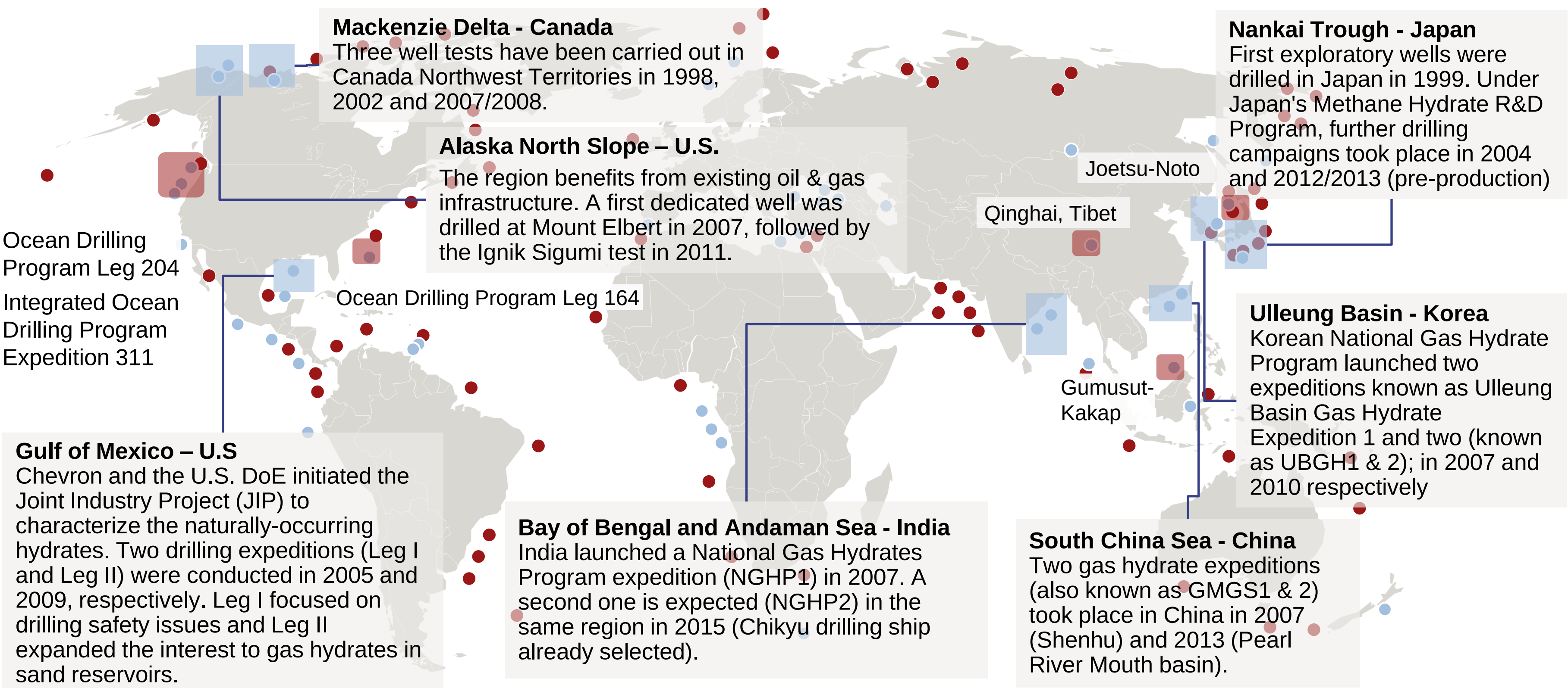
Exploratory drilling campaigns have been relatively rare and have been conducted in Asia and North America

Main Gas hydrates exploration campaigns – drilling programs[1]



1. This map is not comprehensive. Academic projects have also been conducted in the U.S., notably the Ocean Drilling Program (ODP) Leg 164 beneath the Blake Ridge (offshore South Carolina) in 1995, the ODP Leg 204, offshore Oregon in 2004, the Integrated Ocean Drilling Program Expedition 311 on the northern Cascadia margin (offshore Vancouver) in 2005. A project has also been completed in Malaysia (Gumusut-Kakap project), but mainly due to concern on drilling hazards for the gas fields. In addition, China has conducted a permafrost gas-hydrate drilling and testing project in Qinghai, Tibet, with drilling in 2007, 2009 and 201 Finally, Japan is also exploring prospect west, the Joetsu-Noto; 2. Formerly the Mineral Management Service.

Source: A.T. Kearney Energy Transition Institute analysis; U.S. Geological Survey (2014), "International Gas Hydrate Research"; U.S. DoE (2014), "Marine Methane Hydrate Field Research Plan"; U.S. DoE (2014), "Characterizing Natural Gas Hydrates in the Deep Water Gulf of Mexico: Applications for Safe Exploration and Production Activities".

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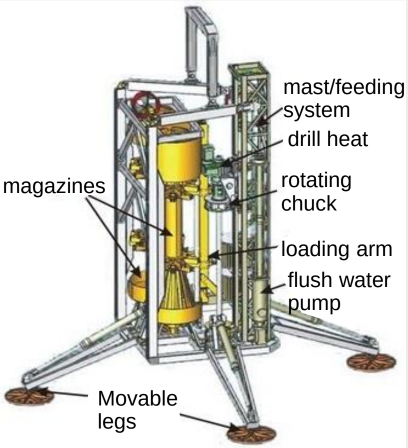
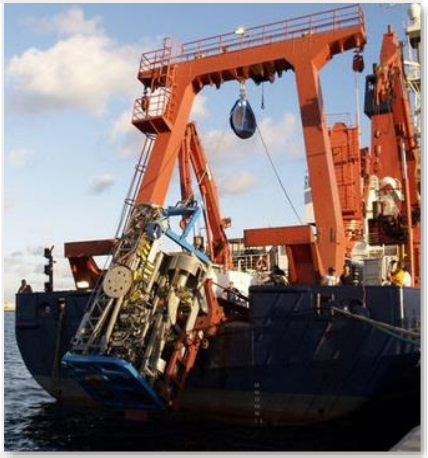
Exploration proved to be successful with conventional technologies, but needs to be further tailored to gas-hydrate properties, if costs are to be reduced

Example of a transportable small-scale seafloor drill rig (Mebo) – sugar project





SUGAR stands for Submarine Gas Hydrate Reservoirs. It is a collaborative R&D project launched in 2008 in Germany, coordinated by the Helmholtz Centre for Ocean Research Kiel (GEOMAR). As of 2015, it starts its third three-year phase. During the project, a transportable seafloor drilling rig known as MeBo (for Meeresboden-Bohrgerät) has been developed. MeBo is lowered to the sea bed with a steel armoured umbilical and operated remotely from the vessel. It can be deployed from conventional vessels (80 m) in water depths of up to 2000 m and is so far used to recover cores of unconsolidated sediments and rocks up to about 70 m in length.

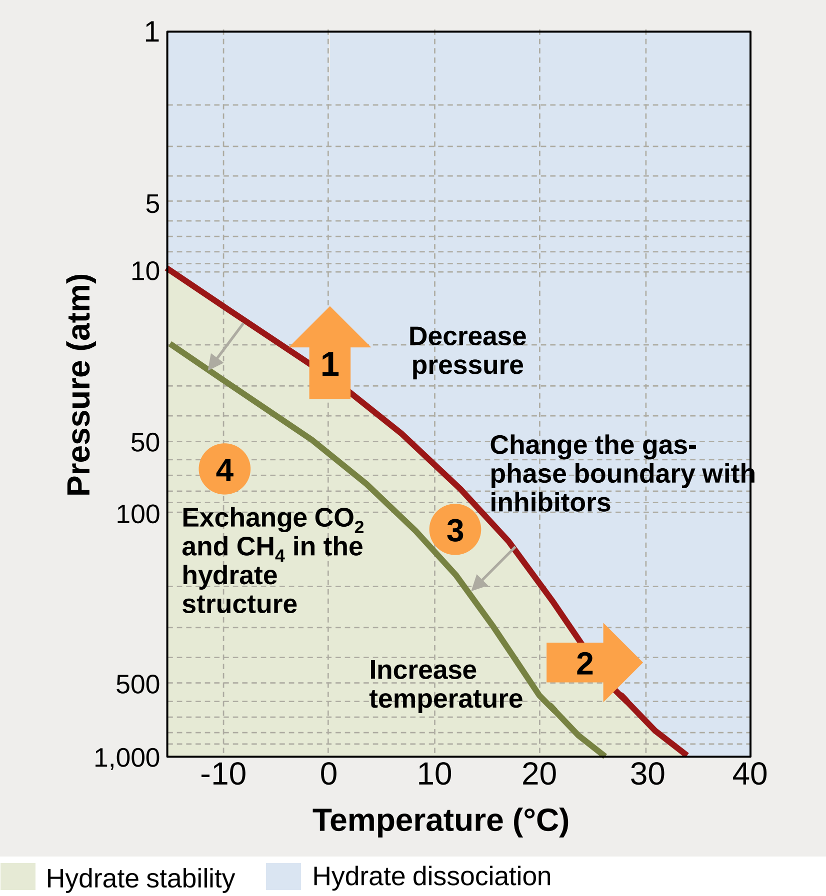
- **Gas-hydrate exploration using conventional technologies has proved successful, with only minor modifications to those technologies.** Except the pressure-coring system, all technologies were derived directly from conventional exploration. Most improvements in the past decade have resulted from a better understanding of the properties of gas hydrates and how they respond to geophysical surveys.
- **However, there are still several challenges for gas-hydrates exploration.** i) The area to be explored: gas-hydrate accumulations are typically more disseminated than conventional gas deposits for equivalent energy resource potential1. ii) Resolution: gas-hydrate remote exploration would benefit from higher resolution due to the importance of distinguishing water from gas[2]. iii) The shallow nature of gas hydrates: logging is critical to detect hydrates but has been primarily developed for deep formations and may need to be improved for shallow sediments.
- **Finally, conventional technologies that proved useful to demonstrate gas hydrate recoverability may not be viable economically.** Compared to conventional gas resources, hydrates deposits tend to be less concentrated and abundant1. As a consequence, if gas hydrate is to be commercially developed, exploration costs need to be reduced. This could be achieved by tailored technologies, and leveraging gas-hydrate properties. For instance, one could use lighter drilling equipment on smaller drilling vessels, as developed in Germany by the SUGAR project.

1. For more information, refer to slide 15; 2. In addition, improving imaging resolution could be useful to remotely monitor reservoir variations during production.
Source: Ruppel (2011), “Methane Hydrates and the Future of Natural Gas”; Max et al. (2013), “Natural Gas Hydrate - Arctic Ocean Deepwater Resource Potential; Consortium for Ocean Leadership (2013), "Marine Methane Hydrate Field research Plan”; Moridis et al. (2011), “Challenges, Uncertainties, and Issues Facing Gas Production From Gas-Hydrate Deposits

3. Production

Production of gas from hydrates requires the dissociation of the hydrate structure

Principle of GaS hydrate dissociation - Pressure (atm), Temperature (oC)



- **Production of gas from hydrates involves dissociating gas molecules from the water entrapping them.** For this to happen, gas hydrates must be moved out of their stability zone. This can be achieved by three methods:
  - Reducing the pressure of the formation;
  - Increasing the temperature of the formation;
  - Changing the formation's chemistry.
- **This has led to the development of four main production techniques[1]:**
  - Depressurization;
  - Thermal stimulation;
  - Chemical inhibitor injection;
  - CO_2 – CH_4 exchange.
- Aside from the question of its economic viability, **hydrate dissociation does not face any major technical hurdles in sand-bearing reservoirs.** However, production from fine-grained clay-rich reservoirs may require further R,D&D efforts: researchers are exploring thermal stimulation using microwave heating, for instance. Since gas hydrates in sand-rich sediments are the primary focus of R&D, there is little activity in alternative production techniques.

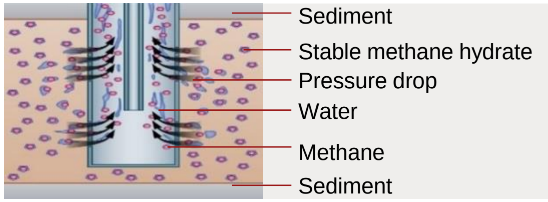
1. Note that those techniques can be combined. More information can be found on slide 41.
2. Source: Kurihara et al. (2011), "Gas production from methane hydrate reservoirs"

Several dissociation techniques have been investigated and tested

Description of Dissociation techniques[1]

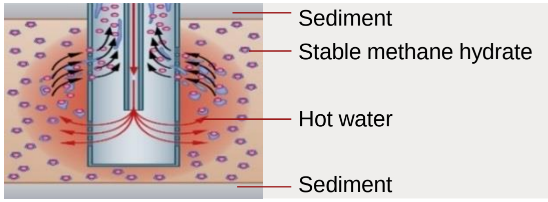
1 Depressuri-zation

Depressurization consists of lowering the pressure of the formation in order to progressively shift the deposit pressure below gas-hydrate stability pressure. It requires the presence of mobile fluids (free water), which can be removed using a downhole pump. As pressure gradient progresses within the reservoir, gas hydrates will dissociate into their water and gas components.



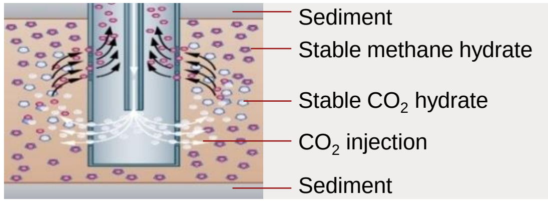
2 Thermal Stimulaion

Thermal stimulation involves heating the deposit above the gas-hydrate dissociation temperature in order to destabilize the hydrate formation. It can be achieved by directly heating the formation – *i.e.* by installing heaters downhole to increase near-wellbore temperature or by thermal flooding, which is done by injecting warm fluids such as hot brine or steam[2]. In practice, thermal production would probably be established between two wells, an injector and a producer.



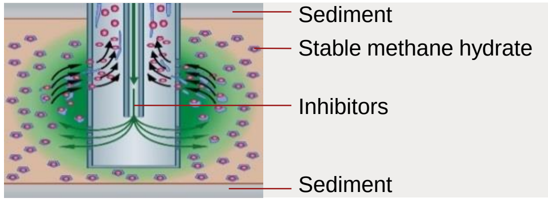
3 CO_2-CH_4 Exchange

CO_2-CH_4 exchange relies on the difference in thermodynamic stability between methane and CO_2 hydrates and works by injecting CO_2 into methane hydrates, resulting in the replacement of CH_4 molecules by CO_2 molecules within the crystalline compounds. Some experimental studies have shown that gas mixtures containing CO_2 and N_2 may be used to improve the exchange rate.



4 Inhibitor Injection

The injection of inhibitors is based on the injection of chemical compounds, such as salt or alcohol, into the gas hydrate reservoir in order to decrease the gas-hydrate stability phase boundary. Since the magnitude of this shift is limited, significant methane hydrate dissociation is not expected when using this method only.



1. While diagrams exhibit single-well application, multi-well settings with separated injecting and producing wells may be favored for all production techniques but depressurization; 2. More innovative ideas such as electromagnetic heating or microwave heating have also been discussed in the literature.

Source: Kurihara et al. (2011), "Gas production from methane hydrate reservoirs"; Ruppel (2011), "Methane Hydrates and the Future of Natural Gas"; Boswell et al. (2014), "Methane Hydrates"; Consortium for Ocean Leadership (2013), "Marine Methane Hydrate Field research Plan"

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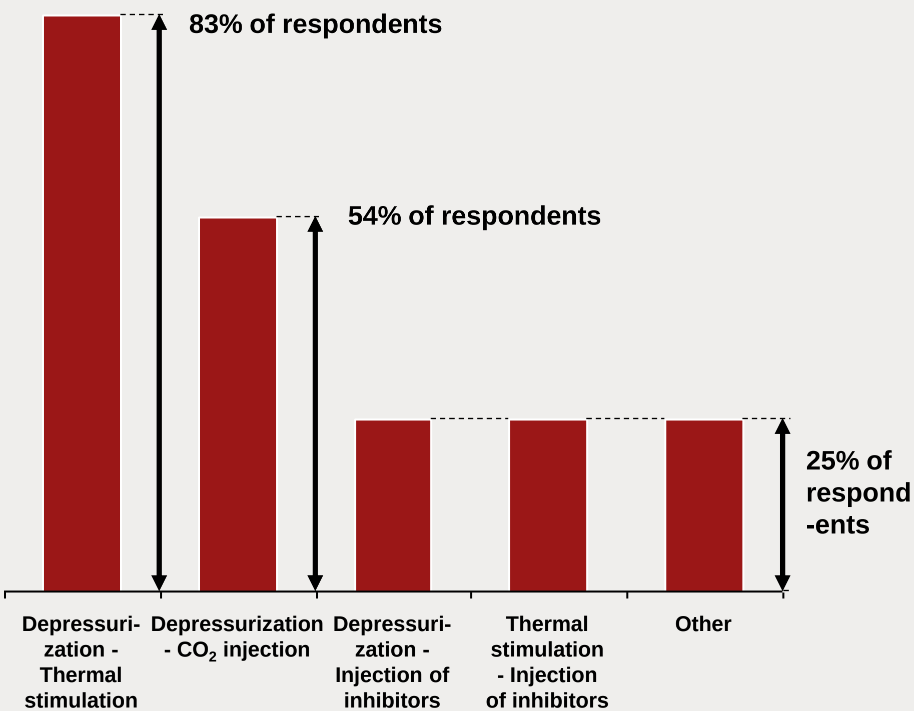
Dissociation techniques are not mutually exclusive and are likely to be combined

Dissociation techniques: most promising combinations

Results from A.T. Kearney Energy Transition Institute Gas Hydrates Survey[1]

In your opinion, which combination(s) of production techniques may be promising in gas-hydrate production?



- **Depressurization is likely to be combined with thermal stimulation,** such as hot-water injection near the borehole. Since pressure and temperature drop as gas hydrates are recovered, secondary gas hydrates may form. However, this has not yet been assessed empirically – the issue has not yet arisen in any short-term production test.
- **Depressurization may also be combined with CO_2 injection** if there are, for instance, severe geomechanical issues. This has been studied extensively by the German SUGAR project. In order to accelerate the exchange reaction and to limit the formation of CO_2-hydrates before the exchange occurs, the SUGAR project explored the injection of supercritically heated CO_2 and the addition of polymers to the CO_2 stream, and the combination of these techniques with depressurization and the supply of heat through a multiple-well system to achieve better production rates.
- **Chemical inhibitors such as glycol or salt may also be injected** to limit the reformation of hydrates, of ice or to improve the recovery rate.

1. The survey was submitted in October 2014 via the distribution list of the Fire In The Ice Newsletter. It aims to provide the view of gas-hydrates stakeholders. The full results can be found in Appendix B – Survey Analysis.

Source: A.T. Kearney Energy Transition Institute analysis

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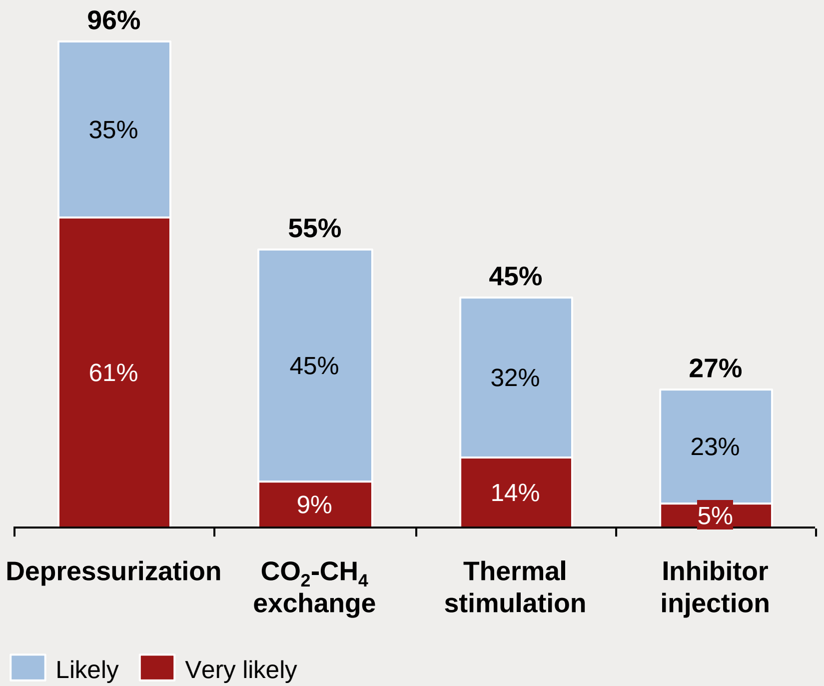
Depressurization stands out as the most efficient dissociation technique for gas hydrates in sand-rich reservoirs

Results from A.T. Kearney energy transition institute gas hydrates survey[1] % of respondents

To what extent do you believe the following production techniques are suitable for producing gas-hydrates accumulations in sand-rich sediments?



- **Depressurization is the most promising dissociation technique for sand reservoirs** and will most likely be used for further production tests or medium-term commercial developments. It was proved onshore during the 2007-2008 Mallik production test in Canada, and offshore in Japan in the 2013 Nankai Trough trial.
- **The prerequisite for depressurization to be effective is the presence of free water, since water acts as pressure-transmitter.** Contrary to what was commonly assumed, gas-hydrate deposits do contain mobile fluids, and tests in North America and Japan demonstrated the presence of 5-10% free water.
- **Depressurization relies on mature technologies and is expected to achieve high recovery rates, in the range of 50%,** in the most complex settings and theoretically around 80% in optimal settings. Depressurization is also less energy-intensive than thermal stimulation, which requires too much energy to have an effect on a sizeable accumulation[2].
- **However, depressurization requires the treatment of large volumes of co-produced water.** In addition, it is less efficient in shallow sediments, where pressure and temperature are lower and where more energy is required. It can also cause secondary hydrate formations in the well and near well-bore, and reduce permeability. In addition, as with all production techniques except CO_2-CH_4 exchange, it could face geomechanical instability.

1. The survey was submitted in October 2014 via the distribution list of the Fire In The Ice Newsletter. It aims to provide the stakeholders' view of gas-hydrates. The full results can be found in Appendix B – Survey Analysis; 2. In addition, artificial warming of the reservoir through thermal stimulation is partially offset by the endothermic nature of hydrate dissociation, which cools the hydrate formation. Refer to Appendix 10 for more information on hydrate depressurization process.

Source: Collett et al. (2000), "Growing interest in gas hydrates" in Schlumberger Oilfield Review, Vol.12 Issue.2; Birchwood et al. (2010), "Development in Gas Hydrates" in Schlumberger Oilfield Review, Vol. 22 Issue. 1; Boswell et al. (2014), "Methane Hydrates"

Interest in the CO_2-CH_4 (methane) exchange method has lost momentum because of reduced permeability and CO_2-sourcing difficulties

Advantages & challenges of CO_2-CH_4 exchange

PROS	**Geomechanical stability**	• Unlike other dissociation techniques, which transform ice into a mixture of water, sand and gas, CO_2-CH_4 exchange preserves a solid structure (with ice water hosting CO_2 instead of CH_4).
PROS	**CO_2 sequestration**	• CO_2-CH_4 exchange would reduce the GHG-emissions balance, as well as – as in enhanced oil recovery – providing an economic incentive in the form of CO_2 sequestration.
PROS	**Limited water co-production**	• During exchange, water remains in the reservoir (in the form of CO_2-hydrates). This avoids the need to remove and treat large volume of water.
PROS	**Shallow reservoir**	• CO_2-CH_4 exchange may better suited to tapping gas hydrates in shallow reservoirs: depressurization would require more energy in shallow reservoirs, however, because pressure is lower.
CONS	**Recovery efficiency**	• The retention of a solid hydrate structure limits the reservoir's ultimate permeability compared with dissociation techniques and CO_2 struggles to penetrate sufficiently throughout the formation.
CONS	**CO_2-hydrate formation**	• In the presence of water, CO_2-hydrates can form before any exchange occurs, reducing the permeability of the reservoir. This can be partially avoided by adding nitrogen to CO_2 during injection[1].
CONS	**Operational complexity**	• CO_2-CH_4 exchange is complex. It requires highly sophisticated equipment and operations compared with depressurization.
CONS	**CO_2 availability and separation**	• CO_2 supply is uneconomic if it is scrubbed from the air or if captured gas is transported over long distances. In a commercial process, the CO_2 would probably come from nearby conventional hydrocarbon reservoirs.

- Structure I type hydrates host methane (CH_4), CO_2 or a mixture of both[2]. Since the structure of hydrates is characterized by a greater affinity[3] to CO_2 than CH_4, ConocoPhillips and partners **have investigated and tested exchanging CO2 and CH4 in a project in Alaska[4].**
- **CO_2-CH_4 exchange is an elegant solution that benefits from strong theoretical advantages.** In particular, it would facilitate social acceptance, since it would mitigate some of the most serious environmental and safety hazards associated with gas-hydrates recovery.
- **The Ignik Sikumi field trial has achieved a "proof-of-concept".** Despite the undisputable scientific success of the Ignik Sikumi field trial, CO_2-CH_4 exchange is still considered impractical and has lost momentum over depressurization, mainly due to reduced permeability and CO_2-hydrate formation. As of 2014, no production tests were being considered and R,D&D activities had been scaled down to lab-scale research[5].

4. Injecting nitrogen may not be the ideal solution for reasons of social acceptance and because of the potential impact on gas hydrates in situ; 2. Refer to appendix 1 for more information on structure type; 3. As evidenced by the higher heat formation of CO_2 and CH_4 hydrates: $CO_2(H_2O)n \rightarrow CO_2(g) + nH_2O$ (ΔHeat = 57.98 kJ/mol) and $CH_4(H_2O)n \rightarrow CH_4(g) + nH_2O$ (ΔHeat = 54.49 kJ/mol); 4. For more information, refer to slide 50; 5Multiple well settings are considered.
Source: A.T. Kearney Energy Transition Instituteanalysis based on Farrell et al. (2010), "CO_2-CH_4 Exchange in Natural Gas Hydrate Reservoirs: Potential and Challenges"; Schoderbek et al. (2013), "ConocoPhillips Gas Hydrate Production Test Final Technical Report"

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Gas-hydrate production raises significant operational challenges in addition to those arising from dissociation

Gas-hydrate-Production challenges in sand-rich sediments using depressurization[1]

Water Production	Stimulation & Artificial Lift	Flow Assurance	Sand Production	Location & Distance To Market
• Significant volumes of water are usually produced together with gas hydrate[2]. Unlike in conventional gas wells, in which water production[3] typically amounts to less than 0.05 L/m^3, water production in gas-hydrate wells can exceed 5 L/m^3. This increases costs, since it requires larger flowlines and since water has to be treated. In Nankai (Japan), water and gas were separated on the seafloor by an electric submersible pump (ESP).	• Artificial lift is likely to be needed because of the low-pressure nature of gas-hydrate formations and the large volume of water that needs to be removed from the formation. Reservoir stimulation (thermal and chemical) methods might also be used on order to help the well to flow. However, doubts about the effectiveness of these techniques are widespread. Fracture stimulations may also not be suitable because of hydrate reformation.	• The endothermic nature of gas hydrates dissociation, together with low operating temperature, can lead to gas hydrates or ice formation near the wellbore[4]. In addition, low operating temperatures require the application of the usual flow assurance measures in the well, and gathering lines and devices.	• Significant amounts of sand can be produced if mitigation actions are not undertaken. In April 2007, a huge amount of produced sand led to the termination of the Mallik production test after 60 hours. While sand-control devices such as sand screens can limit sand production, they can also cause production damage if they or the formation near the borehole become plugged with mobile solids.	• The production of hydrates may, in some cases, be located (i) far from markets, which requires investment in transport infrastructure and means the project would face the usual stranded gas problem[5]; and (ii) in harsh marine or Arctic environments, which increase logistical demands, and operating, drilling and production costs.

Most of these challenges are familiar to the oil & gas industry. However, when combined, as they are in gas-hydrates production, they are poorly understood and this may threaten the technical and economic viability of hydrates production.

1. These challenges may vary according to dissociation techniques used, location and the type of accumulation. Depressurization of gas hydrates in sand-rich sediments is the focus of this slide since is the most likely development approach in the near term; 2. Gas production from coalbed methane reservoirs – another type of unconventional resources – also produce significant volumes of water (up to 17 L/m3); 3. Given in liters of water per cubic meter of gas; 4. Especially for marine sediments; 5. For more information, refer to the A.T. Kearney Energy Transition Institute "Introduction to Natural Gas FactBook"; Source: A.T. Kearney Energy Transition Institute analysis; Yamamoto et al. (2014), "Operational overview of the first offshore production test of methane hydrate sin the Eastern Nankai Trough"; Hancock et al. (2010), "Well Design Requirements For Deepwater And Arctic Onshore Gas Hydrate Production Wells"

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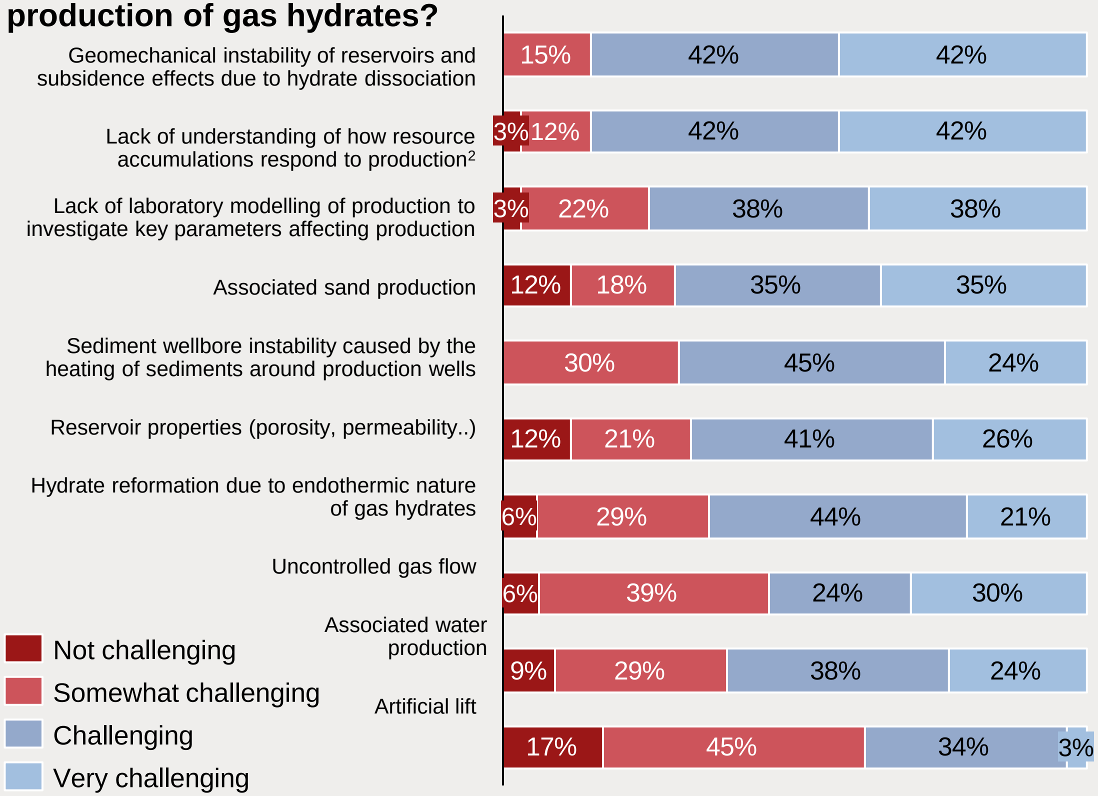
Geomechanical stability and subsequent integrity challenges are among the main uncertainties associated with gas-hydrates production

A.T. Kearney Energy Transition Institute gas-hydrates survey results[1] % of respondents

How would you grade the following challenges associated with the production of gas hydrates?



- **Geomechanical hazards are less understood than other operational challenges** faced by gas-hydrates production. In the absence of long-duration production test, they have not been yet empirically experienced, but only modelled by numerical reservoir simulators. Therefore, geomechanics is one of the biggest uncertainties associated with gas-hydrates production[3].
- **As gas hydrates dissociate, the mechanical strength of the reservoir diminishes**. Indeed, dissociation is accompanied by a decrease in the pressure of the formation and the removal of pore-filling “material”, which puts reservoir integrity at risk. This issue is particularly acute in shallow marine sediments and, as a result, it may be preferable to exploit deeper hydrate formations. In permafrost, the thickness of the overlying ice sheet and a smaller reduction in pressure should minimize the subsidence issue.
- **In addition, uncontrolled gas flow and sediment wellbore instability caused by the heating of sediments** in the vicinity of production wells need to be monitored. Finally, horizontal well completion in shallow, unconsolidated sediments may be challenging.

1. The survey was submitted in October 2014 via the distribution list of the Fire In The Ice Newsletter. It aims to provide the view of gas-hydrates stakeholders. The full results can be found in Appendix B –Survey Analysis; 2. This corresponds to a lack of model calibration; 3. As explained in slide 43, geomechanical hazards are not relevant to gas-hydrate production done using CO_2-CH_4 exchange.

Source: A.T. Kearney Energy Transition Institute analysis

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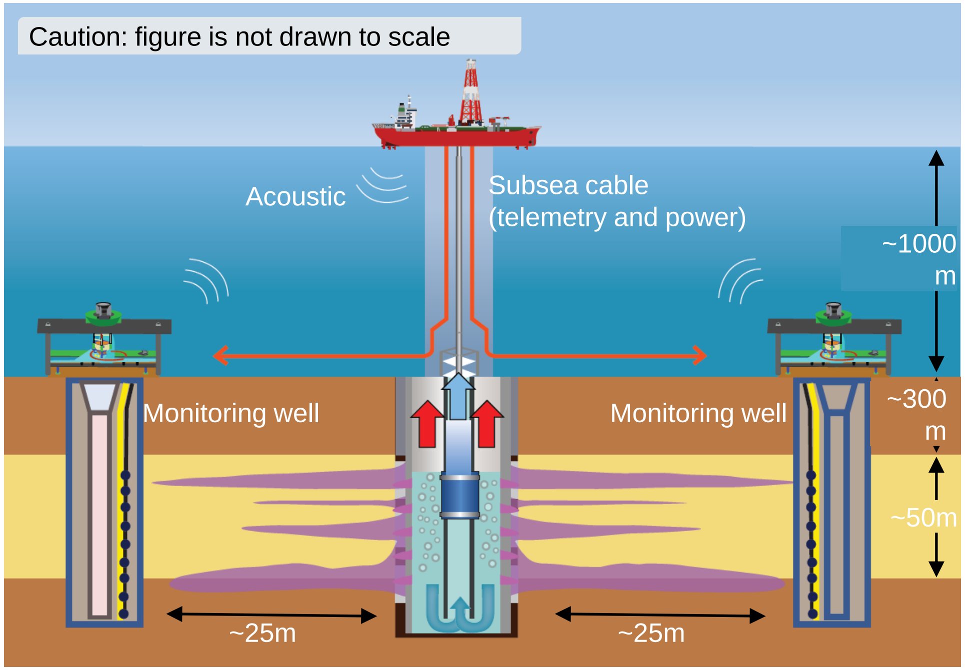
Subsurface monitoring is a crucial dimension of gas hydrate production and necessitates to deploy advanced sensor and detection technologies

Temperature detection during Nankai trough offshore production test in Japan



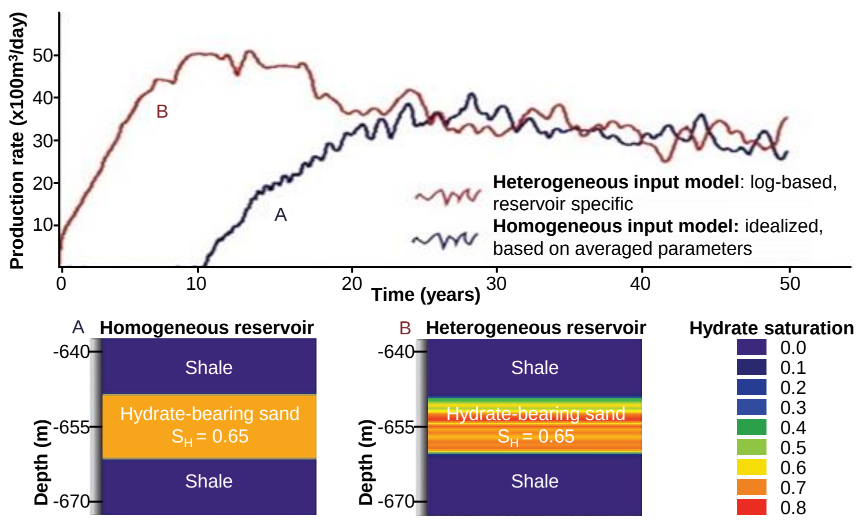
- **Gas-hydrate production requires the deployment of extensive monitoring systems** in order to improve understanding of gas-hydrate dynamics (ultimately optimizing recovery), but also to detect, prevent and mitigate potential safety and environmental hazards1.
- **In Nankai Trough, for instance, two monitoring wells[2] were drilled** in the vicinity of the production well as part of the production test. These wells were equipped with two types of temperature sensors3:
  - Distributed Temperature Sensing (DTS) devices covering the entire borehole for autonomous, long-term monitoring (measurement accuracy of +/- 0.5°C, and autonomous over 18 months);
  - Array-type Resistance Temperature Detector (RTD) devices placed across the gas hydrate reservoir with higher temperature resolution accuracy (+/- 0.1°C) for real-time monitoring during production tests.
- In addition to pressure and temperature measurement, **methane-emission detection and repair devices** will be essential, especially in the Arctic[4]

1. Future monitoring requirements for production systems are as-yet unknown and should be determined by future scientific advances and feedback from production tests; 2. Monitoring wells were designed to minimize thermal disturbance and improve thermal coupling; 3. These items of equipment have been installed by Schlumberger; 4. This is because, deep offshore, methane emissions would probably be oxidized in the water column and converted to CO2 first. See the section on environmental and safety hazards for more information.

Source: Chee et al. (2014), “A Deepwater Sandface Monitoring System for Offshore Gas Hydrate Production”

Without data from long-duration production tests, modeling of future production remains speculative

Example of the evolution in numerical predictions of gas hydrate production via depressurization



The graphs above depict numerical predictions of gas-production rates over time from a gas-hydrate reservoir using depressurization as the production method. Modelling was done with the CMG STARS simulator. In case A, the reservoir was modeled with uniform properties throughout the gas-hydrate sediment. In case B, simulations were able to capture the heterogeneity of the modeled reservoir.

- **To simulate the production profile of a gas-hydrate reservoir, it is necessary to solve a complex combination of equations,** relating to interrelated fluid, heat, and mass transport factors, combined with formation and/or the disappearance of multiple solid phases in the system.
- **Over the past decade, extensive efforts to model and forecast production have led to the development of several methane-hydrate reservoir simulators,** such as TOUGH+/HYDRATE[1], MH-21 HYDRES[2] or CMG STARS[3]. Thanks to advanced numerical models and increased computer power, forward-modeling projections have evolved to (i) reduce or eliminate lag times4, (ii) shorten the time before peak production is reached, and (iii) increase peak production rates.
- **However, without long-duration production tests to calibrate and compare models, the reliability of simulations remains uncertain.** Even if, in field tests to date, production has started immediately and has exceeded the predictions of models, some experts think simulation may be too optimistic. In addition, production models will need to incorporate field-development plans (e.g. well designs, well spacing, stimulation techniques) that are not yet known.

1. Developed by Lawrence Berkeley National Laboratory, with support from NETL; 2. Developed by the National Institute of Advanced Industrial Science and Technology, Japan Oil Engineering Co., Ltd. and the University of Tokyo; 3. Developed by CMG limited; 4. Lag times correspond to the period after the application of the dissociation technique, when gas flow is insufficient or water production too high for production to take place.

Source: Boswell et al. (2014), “Methane Hydrates”; NETL website (accessed October 2014), “Methane hydrate reservoir simulator code comparison study”; Anderson et al. (2008), “Effect of reservoir heterogeneity on productivity of gas hydrates”

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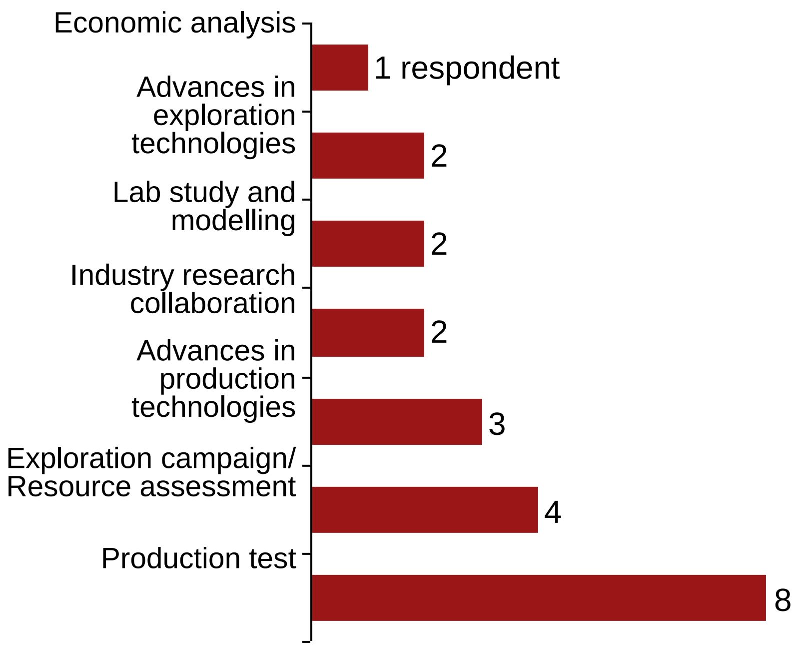
Long-duration production tests are the next prerequisite for assessing production profiles and recovery rates

Next steps for developing gas-hydrates

Results from A.T. Kearney Energy Transition Institute Gas Hydrates Survey[1]

What do you see as the principal steps required to enable the development of gas hydrates?



- **Gas-hydrates stakeholders widely agree that long-duration production tests are the next prerequisite** for gas hydrates development. There is less agreement on the duration needed, but it should last a minimum of three months. Shorter-duration production tests are inadequate/insufficient for:
  - **Assessing the geomechanical impact** of gas-hydrates dissociation on reservoir stability, especially in depressurization;
  - **Refining and improving forward modeling of reservoir performance** to enhance understanding production profiles and recovery rates, and levels of confidence in producing successfully;
  - **Enhancing understanding of potential production challenges,** such as sand management, flow assurance (secondary gas hydrates formation) or gas emissions[2], and developing and testing monitoring and sensor systems;
  - **Improving understanding of production-development** plans needed to recover gas hydrates, including well design, well spacing and any stimulation techniques that may be needed (e.g. hydraulic fracturing, chemical injection …).
- **A long-duration test is expected offshore Japan in Nankai.** However, no firm information is yet available on its likely length or start date. Alaska would be the most likely candidate for a similar effort onshore in the permafrost, but no programs are yet planned[3].

1. The survey was submitted in October 2014 via the distribution list of the Fire In The Ice Newsletter. It aims to provide the view of gas-hydrates stakeholders. The full results can be found in Appendix B – Survey Analysis; 2. Long-term monitoring of gas emissions is important. For instance, there are some concerns that methane gas could, in the long term, accumulate between the formation and the cement surrounding casing strings; this could increase pressure and break the cemented casing; 3. For more information on international projects, please refer to the Outlook section.

Source: A.T. Kearney Energy Transition Institute analysis

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Arctic Mallik was the first dedicated hydrate-research site, and the location of a thermal-stimulation test in 2002 and a depressurization test in 2007-2008

1970s-1980s
Methane hydrates identified in well logs from conventional wells in the Mackenzie Delta-Beaufort Sea region in Northern Canada

1999
Initial research well drilled by a consortium of JNOC, JAPEX, Geological Survey of Canada, USGS and DoE

2000

Early 2000s
Research program on depressurization and thermal-stimulation technologies

March 2002
First drilling for production at the Mallik site

April 2007
First production test - stopped after **60 hours** due to the influx of formation sand

2008

March 2008
Second production test - **6 days**, 13,000 cubic meters produced

April 2008
Well abandoned and equipment decommissioned

Stakeholders

Project owners	• 2002: Consortium of Geological Survey of Canada, JOGMEC, U.S. DOE, U.S. Geological Survey, India Ministry of Petroleum and Natural Gas, etc. (2002) • 2007: JOGMEC and National Resources Canada (2007-2008)
Operator	• Government of Northwest Territories
Contractors	• Inuvialuit Oilfield Services • Schlumberger

Highlights

Main achievement	• World's first production of gas hydrates through thermal stimulation (2002)
Dissociation technique	• 2002: thermal stimulation • 2007-08: depressurization
Gas recovered	• 2002: 360 m3/d (max flow rate) • 2008: 2,000-4,000 m3/d (average)

Source: A.T. Kearney Energy Transition Institute analysis; Boswell et al. (2014), "Methane Hydrates"

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The first and only CO_2-injection field-production trial to date was conducted in 2012 in the Alaska Ignik Sikumi area, with mixed outcomes

2002
Partnership formed between ConocoPhillips and the University of Bergen to develop a CO2 exchange technology

April 2011
First drilling and logging operations at the existing Ignik Sikumi conventional gas-production site

Spring 2013
Release of the final project report

2011

2013

October 2008
Project Start

2011
JOGMEC/ConocoPhillips partnership to continue with research undertaken by the Mallik project in Canada

March 2012
Production phase - **30 days**[1], 1 mmscf produced

May 2012
Final abandonment of the well

Stakeholders

Project owners	• U.S. DoE, JOGMEC, ConocoPhillips
Operator	• ConocoPhillips
Contractors	• Schlumberger • Halliburton • Weatherford

Highlights

Main achievement	• World's first production of gas hydrate using CO2 injection (March 2012)
Dissociation technique	• CO2 injection using "huff & puff" techniques
Gas recovered	• 3,500 m3/d (peak production)

1. The well was produced in four stages: first unassisted flow back phase of 5 day followed by three depressurization phases of 7, 2.5 and 19 days.

Source: A.T. Kearney Energy Transition Institute analysis; Schoderbek et al. (2013), "ConocoPhillips Gas Hydrate Production Test Final Technical Report"

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The world's first offshore depressurization test was successfully conducted in 2013 in Japan Nankai Trough

2001-2008
Seismic surveys and exploration drilling conducted at the eastern Nankai Trough, part of Phase 1 of Japan's Methane Hydrate R&D Program

2009
Development of a depressurization technology, part of Phase 2 of Japan's Methane Hydrate R&D Program

2012

February 2012
Start of drilling operations with the Chikyu deep-water drillship

July 2012
Acquisition of pressured core samples

March 2013
Successful production flow test - 6 days, 120,000 cubic meters produced

2014

Until 2018
Tentative development of a technological platform for commercial production (Phase 3)

Stakeholders

Project owners	• Owner: Japan's Ministry of Industry, Trade and Economy • Coordinator: Japan Oil, Gas and Metals National Corporation (JOGMEC)
Operator	• Japan Petroleum Exploration Company (JAPEX)
Contractors	• Drilling Vessel Chikyu, owned by the Japanese agency CDEX • Japan Drilling Company • Schlumberger • Halliburton

Highlights

Main achievement	• World's first offshore production test of gas hydrate (March 2013)
Dissociation technique	• Depressurization
Gas recovered	• 20,000 m3/d (average)

Source: A.T. Kearney Energy Transition Institute analysis; Boswell et al. (2014), "Methane Hydrates"

Korea has commissioned a drilling ship to start its first production test in 2015 in the Ulleung Basin

2005
Korean government launches 10-year Korean National Gas Hydrate Program

2006-2008
Acquisition of wireline/vertical seismic profile data (2D and 3D)

2010
Second Ulleung Basin Gas Hydrate Drilling Expedition (UBGH2): 13 sites analyzed

2014
Drilling ship commissioned for a production test of hydrates in sand reservoirs identified during UBGH2

2007

2015

2007
First Ulleung Basin Gas Hydrate Drilling Expedition (UBGH1): 5 sites analyzed

2013
Cooperation announced with the U.S. on gas hydrates

2015
After delays, first production test is expected mid-to-late 2015

Stakeholders	
Project owners	• Korean government & Ministry of Trade, Industry and Energy, Korea Institute of Geoscience and Mineral Resources (KIGAM), Korea Gas Hydrate R&D Organization, Korea gas Cooperation, USGS.
Operator	• Korea National Oil Cooperation
Contractors	• Geotek • Fugro • Schlumberger

Highlights	
Main achievement	• First production test outside Japan and North American (expected 2015)
Dissociation technique	• Depressurization
Gas recovered	• n/a

Source: A.T. Kearney Energy Transition Institute analysis; Boswell et al. (2014), "Methane Hydrates"

4. Environmental and safety hazards

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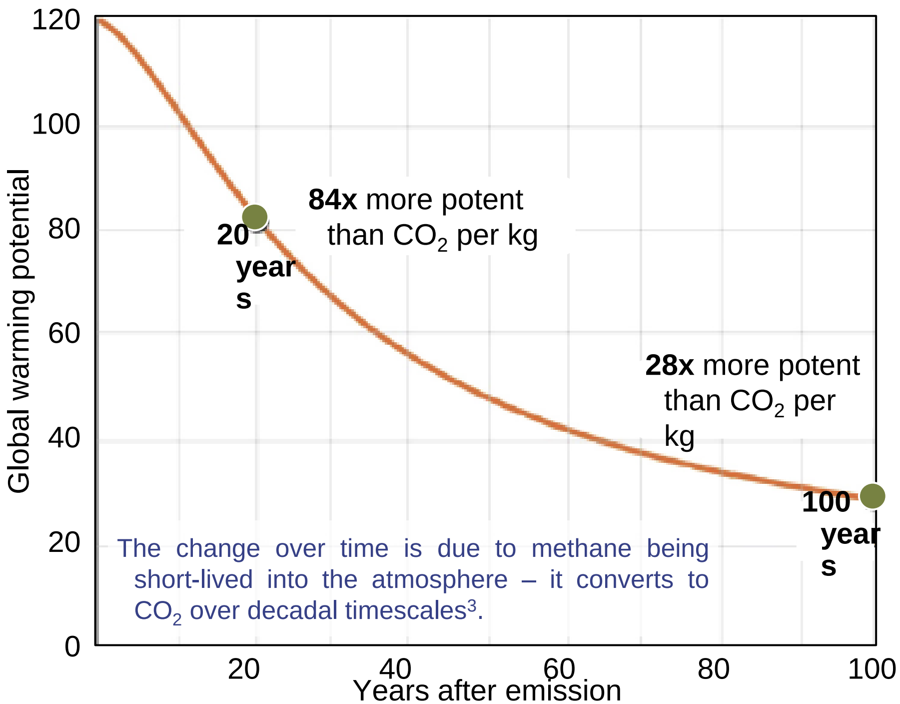
Environmental concerns about gas-hydrate dissociation stem from the extensive assumed size of the resource and methane's global warming potential

Methane global warming potential over time

Estimates without feedback, according to IPCC 2013[1]



- **Gas-hydrates accumulations are thought to represent a substantial amount of the methane stored on Earth and are stable under high pressure and/or low temperature conditions only[2]**. As a consequence, there are concerns that climate change could cause the dissociation of gas hydrates, and the subsequent widespread release of methane.
- **Like CO_2, methane is a potent greenhouse gas** (GHG). However, according to the IPCC[1], an equivalent quantity of methane would entail 84 and 28 more radiative forcings than CO2 over 20- and 100-year horizons, respectively (this is known as global warming potential – GWP).
- **The present-day concentration of CH4 in the atmosphere is far lower than that of CO_2** (~208 times lower). CH4 emissions originate mainly from anthropogenic sources (e.g. enteric fermentation from ruminants, waste disposal in landfills, and oil and gas activity). However, based on past warming events, some scientists have raised the alarming prospect that climate change could cause gas-hydrate dissociation and lead to further releases of methane into the atmosphere, amplifying global warming and further destabilizing gas hydrates (this is known as the clathrate-gun hypothesis). The latter has been tested and discussed in the academic literature over the past decade.

1. IPCC for Intergovernmental Panel on Climate Change. Figures do not include carbon feedback, since the IPCC has acknowledged the considerable uncertainties that would arise from including climate carbon feedback (CCF) in GWP. Including carbon feedback, GWP would be 86 and 34, for 20-year and 100-year horizons respectively; 2. Even according to the most modest estimates, gas hydrates still represent a very large amount of the mobile carbon stored on Earth. For more information on gas-in-place assessments and the gas hydrate stability zone, please refer to Section 2; 3. Methane has a lifetime of 12.4 years. It first reacts with OH (CH4 + OH → CH3 + H2O), and then with water vapor and other gases, and ultimately forms CO2.

Source: A.T. Kearney Energy Transition Institute analysis; IPCC (2013), "Climate Change 2013: The Physical Science Basis"; Allen (2014), "Methane emissions from natural gas production and use: reconciling bottom-up and top-down measurements"; Ruppel (2011), "Methane Hydrates and Contemporary Climate Change"

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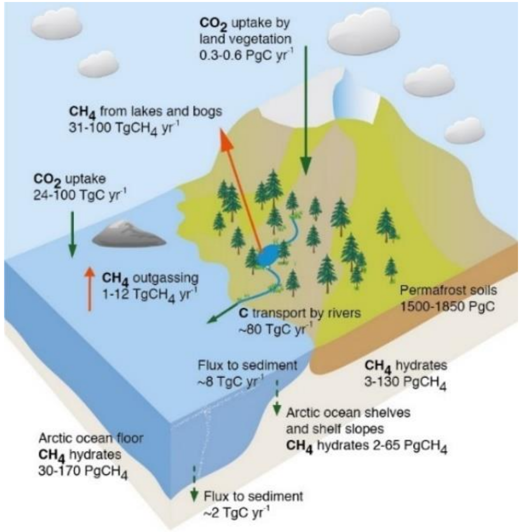
The likelihood of methane being released from gas hydrates as a result of climate change, and the probable impact of such a release is poorly understood

Current major carbon pools and flows in the arctic domain, simplified[1]



Recent studies (*e.g.* Whiteman *et al.*) have raised the alarm that methane emissions could occur in the Arctic, especially over the East Siberian Shelf and in Siberian Lakes (*e.g.* Shakhova *et al.*). However, there is a vigorous academic debate on the origin and potential impact of these emissions. As acknowledged by the IPCC: "How much of this CH_4 originates from decomposing organic carbon or from destabilizing hydrates is not known. There is also no evidence available to determine whether these sources have been stimulated by recent regional warming, or whether they have always existed […] since the last deglaciation". More research is therefore urgently needed.

- **The response of gas hydrates to climate change has only been investigated recently**. Modeling in this field remains in its infancy. As a consequence, the likelihood, and impact, of gas-hydrate dissociation due to climate change is still poorly understood and more research is needed.
- **The first uncertainty is the amount of gas hydrates stored on Earth**. Global gas-in-place estimates range over an order of magnitude (1,000-20,000 tcm, with most estimates around 3,000 tcm)2. Estimates are even more uncertain at the regional level. For instance, there are no models for Antarctic reservoirs, and estimates for Arctic permafrost have only been done recently.
- **In the permafrost, additional uncertainty arises from the origin of methane emissions, whereas in the case of ocean sediments, the mechanisms by which methane is released and its ability to reach the atmosphere are also disputed**. So are the biochemical and chemical consequences that gas-hydrate releases would have on oxidation mechanisms (e.g. there may be resource limitations hindering methane oxidation in the ocean).
- **Finally, confidence in climate feedback modeling is low** and there are considerable uncertainties about the chemical impact of a vast amount of methane being released into the atmosphere (e.g. methane oxidation in the atmosphere may be limited by the supply rate of OH, which would result in an increase in the lifetime of methane).

1. Graph courtesy of IPCC (2013), "Carbon and Other Biogeochemical Cycles"; 2. For more information, please refer to slide 29.
Source: Reagan and Moridis (2007), "Oceanic gas hydrate instability and dissociation under climate change scenarios"; Maslin et al. (2010), "Gas hydrates: past and future geohazard?"; Shakhova et al. (2010), "Predicted Methane Emission on the East Siberian Shelf"; Whitemann et al. (2013), "Climate science: Vast costs of Arctic change"

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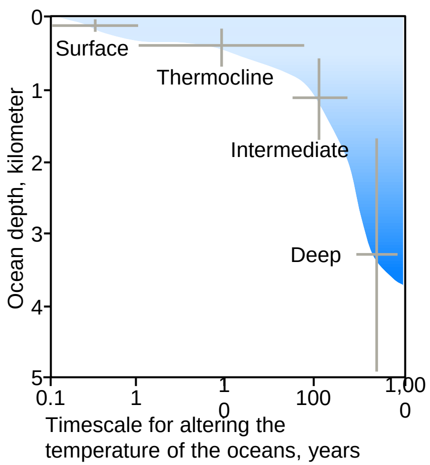
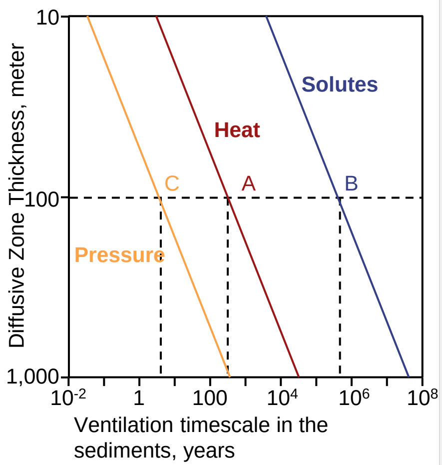
Climate change’s impact on gas hydrates is expected to be mitigated by slow thermal diffusivity in the sediments and methane oxidation in the water column

Thermal diffusivity and ocean thermal inertia estimates – ventilation timescale[1]





Ocean thermal response varies according to depth, as highlighted in the graph above (left), but also from place to place, especially in deep-water locations, due to ocean currents. In sediments, the diffusion of heat towards deeper layers takes time and varies primarily according to depth, but also according to the composition of the sediment and to the geothermal gradient. As highlighted in the graph above (right), heat can diffuse approximately 100 meters in about 300 years (point A). Solutes such as dissolved methane diffuse even more slowly (100 meters in about 30,000 years, point B), while pressure perturbation (e.g. following a sea-level rise) diffuses more quickly (100 meters in about 3 years, point C).

- **As a result of thermal inertia, heat diffusion and the melting of permafrost take time, and should be slow enough to insulate most hydrate deposits from expected anthropogenic warming over a 100-year timescale[2].** Nevertheless, temperature increases in high latitudes, such as the Arctic, are expected to be much higher than increases in the mean global temperature, and are therefore more likely to affect gas-hydrates reservoirs. Rises in sea level would result in pressure increases at the seafloor that may mitigate further dissociation of offshore gas-hydrate deposits. However, it is likely to be insufficient to negate the warming.
- **Even if warming were to reach the gas hydrate stability zone, the fate of any methane released would be uncertain.** Gas could escape if the pressure exceeded the sediment’s lithostatic pressure, but it might also remain in place. In addition, since gas-hydrate dissociation will start at the edge of the stability zone, even if gas were able to migrate, it might subsequently be trapped in newly formed hydrates.
- **Finally, even if methane were able to migrate towards the seafloor, it would probably not reach the atmosphere. Most methane is expected to be oxidized in the water column** rather than released by bubble plumes or other “transport pathways” directly into the atmosphere as methane. Nevertheless, the oxidation of methane produces CO_2, which will have an impact on ocean acidification and will remain in the atmosphere.

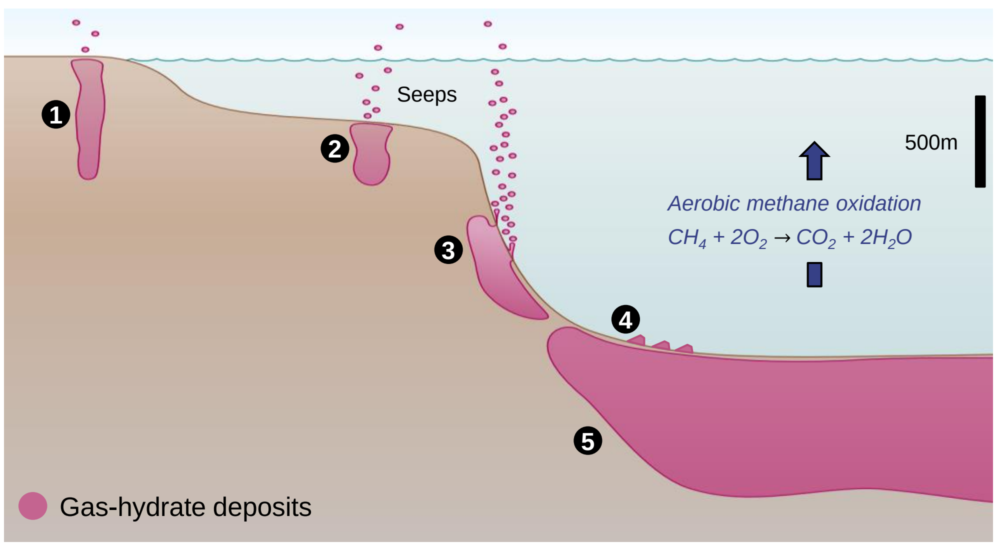
1. Graphs adapted from Archer (2007), “Methane hydrate stability and anthropogenic climate change”. In the graph on the right, ventilation timescale corresponds to the timescale required by temperature (heat), pressure and solutes such as methane to diffuse through the sediments; 2For more information on negative and positive climate feedback, please refer to Appendix 1

Source: IPCC (2013), “Carbon and Other Biogeochemical Cycles”; Reagan and Moridis (2007), “Oceanic gas hydrate instability and dissociation under climate change scenarios”; Maslin et al. (2010), “Gas hydrates: past and future geohazard?”

The susceptibility of gas-hydrate deposits to climate-change-induced dissociation varies significantly, according to reservoir location

Gas hydrate sectors, estimated share of gas-in-place and susceptibility to climate change[1]

1 Thick onshore permafrost	2 Subsea Permafrost	3 Continental slopes (upper)	4 Seafloor mound/seep	5 Deep water
1%	0.25%	3.5%	trace	~95%
contentious	high	high	high	very low



- **The risk of climate change causing gas-hydrate dissociation and methane leaks varies** significantly **by location**. This can be explained by depth differentials, the existence of mitigation mechanisms such as water-column oxidation, or by the exposure of gas-hydrate deposits to varying regional warming phenomena[2].
- **As a rule-of-thumb, gas hydrates held within subsea permafrost on the circum-Arctic ocean shelves and on upper continental slopes are the most prone to dissociation[3]**. The latter are believed to store a greater quantity of gas hydrates than the former, but methane releases are less likely to reach directly the atmosphere because of oxidation in the water column.
- However, **it is very unlikely that climate warming will disturb gas-hydrate deposits that are held in deep-water reservoirs (around 95% of all deposits) on a millennial timescale**. Finally, gas hydrates in seafloor mounds may also dissociate as a result of warming, overlying water or pressure perturbation, but these account for a very limited share of gas hydrates in place.
- **The sensitivity of gas-hydrate deposits in onshore permafrost**, especially at the top of the hydrate stability zone**, is more uncertain and subject to greater debate[4].**

1. Courtesy of maribus (2014), "Energy from burning ice"; 2. High-latitude warming is expected to be much greater than global-mean-temperature warming – for more information, refer to slide 55; 3. Subsea permafrost, which were flooded under relatively warm waters due to sea level rises thousands of years ago, have been exposed to dramatic rises in temperature that have led to a significant degradation both of subsea permafrost and the gas hydrates within it; 4. For more information on this debate, please refer to slide 58.

Source: Moridis et al. (2011), "Challenges, uncertainties and issues facing gas production from gas hydrate deposits"; Ruppel (2014), "Permafrost-Associated Gas Hydrate: Is It Really Approximately 1% of the Global System?"

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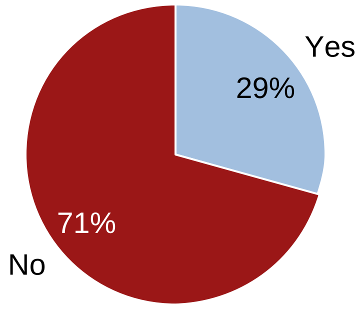
Despite modeling uncertainties, large methane releases to the atmosphere as a result of methane-hydrate dissociation are very unlikely in this century

Producing gas hydrates: a solution to mitigate their natural melting?

Results from A.T. Kearney Energy Transition Institute gas-hydrates survey[1]

Do you believe that producing gas hydrates can be a solution for mitigating the climatic impact of natural dissociation?



It is sometimes assumed that producing gas hydrates would help mitigate the impact of the climate-change-induced melting of methane hydrates. The reasoning behind this is that using the carbon as opposed to allowing it to escape into the atmosphere results in the release of CO_2 instead of methane. However, the deposits most suitable to production (high-concentration deep-water deposits in sand-rich sediments) are not the most prone to climate-change-induced dissociation. With notable local exceptions (*e.g.* in subsea permafrost), producing gas-hydrate resources should not be considered a solution for mitigating the climate impact of natural melting.

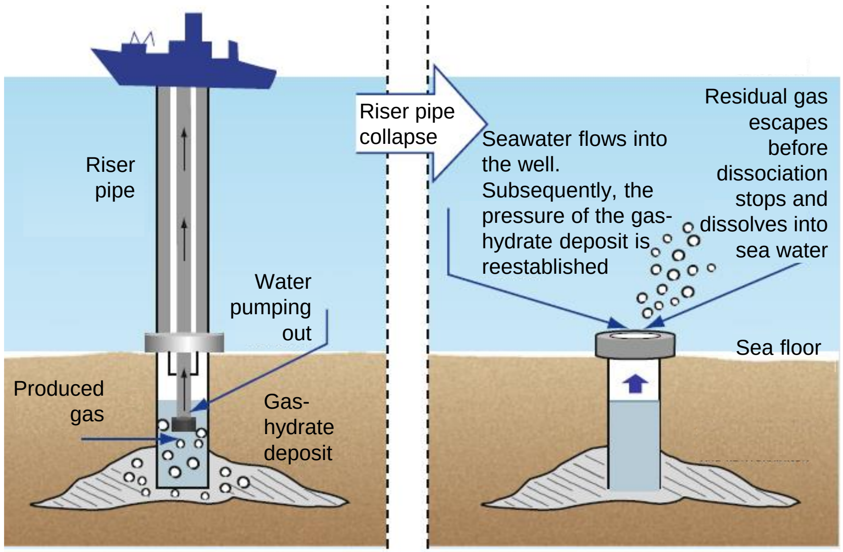
- **The potential impact of climate change on gas hydrates remains uncertain.** As the reservoir of carbon is very large, it could potentially act as a powerful climate feedback mechanism. However, the IPCC acknowledges that **"although poorly constrained, the 21st century global release of CH_4 from hydrates to the atmosphere is likely to be low"[2].**
- In addition to limited destabilization risks on a century timescale, **recent academic studies also converge on three main points:**
- Gas-hydrate dissociation is likely to be regional, rather than global, and more likely to happen in subsea permafrost and upper continental shelves, which are more exposed to the propagation of warming than deep reservoirs, and afforded less insulation by the ocean's long ventilation time;
- Methane releases from gas-hydrate dissociation are likely to be "chronic" rather than "explosive", as once assumed;
- Subsequent emissions to the atmosphere caused by hydrate dissociation would be in the form of CO_2 as a result of methane oxidation in the water column.
- **Nevertheless, it is still possible for substantial quantities of methane to be released.** Archer *et al*. calculated that between 35 and 940 GtC of methane could escape as a result of global warming of 3°C, with maximum consequences of adding a further 0.5°C to global warming. On top of the uncertainty reflected in the range above, there are other considerable uncertainties, notably concerning the effectiveness of mitigation mechanisms and the long-term outlook, since methane will continue to be released, even if warming stops.

1. The survey was submitted in October 2014 via the distribution list of the Fire In The Ice Newsletter. It aims to reflect the views of various gas-hydrates stakeholders. The full results can be found in Appendix B – Survey Analysis; 2IPCC also noted that "accounting for an unanticipated release of GHGs from methane hydrates, not included in studies assessed here, would also reduce the anthropogenic CO2 emissions compatible with a given temperature target".

Source: Boswell and Collett (2010), "Current perspectives on gas hydrate resources"; IPCC (2013), "Carbon and Other Biogeochemical Cycles"; Archer (2007), "Methane hydrate stability and anthropogenic climate change";

Methane emissions associated with gas-hydrate recovery should not raise more severe challenges than those encountered in conventional gas exploitation

Schematic of the natural fail-safe mechanism during offshore production[1]



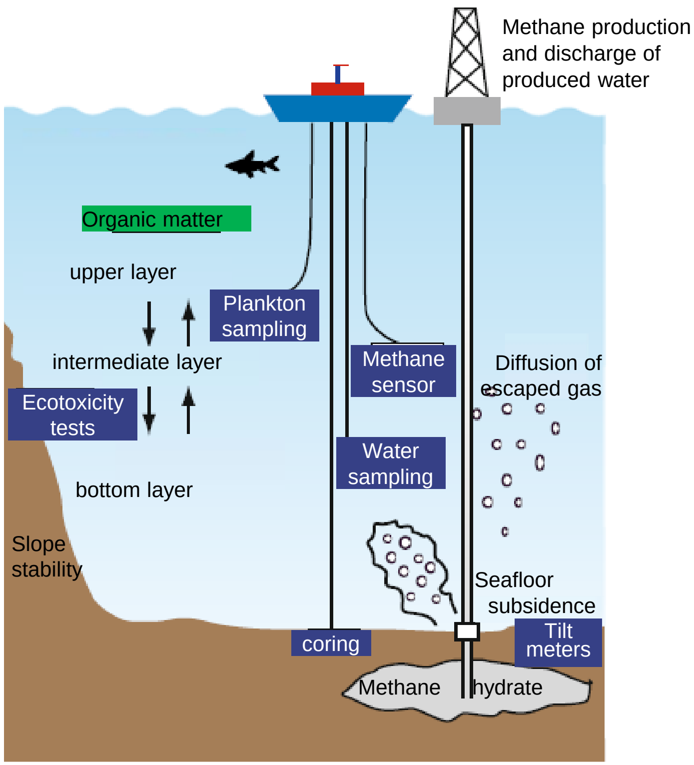
If an accident similar to the 2010 Macondo disaster in the Gulf of Mexico was to happen, seawater would flow into the production well. Therefore, the pressure on the deposit would increase and be restored, and hydrate dissociation – and subsequent gas production – would soon stop.

- **Producing gas hydrates is not expected to increase the risk of significant methane emissions, nor of gas blow-outs, compared with conventional gas operations.** In fact, gas hydrates are stable by nature: unlike conventional gas, if stimulation such as depressurization stops, hydrates reform and gas is trapped in ice instead of escaping.
- A study by Moridis and Reagan of the response of a gas-producing hydrate deposit following a well shut-in shows hydrate reformation and system stability within a very short time. In addition, no major emission was detected during production tests offshore Japan or in the Arctic.
- **The main concern relates to the escape of gas from the wellhead after cementing.** If gas were to accumulate between the cement and the formation, it could compromise the casing over the long term. Therefore, low-heat-of-hydration cements should be applied.
- **More than anything else, gas hydrates may suffer from negative public perceptions.** Engaging stakeholders will therefore be vital to avoid inaccurate perceptions.

1. Courtesy of Giavarini and Hester (2011), "Gas Hydrates Immense Energy Potential and Environmental Challenges".
Source: Moridis and Reagan (2014), "Response of a Gas-Producing Hydrate Deposit Following a Well Shut-In"; Nagakubo et al. (2010), "Environmental Impact Assessment Study on Japan's Methane Hydrate R&D Program"

Aside from concerns and uncertainties relating to methane emissions, environmental issues do not seem to be a major impediment to gas-hydrates deployment

Schematic diagram of the marine environment and remote monitoring required[1]



- **Gas-hydrate recovery is expected to entail large volumes of co-produced water**, although the amount would be highly variable[2]. This would be especially challenging if the most promising technique, depressurization, were used to dissociate gas-hydrate deposits. Indeed, **depressurization uses mobile water as a pressure-transmission medium** (*i.e.* water is produced to reduce pressure in gas-hydrates reservoirs).
- **Water production is common in oil and gas production[2]**. However, when the water-to-gas ratio is too high, conventional oil and gas wells are typically shut-in or worked over.
- In addition to operational challenges[3] during production and the potential need for artificial lift, for instance in the form of electric submersible pumps, **co-production of water may damage marine ecosystems[4]**. The water in gas hydrates contains no salts or impurities and can consequently hurt marine wildlife.
- **As a consequence, in some cases significant volumes of water may need to be treated before being disposed of**, and adequate sensors will be needed to help conserve the environment, especially in marine settings.

1. Courtesy of Giavarini and Hester (2011), “Gas Hydrates Immense Energy Potential and Environmental Challenges”; 2. Coalbed methane, another type of unconventional gas reservoir, suffers from similar water co-production challenges; 3. Production challenges are detailed in slide 44; 4. Challenges associated with co-produced water are not limited to the use of depressurization method. Proper treatment and disposal of co-produced water may for instance be much more difficult if chemical techniques are applied.

Source: A.T. Kearney Energy Transition Institute analysis; Moridis et al. (2011), “Challenges, Uncertainties, and Issues Facing Gas Production From Gas-Hydrate Deposits"

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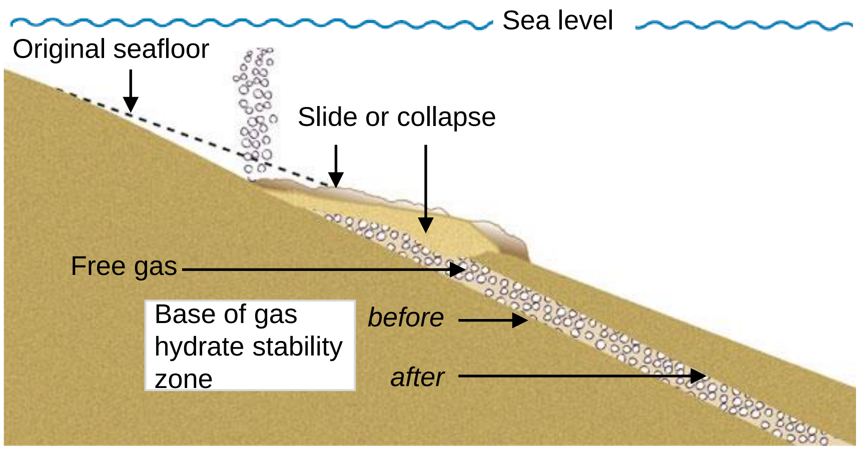
Seafloor stability and submarine slope failure resulting from gas-hydrate dissociation have raised serious safety concerns

How submarine slope failure could be Triggered by hydrate dissociation[1]



When hydrates are close to the seafloor on the upper continental margin, and the temperature is almost at hydrate stability temperature, an increase in temperature resulting from ocean warming or hot drilling fluids could lead to hydrate dissociation. Hydrate dissociation can cause significant increases in pore pressure within the sediments due to gas expansion and to loss of sediment strength in unconsolidated deposits. If pressure increases are sufficient, and especially if they occur suddenly and rapidly, this can lead to the formation of pockmarks on flat areas or to submarine landslides on sloping floors.

- **It has been postulated that gas-hydrate dissociation could trigger submarine landslides**, **and subsequently cause tsunamis.** In 1998, 2,000 people died in Papua New Guinea as a result of a tsunami that was caused by submarine slope failure. **However, the role of gas hydrates as a potential root cause of landslide has not been proved**. Extensive research has been carried on Norway's continental shelf to analyze whether hydrate dissociation could have played a role in the detachment of the 300 km-length Storegga Slide 8,000 years ago[2]. The study concluded that detachment had most likely been caused by a major earthquake rather than by hydrate dissociation.
- In addition to slope failure on the continental margin, **hydrate dissociation may also occur on a flat area on the seafloor**, causing the formation of holes called pockmarks, ranging in diameter from meters to kilometers. Even if deep-water gas-hydrate sediments are unlikely to dissociate[3] as a result of climate change, there are major uncertainties concerning the impact on sediment stability[4] of long-duration gas-hydrate production. As a rule of thumb, it is assumed that the deeper the sediment, the more stable, but this hypothesis will need to be validated by long-duration production tests. If subsidence were a likely outcome, CO_2-CH_4 production techniques[5] could be favored.
- Finally, gas blow-outs are unlikely to be a major issue because of the endothermic — and therefore self-limiting — nature of the gas-hydrate dissociation process[6].

1. Courtesy of Giavarini and Hester (2011), “Gas Hydrates Immense Energy Potential and Environmental Challenges”; 2. At the time of the Storegga slide detachment, temperature had risen by around 8°C since the previous deglaciation; 3. Please refer to slide 57 for more information; 4. Gas-hydrate drilling hazards for conventional oil and gas operations are also examined in slide 18; 5See Section 3 for more information; 6Refer to slide 59 for more information.

Source: Maslin et al. (2010), “Gas hydrates: past and future geohazard?”; IPCC (2013), “Carbon and Other Biogeochemical Cycles”

5. Outlook

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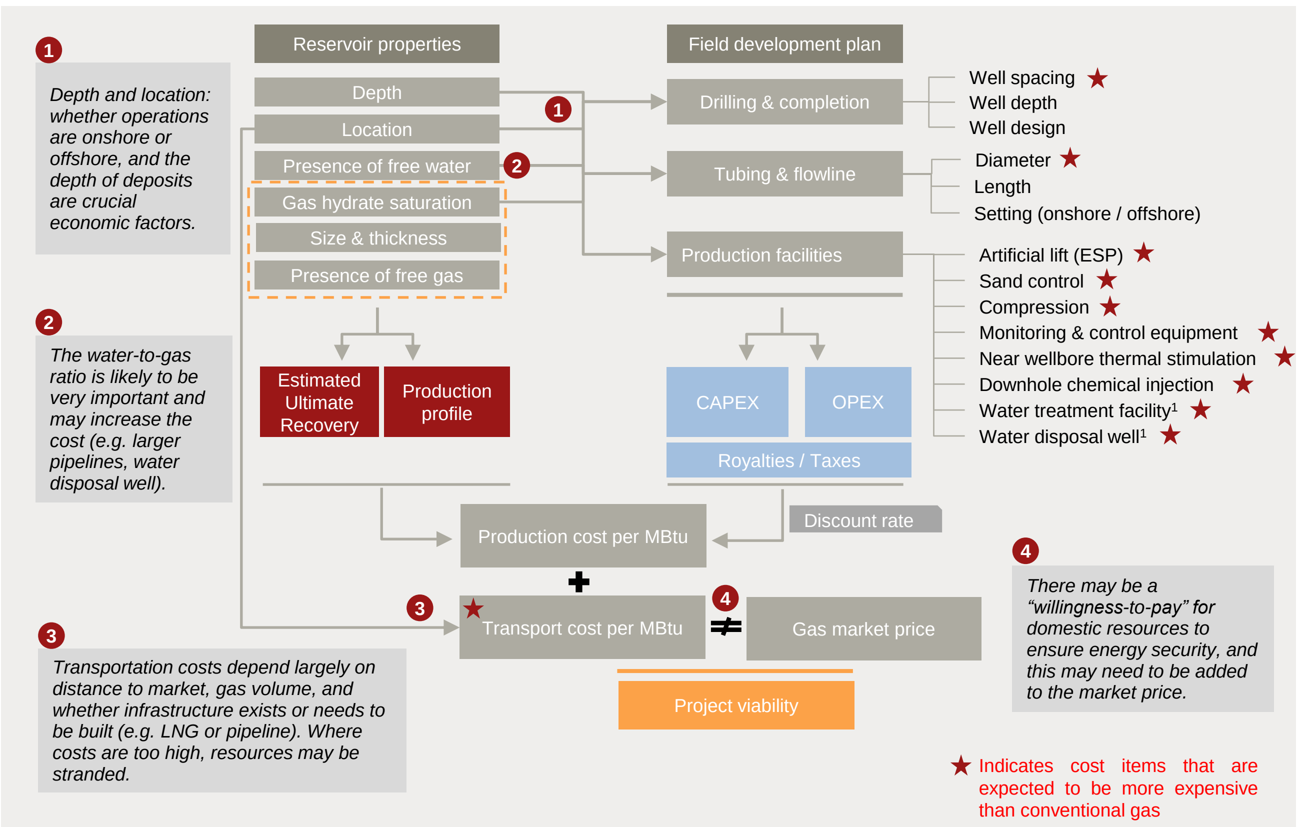
In the absence of long-duration field trials, the economics of gas-hydrate production remain highly speculative

Main parameters impacting gas-hydrate economics

Non-exhaustive for illustrative purposes only



- **Economic assessment of gas hydrates is still at its infancy.** With the exception of Walsh and Masuda reports, no assessment of gas hydrates’ economic viability has been conducted so far.
- **This is due to the early stage of maturity of gas-hydrate projects.** Although exploration has proved successful in a number of places, and production trials have demonstrated several dissociation techniques and effectively produced methane for a few days, there have not been any long-term production tests to further assess production profiles, recovery rate and field development needs2.
- **As a consequence, economic evaluation remains highly speculative,** even if the most impactful parameters have been identified.

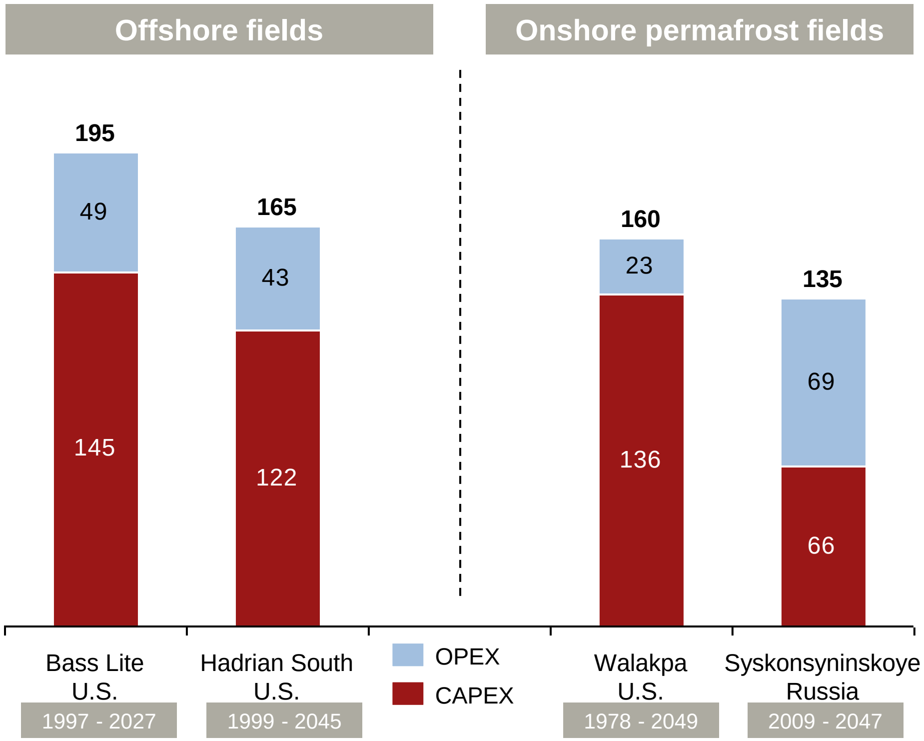
1. If and when requested; 2. For more information, please refer to slide 48.

Source: A.T. Kearney Energy Transition Institute; Walsh et al. (2008), "Preliminary report on the economics of gas production from natural gas hydrates"; Walsh et al. (2009), “Preliminary report on the commercial viability of gas production from natural gas hydrates”; Masuda et al. (2010), “Model Calculation on Economics of Depressurization-Induced Gas Production from Oceanic Methane Hydrates”; Moridis et al. (2011), “Challenges, Uncertainties, and Issues Facing Gas Production From Gas-Hydrate Deposits"

Gas-hydrate deposits in a permafrost environment would be less difficult to exploit than marine accumulations thanks to land-based operations

Comparative cost of conventional natural gas production – *for illustration only*[1]

$ /1,000scm



- Despite uncertainty on gas-hydrate economics, **it is largely agreed that deposits in the Arctic would be easier to exploit than deep-water marine accumulations**. Despite significant developments in deep-water oil and gas operations over the last decades, they remain on average more expensive and risker than onshore operations, even in frontier environments, such as Arctic permafrost.
- **In addition, the business cases for gas hydrates would be improved in locations where synergies with conventional oil and gas operations could be leveraged**. In those regions, such as the Gulf of Mexico or Prudhoe Bay: (i) gas-hydrates exploration may benefit from accumulated knowledge, which would reduce the cost of data acquisition (*e.g*. use existing 3D survey) and resource assessment; (ii) produced gas may use existing transport facilities, sidestepping stranded gas issues[2]. Access to market could be a major economic constraint for some gas-hydrates development; (iii) gas hydrates may provide a valuable source of gas for conventional oil fields that are running short of fuel gas or of injection-gas needed to maintain the reservoir pressure (some projects are exploring this opportunity in Alaska).

1. OPEX and CAPEX can vary tremendously between fields. Note that the Walkapa field is community owned and that the price is heavily regulated and subsidized. Natural gas production costs have been calculated based on Rystad database with a 8% discount rate. CAPEX include exploration CAPEX, facility CAPEX, well CAPEX and abandonment costs. OPEX include production OPEX, transportation OPEX and selling, general and administrative OPEX; 2Stranded gas correspond to gas fields that are too small or remote to justify pipelines or liquefaction investment plant. For instance, several pipeline projects have been proposed in Alaska to exploit natural gas from the Prudhoe Bay area, but all of them were abandoned on economic grounds.

Source: A.T. Kearney Energy Transition Institute analysis based on Rystad database (accessed December 2014); Walsh et al. (2009), "Preliminary report on the commercial viability of gas production from natural gas hydrates"; Moridis et al. (2011), "Challenges, Uncertainties, and Issues Facing Gas Production From Gas-Hydrate Deposits"

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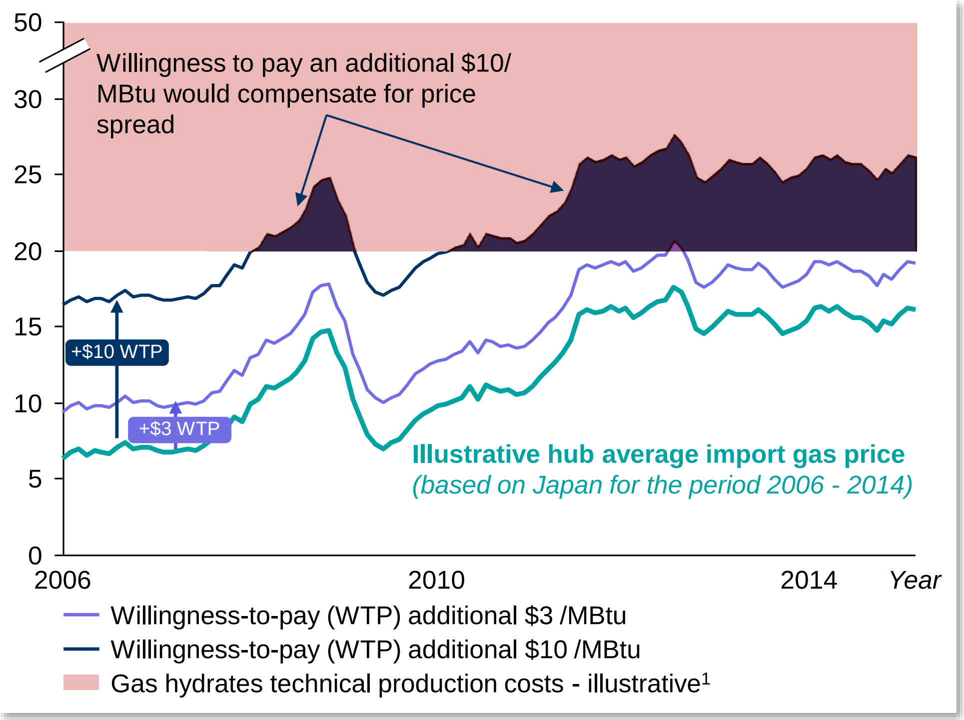
Gas prices and willingness to pay for domestic resources will be crucial parameters to make gas hydrates economically viable

Break-even gas prices vs. Gas-hydrate costs

$ /Mbtu, illustrative



- **The economic viability of gas-hydrates development will obviously depend on gas prices.** According to several commodity brokers, U.S. natural gas prices will remain relatively stable over the next 20 years. Spreads between U.S. and Asian wholesale prices may decrease, having reached a decadal peak in 2013 (e.g. an average $13.95 /MBtu spread between U.S. Henry Hub and Japanese LNG prices in that year). This is due to more liquid markets, new liquefaction capacity3 and changes in previously prevailing oil-indexed contracts.
- **Even if gas-hydrates costs remain higher than gas prices, they could yet be developed in countries rich in gas hydrates, but lacking domestic resources.** In these countries, public authorities may be prepared to pay a premium for energy supply security and local development benefits, such as direct and indirect jobs. The latter are typical examples of positive externalities, which may be measured by "willingness to pay". Whether the willingness to pay for domestic resources will compensate for the spread between gas-hydrate costs and natural gas prices will be crucial and has not been determined yet.

1. Including transport cost to market, but without taxes; 2. For instance, Goldman Sachs wrote in June 2014 that natural gas will trade "largely" at $4-5 /MBtu for the next 20 years in the U.S; 3. Australia is expected to become the leading LNG exporter by 2020 and new countries may start LNG exports, such as Russia with Yamal LNG, East Africa or the U.S. The Panama Canal enlargement could allow LNG carriers to reach Asia from new regions.

Source: A.T. Kearney Energy Transition Institute analysis; Bloomberg (2014), "Goldman Says Shale Gas Boom Driving Fear Out of the Market"; IHS (2015), "Historical Monthly Gas Prices for LNG Importers"

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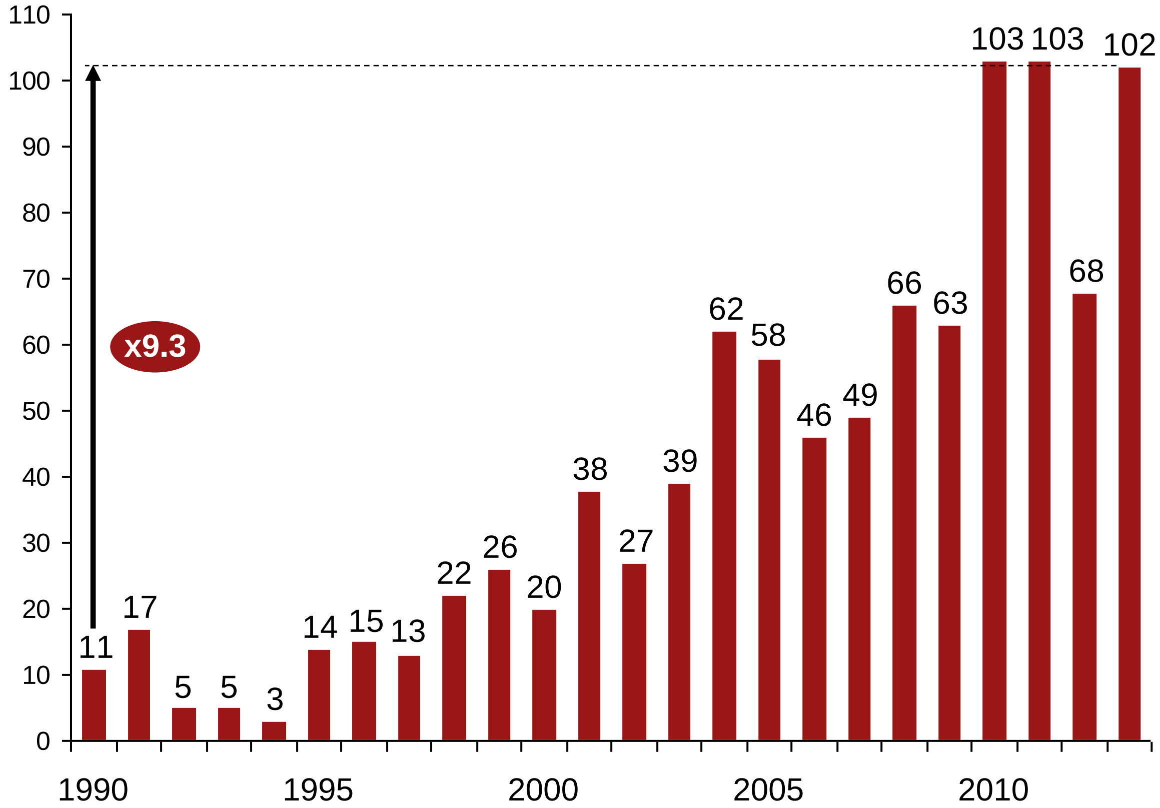
Research and development continues to be active, despite a loss of momentum following the North American shale gas revolution

Patenting rate for upstream gas-hydrate technologies

of patents filed per year[1]



- **Gas hydrates started to be envisioned as a potential energy source in the 1990s, due** to a 10-year U.S. national R&D program launched in 1982 and subsequent drilling programs, such as the Ocean Drilling Program in the U.S. and drillings tests in Japan and Canada.
- Thanks to these scientific programs, and also the growing importance of natural gas, **interest in gas hydrates as a resource increased significantly in the 2000s**. Field trials demonstrated the feasibility of gas-hydrates production, and also helped to enhance understanding of gas-hydrates accumulation, notably by leading to a consensual view on the presence of high-concentration deposits in sand-rich sediments.
- **Due to the unconventional gas revolution in North America, gas-hydrate R&D has lost momentum.** Oil majors such as ConocoPhillips have reduced their involvement and Canada has shut down its gas-hydrates program. **Nevertheless,** thanks to sustained interest in Asia, and to continued R&D programs in the U.S. and also Europe (e.g. SUGAR), the **patenting rate has remained strong since the late 2000s.**

1. The A.T. Kearney Energy Transition Institute has analyzed patents (applications) from 50 patent offices, based on the Thomson Derwent World Patents Index (DWPI). More information on methodology and full results are available in Appendix A – patent analysis.

Source: A.T. Kearney Energy Transition Institute analysis, based on Thomson DWPI (accessed October 2014)

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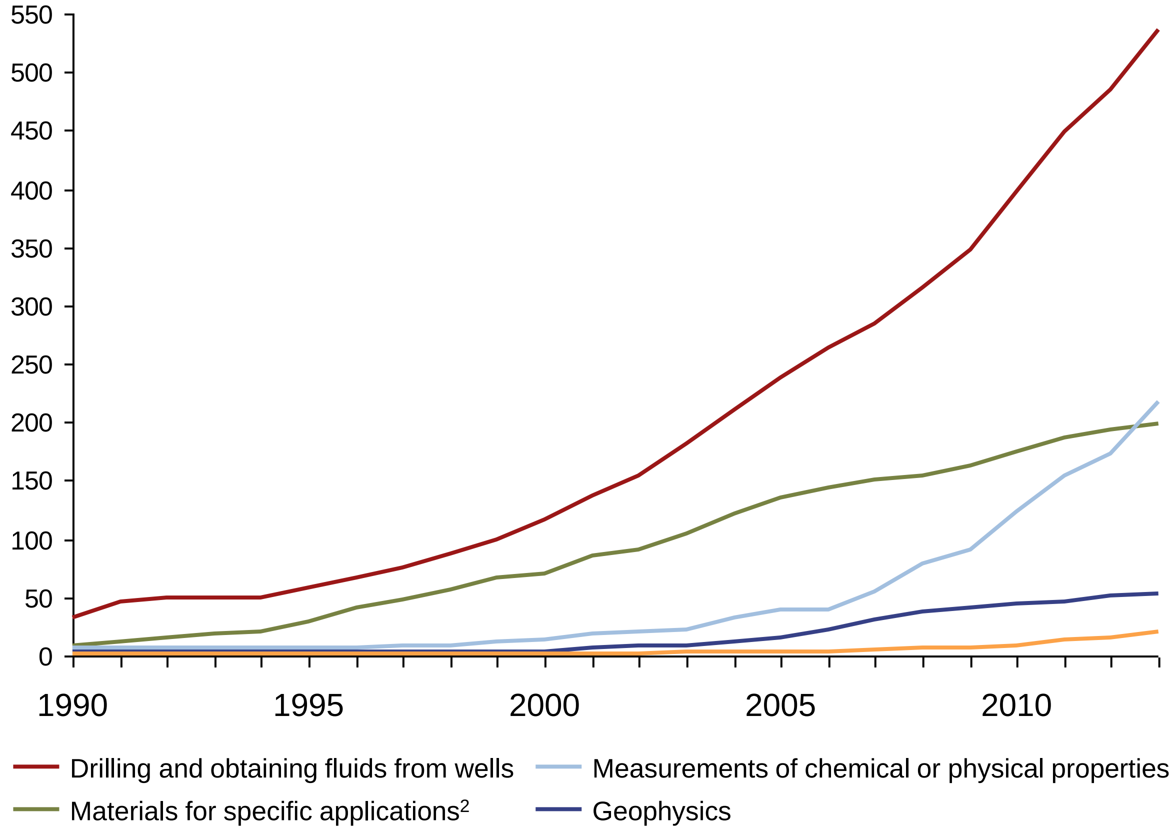
Most research and development is focused on drilling and gas recovery from gas-hydrate deposits

Upstream gas-hydrate patents by technology category[1]

Cumulated # of patents filed since 1960



- **Since the 2000s, endeavors to develop technologies related to drilling and gas recovery from gas-hydrate deposits have increased,** and there have been constant efforts to innovate with borehole and well treatment. These are reflected in the number of patents filed for these technologies. This has led to important improvements in production technologies, especially on equipment designed to recover natural gas from gas-hydrate wells.
- **Chemical and physical measurement tool development has also gained momentum since the mid-2000s.** But other exploration technologies for gas hydrates, such as those related to geophysics and measurement of electric or magnetic variables have seen only moderate development. This is because identification and characterization of gas hydrates has been done primarily by using conventional exploration technologies, whereas gas-hydrate production required development of customized technologies, at least for dissociation in situ.

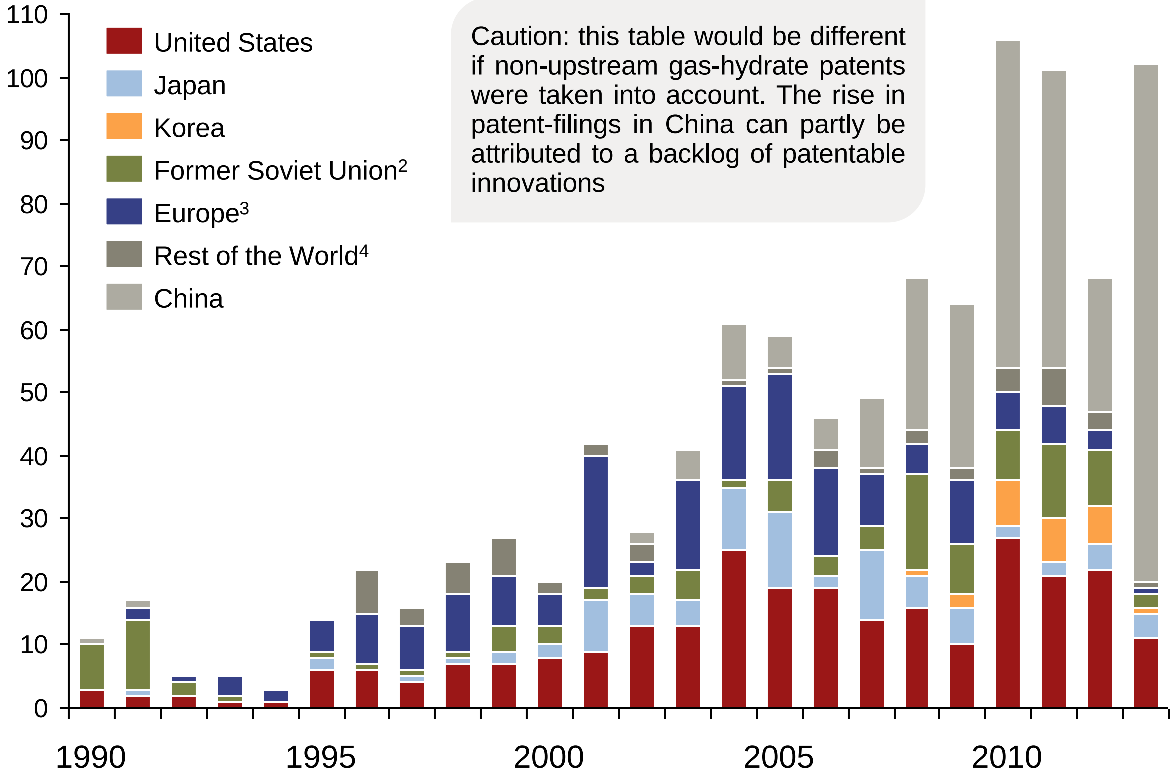
1. The A.T. Kearney Energy Transition Institute has analyzed patents (applications) from 50 patent offices based on the Thomson Derwent World Patents Index (DWPI). Categories correspond to International Patent Classification (ICP) classes. Note that a single patent can be filled under several IPC classes. More information on methodology and full results are available in the Appendix A – PATENT ANALYSIS; 2This includes compositions for treating boreholes or wells.

Source: A.T. Kearney Energy Transition Institute analysis, based on Thomson DWPI (accessed October 2014)

China is taking over traditional players as the main R&D driver for gas-hydrates upstream activities

Upstream-related gas-hydrate patents by country[1]

of patents filed per region per year



- **Gas-hydrates R&D has traditionally been driven by the U.S. and Japan.** The Japanese government has invested estimated $50-100 million per year in the framework of Japan's 18-year Methane Hydrate R&D Program launched in 2001, while the U.S. has continuously invested around $10 million per year since the Methane Hydrate Research And Development Act passed in 2000.
- **Europe has shown some interest in gas-hydrates RD&D,** initially in Norway, with hydrate resources thought to exist in Svalbard. In addition, there are concerns over methane hydrates presenting hazards for conventional drilling in the North Sea. More recently, interest has risen in Germany, though the Submarine Gas Hydrate Reservoirs (SUGAR) project, a collaborative R&D venture launched in 2008, which has received funding for a third phase (2015-2018).
- **Finally, important R&D programs have been launched in Asia,** primarily in Korea, Taiwan, India, and China. China has become the largest driver of upstream-focused patenting, ahead of the U.S.

1. The A.T. Kearney Energy Transition Institute has analyzed patents applications from 50 patent offices based on the Thomson Derwent World Patents Index. Country correspond to the "priority" country. More information on methodology and full results are available in the Appendix A – PATENT ANALYSIS. 2Includes patents filed in the Russian Federation patent office, the Ukrainian patent office and the Former Soviet Union office; 3Includes patents filed in the European patent office, and in specific national patent offices in European countries; 5Includes patents filed in the patent Cooperation Treaty Office and other national offices not cited above.

Source: A.T. Kearney Energy Transition Institute analysis, based on Thomson DWPI (accessed October 2014)

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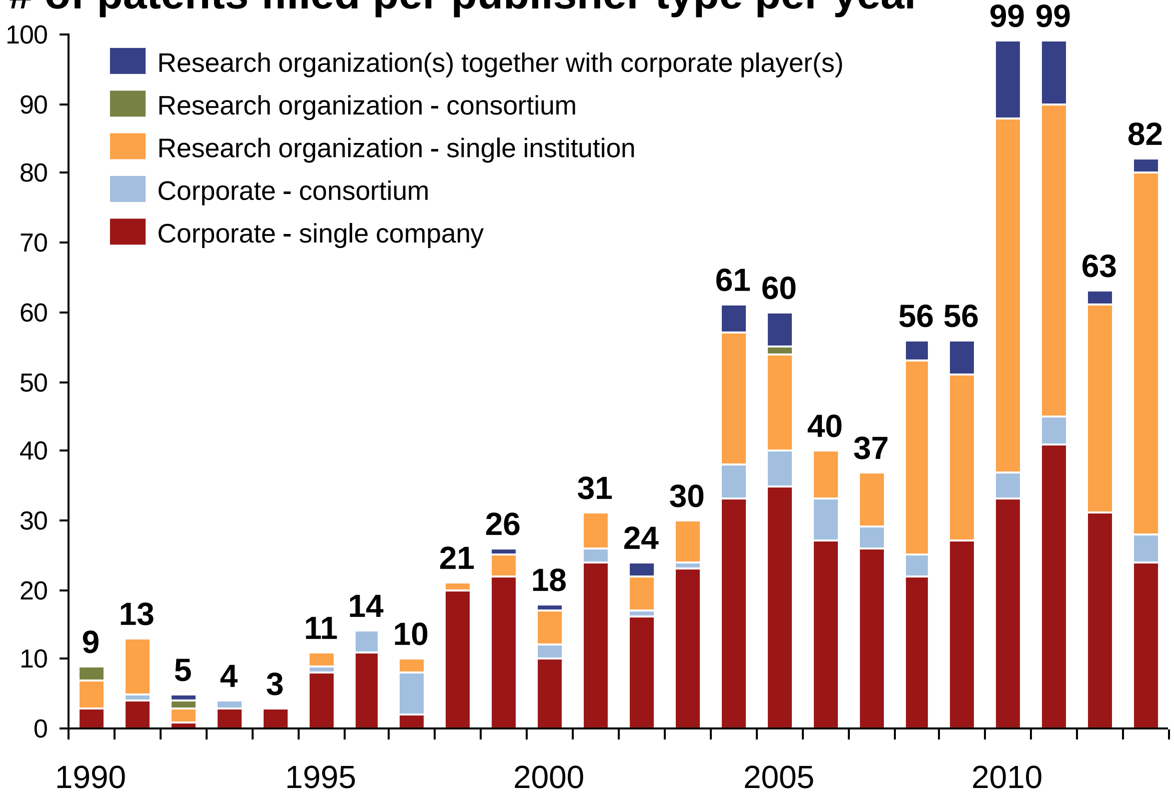
Gas-hydrates activities are increasingly driven by research organizations, such as universities and public laboratories

Upstream gas-hydrate patents filed by publisher type[1]

of patents filled per publisher type per year[2]



- **Corporate players from the oil and gas, or chemicals industries have historically been important drivers for gas-hydrates research and development (R&D).** Therefore, most patents were filled by industry until the mid-2000s.
- In parallel to the emergence of Asian countries in the gas-hydrate field**, the role in gas-hydrate R&D of research-focused organizations such as universities, research institutes or public laboratories has grown.** These organizations now account for the majority of patent applications related to upstream gas hydrates.

1. The A.T. Kearney Energy Transition Institute has analyzed patents applications from 50 patent offices based on the Thomson Derwent World Patents Index. Country correspond to the “priority” country. More information on methodology and full results are available in the Appendix A – PATENT ANALYSIS; 2Note that the total number of patents slightly differs from previous slide since patents published by individuals have not been taken into account for this analysis.

Source: A.T. Kearney Energy Transition Institute analysis, based on Thomson DWPI (accessed October 2014)

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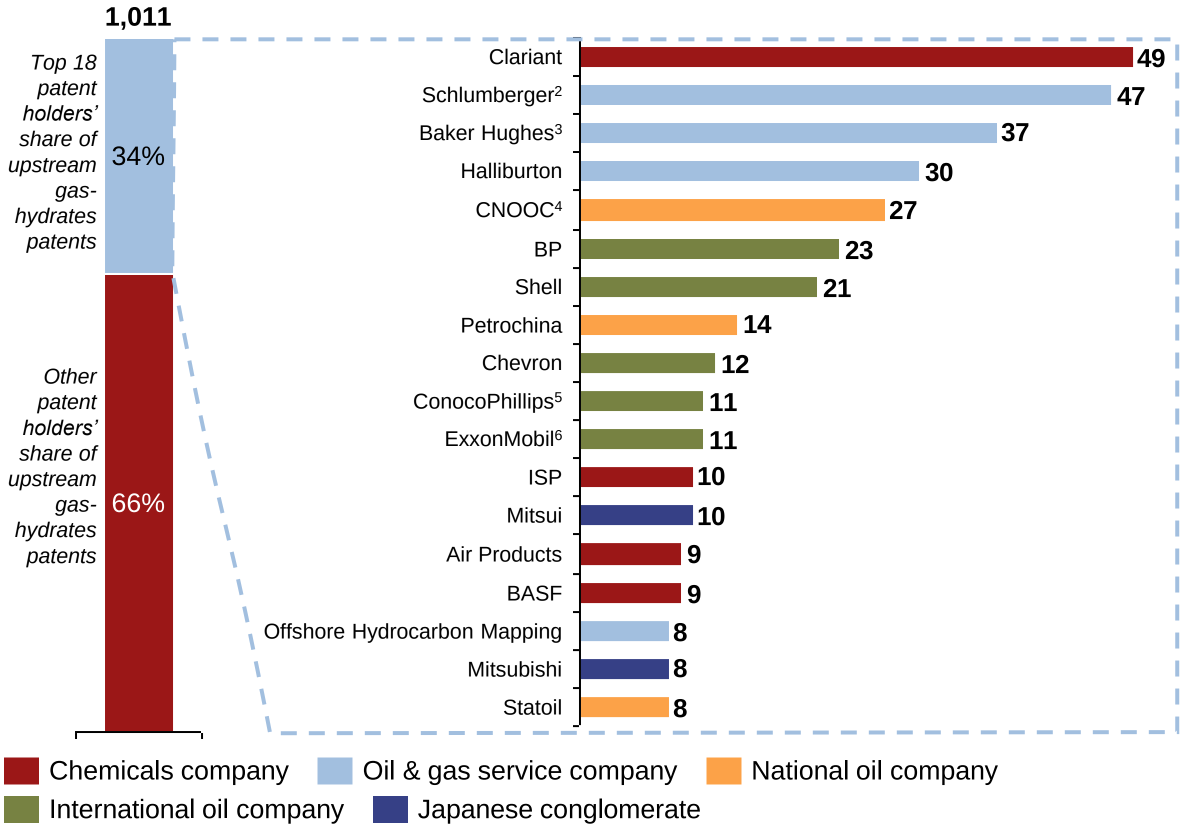
Oil and gas service companies are the most active corporate players

Main organization for gas-hydrate patent filling

Cumulated # of patents related to upstream operations filled since 1960



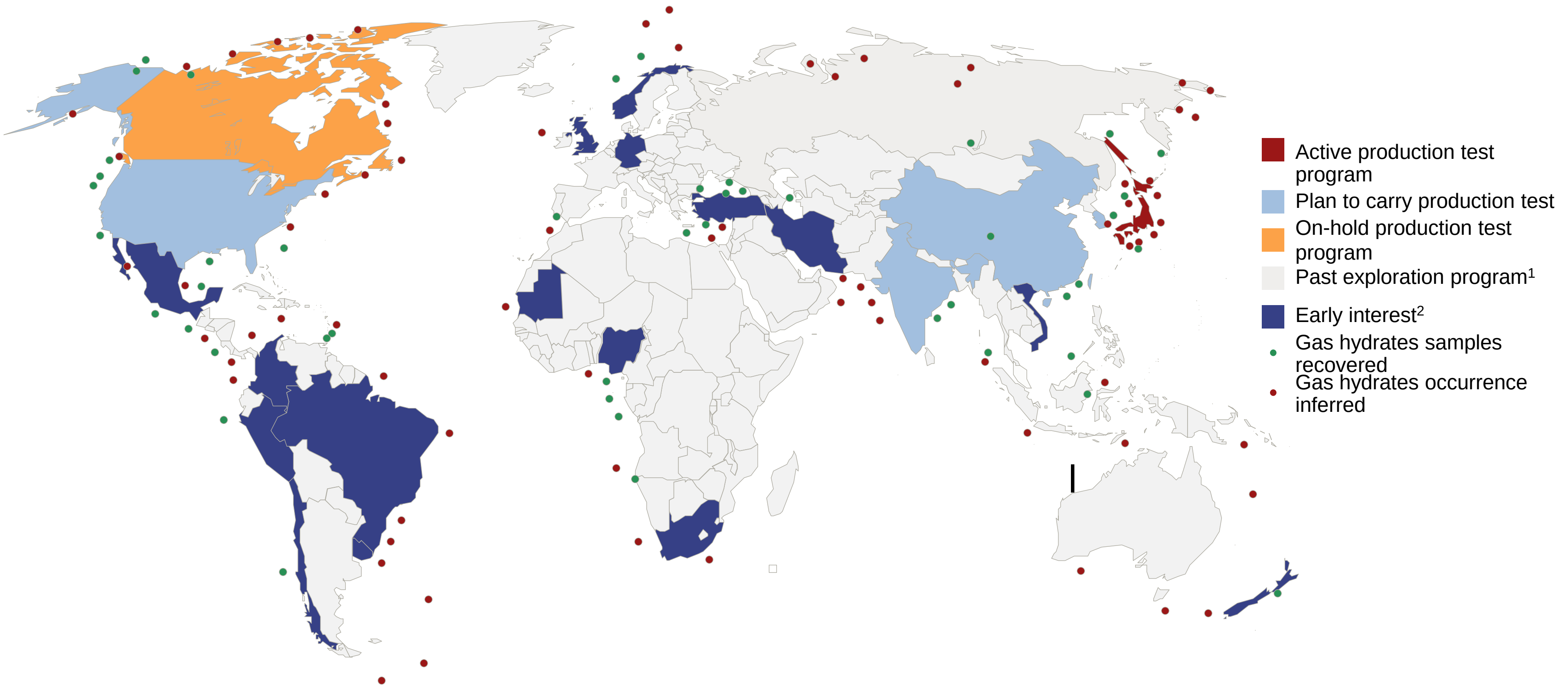
- **Oil and gas service companies have been very active in gas-hydrate** research and development (R&D) as reflected by the number of patents they have published. So have chemicals companies, due to their longstanding interest in gas hydrates through the flow assurance prism.
- **International oil & gas companies (IOCs) also used to be strong drivers of gas-hydrates R&D.** The Joint Industry Project was for instance formed under the management of Chevron, while ConocoPhillips (COP) was leading the Ignik Sikumi production test. More recently, and as a result of the development of shale and tight resources in the U.S., involvement of IOCs has been decreasing. COP, for example, has suspended its research activity in gas hydrates.
- **The role of national oil and gas companies has increased,** especially in China and Japan. Meanwhile, Statoil stands out as one of the most active corporate players.

1. The A.T. Kearney Energy Transition Institute has analyzed patents applications from 50 patent offices based on the Thomson Derwent World Patents Index. Country correspond to the "priority" country. More information on methodology and full results are available in the Appendix A – PATENT ANALYSIS. 2. Includes patents published by Schlumberger, PRAD Research, and Development and M-I Swaco; 3. Includes patents published by Baker Hughes, and BJ Services; 4. CNOOC for China National Offshore Oil Corporation;
5. Includes patents published by ConocoPhillips, Conoco and Phillips Petroleum company; 6. Includes patents published by Exxon Mobil, Exxon and Mobil.

Source: A.T. Kearney Energy Transition Institute analysis, based on Thomson DWPI (accessed October 2014)

A lot of countries have expressed interest in gas-hydrate development, but only a few have effectively launched R&D programs

Main countries active in Gas hydrates development



1. Russia and Malaysia carried out research on gas-hydrates primarily for safety hazards due to conventional gas production; 2. Interest can be in the form of active characterization efforts (e.g. seismic survey in Colombia or New Zealand) or early plans (e.g. Iran ambition in the Sea of Oman, or Turkey in the Thrace region).

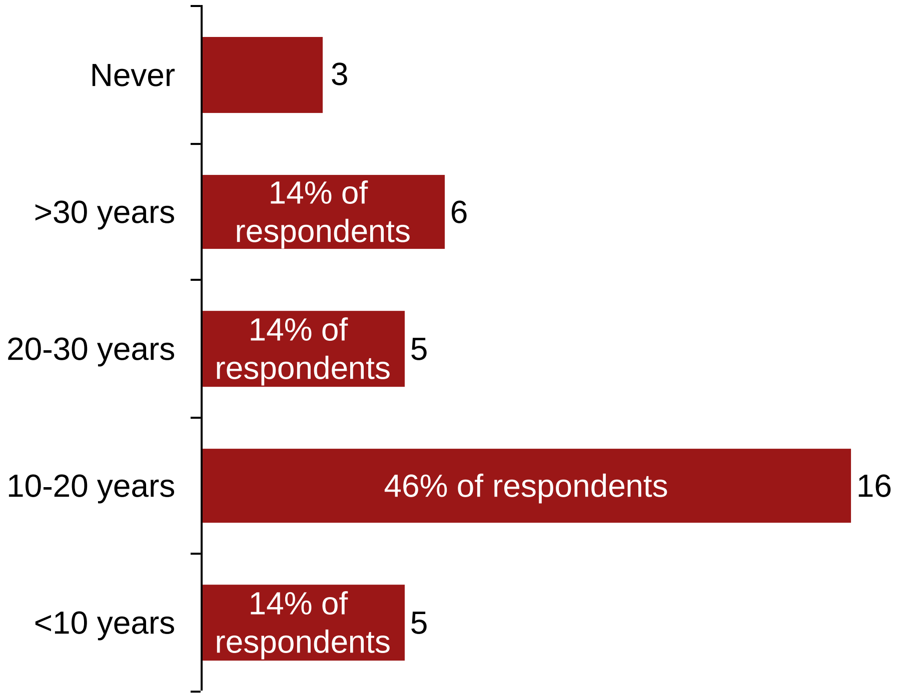
Source: A.T. Kearney Energy Transition Institute analysis; USGS (2014), "International Gas Hydrate Research"; Thomson Reuters (12th Oct. 2014), "Iran finalizes gas hydrate plan"; Daily Sabah (15th Sept. 2014), "Halliburton to explore natural gas reserves in Turkey"

Near-term outlook for gas hydrates remains highly uncertain

Gas-hydrate development outlook

Results from A.T. Kearney Energy Transition Institute Gas Hydrates Survey[1]

Over what timeframe do you think gas hydrates will be produced economically?



- **Developing gas hydrates is not the hair-brained idea of a few researchers.** Exploration campaigns and production tests have shown that gas-hydrate deposits in sand-rich sediments could be tapped using existing technologies with small adjustments. Of crucial importance has been the demonstration that these reservoirs can exhibit a high level of gas-hydrate concentration.
- **However, R,D&D is still needed to assess the economics of gas-hydrate production,** and to address environmental and safety concerns such as geomechanical stability and subsidence issues. In particular, long-term production patterns of gas-hydrate accumulations remain uncertain, making long-term production tests a pre-requisite for effective evaluation of the commercial viability of gas hydrates. These tests will help to refine and calibrate reservoir models and to assess well-spacing requirements, the production profile, the lag between the times when dissociation techniques are applied and gas production starts, recovery rates, and the need for artificial-lift and sand-control facilities.
- **Gas-hydrate stakeholders are currently torn between optimism and caution when it comes to commercial development of gas hydrates.** It is largely agreed that gas-hydrate exploitation is unlikely to be competitive with conventional and other unconventional resources such as shale gas or coalbed methane. So gas-hydrate development is likely to be envisioned only for regions that lack domestic resources or in the very long term, if existing resources become exhausted.

1. The survey was submitted in October 2014 via the distribution list of the Fire In The Ice Newsletter managed by the U.S. Department of Energy's National Energy Technology Laboratory. It aims to provide the view of gas-hydrates stakeholders. Full results can be found in Appendix B – Survey Analysis.

Source: A.T. Kearney Energy Transition Institute analysis

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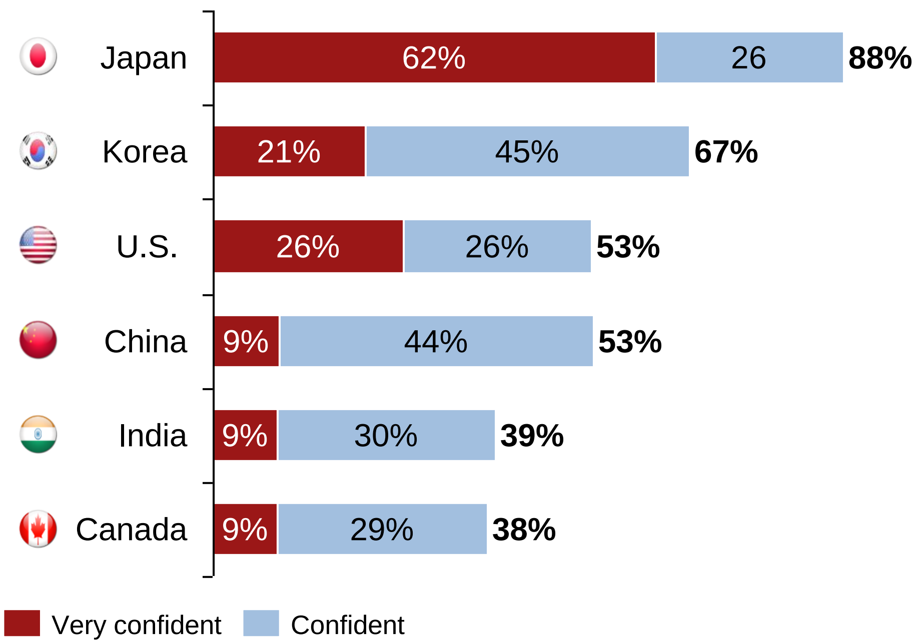
Japan's successful offshore test has invigorated gas-hydrates stakeholders and brightened the outlook for gas-hydrates development in Asia

Regional likelihood of gas-hydrate development

Results from A.T. Kearney Energy Transition Institute Gas Hydrates Survey[1]

Are you confident that gas hydrates will be recovered within the next 20 years at a commercial scale in these countries?



- **Following the shale gas revolution of the late 2000s, gas-hydrates development has been at a standstill.** The fall in gas prices in North America led to oil majors suspending or reducing their gas-hydrate programs. Nevertheless, R&D did not stop, and even increased in intensity in Asia, as reflected in the patents publishing rate, as well as the exploratory campaigns that took place in China, Korea or India.
- **Whether gas-hydrate resources may change the game should be assessed on a regional basis.** It is work in the Nankai Trough and the announcements that Japan plans to start commercial production by the end of this decade, which has really invigorated gas-hydrates stakeholders and put back gas hydrates in the spotlight.
- **Most stakeholders appear confident gas hydrates could be developed at a commercial scale in Japan,** and, to a lesser extent, in Korea. Feelings are more mixed about prospects in China and the U.S., even if the latter is the most likely location for Arctic development2. There is even more uncertainty over India, given the presence of clay-rich sediments, rather than sand, in the Krishna-Godovari basin. Meanwhile, activities have been suspended in Canada, and all other countries are lagging behind.

1. The survey was submitted in October 2014 via the distribution list of the Fire In The Ice Newsletter managed by the U.S. Department of Energy's National Energy Technology Laboratory. It aims to provide the view of gas-hydrates stakeholders. Full results can be found in Appendix B –Survey Analysis; 2. Japan could support U.S gas-hydrate activities as illustrated by JOGMEC involvement in the Ignik Sikumi test and by the Memorandum of Understanding signed in November 2014 with NETL.

Source: A.T. Kearney Energy Transition Institute analysis

Appendix & bibliography

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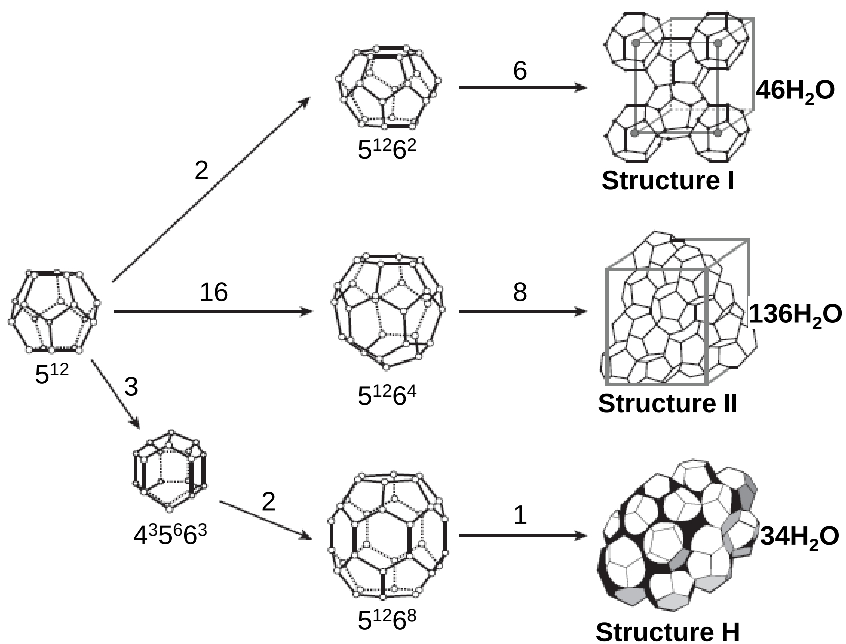
Appendix 1 – Gas-hydrate structures

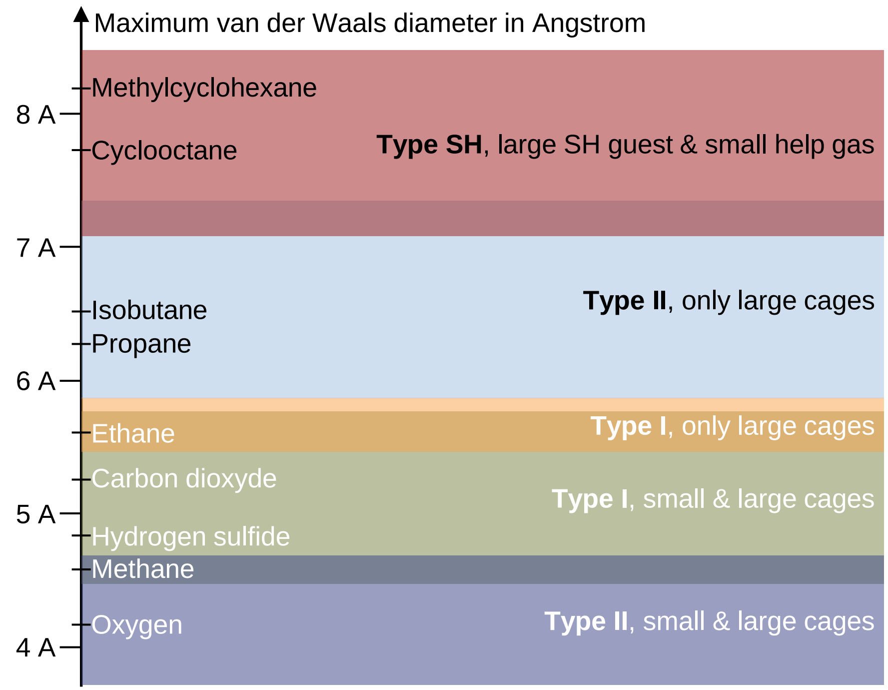
Common gas hydrate structures



How to read this graph

The smallest Structure I crystal unit is composed of 46 water molecules, which form 6 large cages and 2 small cages. The common notation for the Structure I small cage in hydrate literature is 5^{12}, which indicates that the cage has 12 five-sided faces. The Structure I large cage is referred to as a $5^{12}6^2$ cage and has 12 five-sided faces and 2 six-sided faces.

Relation between host gas and structure



The type of structure formed depends primarily on the size of the encased molecule. In nature, most gas-hydrate deposits are Structure I because they are composed of pure methane and do not contain heavier hydrocarbons. Conversely, in oil and gas pipelines, hydrates are mainly Structure II or Structure H, although these are rarer because of the presence of larger hydrocarbons such as propane.

Source: Giavarini and Hester (2011), “Gas Hydrates Immense Energy Potential and Environmental challenges”; Sloan and Koh (2007), “Clathrate Hydrates of Natural Gases Third Edition”

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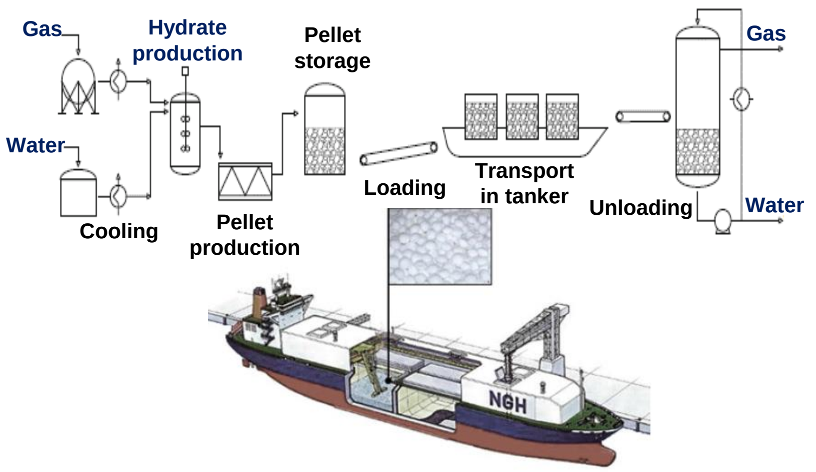
Appendix 2 – Industrial applications of gas hydrates: transportation

Process for transporting natural gas in The form of hydrates and vessel diagram[1]



Transportation of natural gas in the form of gas hydrate pellets relies on a kinetic anomaly, known as the self-preservation phenomenon. Under relatively mild pressure and temperature conditions, the formation of a thin ice film around gas-hydrate pellets prevents further destabilization of the gas hydrate. This phenomenon makes it possible to store natural gas in hydrate pellet form far outside its thermodynamic stability field for long periods[2].

- **Gas-hydrate transportation presents several advantages.** Gas hydrates have a high volumetric energy density and can be transported under relatively mild pressure and temperature conditions compared with competing technologies. In addition, gas-hydrate transportation presents few ignition and uncontrolled-burning hazards.
- **Several research and development programs on gas hydrate transportation have been carried since the early 1990s.** At present, these are dominated by Japanese enterprises, notably Mitsui Engineering & Shipbuilding and Chugoku Electric Power Company, which jointly implemented a first overland transportation demonstration project in 2011[3].
- **While the key steps in the production and transportation of gas-hydrate pellets have now been identified, further engineering efforts remain necessary[4].** In addition, the economics of gas-hydrate transportation remain uncertain. Some studies suggest that hydrate technology may be a competitive solution for small production capacities and small-to-medium transportation distances5. But others suggest there would be no economic benefit, compared with competing technologies, in shipping methane hydrates from offshore sources to land because of high infrastructure and production costs.

1. As proposed by MEC; 2. According to Giavarini and Maccioni (2004) it can take over 40 days for complete hydrate dissociations at pressures slightly higher than atmospheric (2–3 bar) pressure, and temperatures between -5°C and -3°C. The addition of chemicals can further increase hydrate preservation; 3. In this project, a NGH production plant with 5 tonne-per-day capacity was built in Nanai. Produced NGH was transported by purpose-built tank trucks to two users' sites located ~100km away; 4. Especially on the optimization of gas-hydrate production and recovery processes; 5. Between about 1,500 and 6,000km.

Source: Rehder et al. (2012), "Methane Hydrate Pellet Transport Using the Self-Preservation Effect: A Techno-Economic Analysis"; Giavarini and Hester (2011), "Gas Hydrates Immense Energy Potential and Environmental Challenges"; Nogami et al. (2011), "World's First Demonstration Project of Natural Gas Hydrate (NGH) Land"

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Appendix 3 – Geologic controls on the occurrence of gas hydrates in nature

Gas-hydrate formation: main parameters

Gas hydrate stability conditions	Gas hydrates only form under a limited range of temperatures and pressures.
Source of gas	The availability of natural gas from microbial or thermogenic sources are among the conditions that determine the formation and distribution of gas hydrates. Microbial gas[1] is produced at shallow depths from the decomposition of organic matter under the action of microorganisms. Microbial-gas production within the gas hydrate stability zone (GHSZ) is limited by the organic content of the sediments and microbial conversion efficiency. Thermogenic gas is generated during the thermochemical alteration of organic matter. While it represents large amount of natural gas, it is typically generated below the base of the GHSZ.
Gas migration	Migration pathways – through the rock matrix, producing high concentrations of gas hydrates at the base, or through fractures that can transport gas high into the GHSZ – are therefore critically important, and affect the distribution and concentration of gas-hydrate accumulations. The concentration of gas hydrates is usually greatest at the base of the GHSZ because gas hydrates are self-trapping. Once it forms, it does not move and it renders the rock impermeable to further gas flow. Thus the base of the GHSZ is fed by all the gas coming up from below, whether thermogenic or biogenic. Sometimes the only gas hydrate that forms above the base of the GHSZ comes from *in situ* decay of organic matter. Since organic matter in sediments is relatively dilute, little hydrate forms. However, in some formations, there is substantial gas hydrate above the base of the gas hydrate stability zone, maybe because of the rapid ascent of gas via fractures.
Availability of water	Gas hydrates form in the gas hydrate stability zone when sufficient amounts of gas mixed with water are present in sediment pores.
Reservoir rock	The nature of the sediment in the gas hydrate stability zone determines the physical nature of *in situ* gas-hydrate deposits.

1. Also known as biogenic gas.
Source: Tissot et al. (1974), "Influence of Nature and Diagenesis of Organic Matter in Formation of Petroleum"; Kleinberg (2009), "Exploration strategy for economically significant accumulations of marine gas hydrate"; Giavarini and Hester (2011), "Gas Hydrates Immense Energy Potential and Environmental Challenges"

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Appendix 4 – Ulleung Basin Gas Hydrate (UBGH) exploration campaigns

2000 - 2004
Regional seismic survey and basic R&D

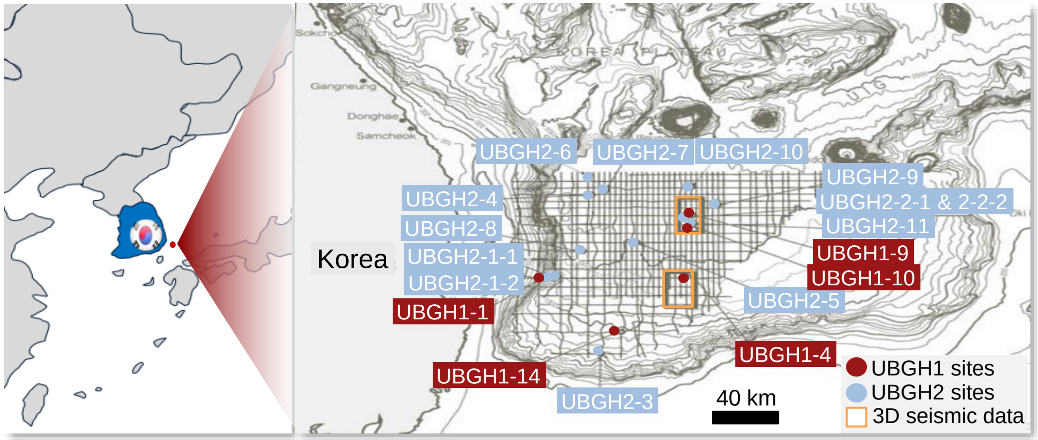
2005 - 2007
UBGH1: first expedition and first large-scale exploration and drilling campaign

2008-2011
UBGH2: research program on depressurization and thermal stimulation technologies

2012-2015
Production test and confirmation of production methods

2000

2010



Main stakeholders

Research centers and public organiza-tions[1]	• Korean Gas Hydrate Research and Development Organization • Korea Ministry of Knowledge Economy • Korea Institute of Geoscience and Mineral Resource • Korea Institute of Ocean Science and Technology • Korea Ocean Research and Development Institute • Korea Advanced Institute of Science and Technology
Industrials	• Korean Gas Corporation; Korean National Oil Company • Fugro; Schlumberger; Geotek

Project outcomes

UBGH1

- Continuous logging while drilling (LWD) downhole logs were acquired from 5 boreholes to determine the distribution of potential methane-hydrate zones.
- Three coring and *in situ* testing boreholes were drilled to determine the structure of hydrate sediments and the properties of methane-hydrates.
- Methane hydrates were found in coarse-grained sediments and silty layers with saturation levels of 30-60%, as well as in fractures near the seafloor.

UBGH2

- LWD data from 13 boreholes drilled confirmed the occurrence of methane hydrates.
- Shipboards analysis of recovered core samples confirmed that gas hydrate mainly occur as pore-filling type within discrete turbidite sand or ash layers, or as fracture-filling veins and nodule in pelagic/hemipelagic mud, particularly in chimney the structures.
- Several scientific data were obtained from deposit structures.

1. Additional scientific support was provided by the U.S. Geological Survey, Geological Survey of Canada and Oregon State University.

Source: A.T. Kearney Energy Transition Institute analysis; Consortium for Ocean Leadership (2013), "Historical Methane Hydrate Project Review"; USGS (2014), "International Gas Hydrate Research"; Ryu et al. (2013), "Scientific results of the Second Gas Hydrate Drilling Expedition in the Ulleung Basin (UBGH2)"

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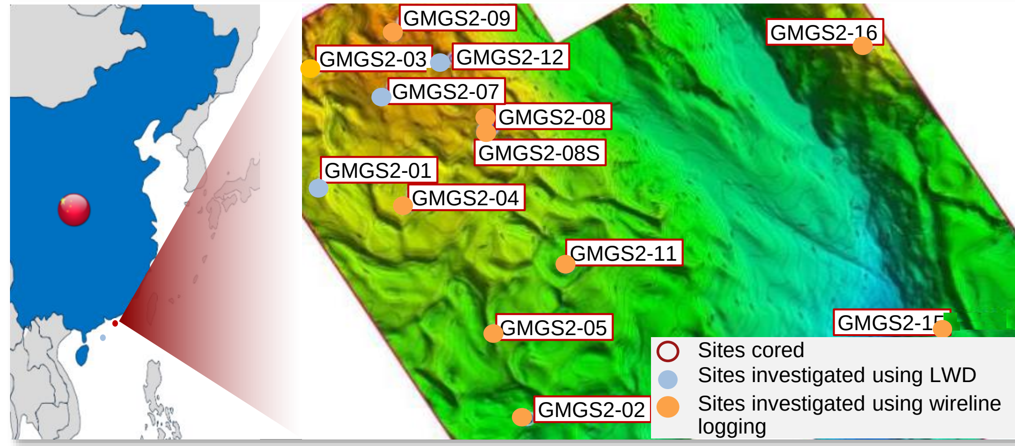
Appendix 5 – GuangZhou Marine Geological Survey (GMGS) exploration campaigns



Main stakeholders

Research centers and public organiza-tions[1]	• Guangzhou Center for Gas Hydrate Research • Guangzhou Marine Geological Survey • China Geological Survey • Ministry of Land and Resource of China
Industrials	• Fugro • Schlumberger • Geotek

Project outcomes

GMGS 1

- Eight sites were drilled and subsequently logged, with sampling and testing holes drilled at five of them.
- Base of gas hydrate stability zone was determined at all sites
- Methane hydrate-bearing sediment layers were found at three sites in pore-filling types at 25-47% saturation, while no gas hydrate deposits were found at the two other cored sites.

GMGS 2

- Among 13 sites investigated, logging while drilling (LWD) and wireline drilling data were recovered from 13 and three of them, respectively. Nine out of 13 sites investigated were found to contain hydrate deposits.
- At the five sites cored for further analysis, deposits were found in massive forms, disseminated form in deeply buried fine-grained sediments, dense, thin veins in shallow, fine-grained sediments, as well as disseminated in coarse-grained sediments.

Source: A.T. Kearney Energy Transition Institute analysis; Consortium for Ocean Leadership (2013), "Historical Methane Hydrate Project Review"; USGS (2014), "International Gas Hydrate Research"; Zhang et al. (2007), "China's First Gas Hydrate Expedition Successful"; Zhang et al. (2014), "GMGS2 Expedition Investigates Rich and Complex Gas Hydrate Environment in the South China Sea"

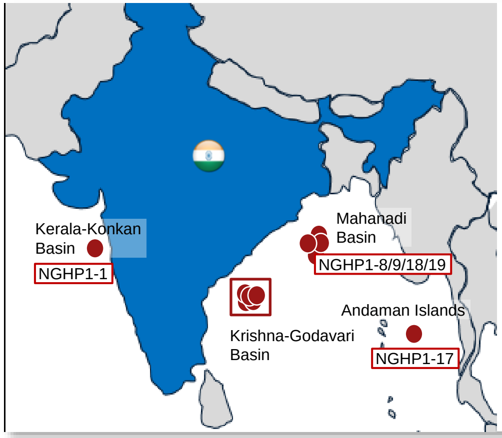
Appendix 6 – National Gas Hydrate Program (NGHP) exploration campaigns

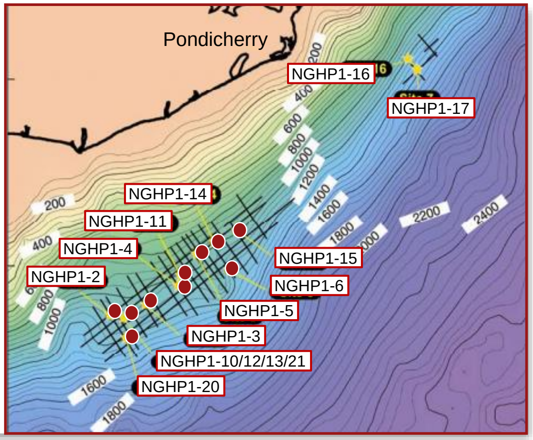
2000

2006
NGHP1:
scientific ocean drilling/coring, logging and analytical activities

2010

2014-2017
NGHP2-NGHP3:
data collection, analysis, identification of sites and pilot production testing





Main stakeholders

Research centers and public organiza-tions[1]	• Directorate General of Hydrocarbons • Ministry of Petroleum and Natural Gas, Government of India • U.S. Geological Survey
Industrials	• Consortium for Scientific Methane Hydrate Investigations lead by Overseas Drilling Limited and Fugro

Project outcomes

NGHP1

- At the time, NGHP1 was one of the most complex and comprehensive methane hydrate field studies ever undertaken. It included a comprehensive analysis of methane-hydrate-bearing marine sediments in both passive continental margins and marine accretionary wedge settings; 39 holes were drilled or cored at 21 sites; 12 holes were logged with logging-while-drilling tools and 13 others were wireline logged.
- Most of the methane hydrate recovered was characterized as pore-filling grain, disseminated in coarser grains, or fracture filling in clay-dominated sediments. One of the thickest and deepest methane-hydrate occurrences was discovered in the Krishna-Godovari Basin, at site NGHP1-10.
- Hydrate deposits were found to be more concentrated in fracture or sand-rich sediments.
- Some vertical fractures have been identified as providing the conduits for gas migration to horizontal or sub-horizontal coarse-grained.

Source: A.T. Kearney Energy Transition Institute analysis; Consortium for Ocean Leadership (2013), "Historical Methane Hydrate Project Review"; Press Information Bureau Government of India (2014), "Memorandum of Understanding between India and United States for cooperation in gas hydrates"; Collett et al. (2008), "Indian continental margin gas hydrate prospects: results of the Indian national gas hydrate program (NGHP) Expedition 01"

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Appendix 7 – Gulf of Mexico Joint Industry Project (JIP)

2000

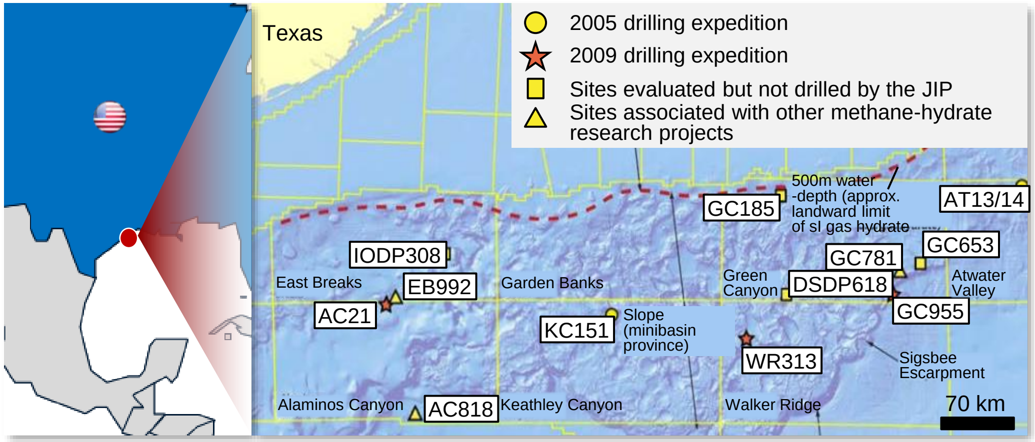
2001
Formation of the JIP: in order to address the challenges that gas hydrates pose for deep-water exploration and production

2005
JIP Leg I: scientific drilling, logging and coring to assess gas-hydrate-related hazards

2009
JIP Leg II: intended to expand previous JIP work to the direct evaluation of gas hydrate in sand-dominated reservoirs

2010

2014
End of the JIP



Main stakeholders

Research centers and public organiza-tions[1]	• U.S. Department of Energy • U.S. Geological Survey • Minerals Management Service1
Industrials	• Chevron • Schlumberger • Halliburton • ConocoPhillips • Total • Japan Oil Gas and Minerals Economic Corporation • Reliance Industries • StatoilHydro • Korea National Oil Company

Project outcomes

JIP 1

- Drilling, coring and downhole-logging operation were safely conducted at five wells at two deep-water locations, in the Atwater Valley and Ketathley Canyon areas.
- Demonstration of the viability of pre-drill technologies for gas-hydrate identification and characterization, as well as the ability to operate safely in areas of hydrate occurrence.
- Seismic, electrical and strength properties were recorded for the first time on sediment cores that had been retrieved and maintained at in situ pressure conditions.

JIP 2

- The drilling of seven wells at three sites confirmed reservoir-quality sands within the methane stability zone in all wells drilled with methane hydrate occurrences.
- In WR313, drilling results confirmed the link between significant peak-trough amplitude and high methane-hydrate saturations in sand. It also indicated that methane hydrates may occur over large distances, well above the base of the gas hydrate stability zone.
- Methane hydrates shortage in well GC955-I stressed the need for a petroleum-system approach. At sites CG955 and WR313, gas may come primarily from deeper sources.

1. Replaced by the Bureau of Ocean Energy Management and the Bureau of Safety and Environmental Enforcement as part of a major reorganization.
Source: A.T. Kearney Energy Transition Institute analysis; Consortium for Ocean Leadership (2013), "Historical Methane Hydrate Project Review"; Ruppel et al. (2008), "Scientific results from Gulf of Mexico Gas Hydrates Joint Industry Project Leg 1 drilling: Introduction and overview"

Appendix 8 – Alaska Mount Elbert Stratigraphic Test Well

2000

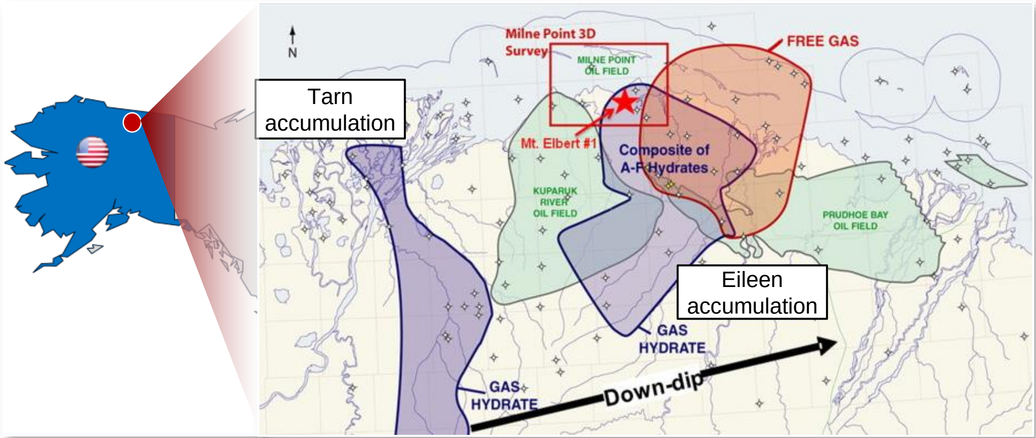
2001-2002
Beginning of the project, building of a team

2003-2004
Phase 1 study: reservoir characterization and well-log acquisition

2005
Phase 2 study: development of more detailed reservoir models

2007
Drilling of a stratigraphic test well Alaska North Slope Milne Point Unit to acquire a full suite of wireline log, core, and formation pressure test data

2010



Main stakeholders

Research centers and public organiza-tions[1]	• United States Geological Survey • U.S. Department of Energy • Lawrence Berkley National laboratory • Isotech Laboratories
Industrials	• BP Exploration Alaska • ASRC Energy Services • Ryder-Scott Company • APA Petroleum Engineering • Fekete • GeoTek • Weston Solutions

Project outcomes

MT ELBERT TEST

- Reservoir characterization, reservoir modeling, and associated studies indicate that 0-12 trillion cubic feet (tcf) of gas may be technically recoverable from 33-44 tcf gas-in-place within the Alaska North Slope Eileen gas-hydrate accumulation.
- Data from the Mount Elbert #1 well reduced uncertainties relating to key gas-hydrate-bearing reservoir properties, enabled further refinement and validation of the numerical simulation of production potential of gas hydrate resources in the region, and helped determine the viability of field sites for potential future long-term production testing.
- Successful operations demonstrated that scientific research into gas hydrates, drilling, data acquisition, and testing programs can be safely, effectively, and efficiently conducted within Alaska North Slope infrastructure.

Source: A.T. Kearney Energy Transition Institute analysis; Consortium for Ocean Leadership (2013), "Historical Methane Hydrate Project Review"; U.S. DoE Office of Fossil Energy (2014), "Resource Characterization and Quantification of Natural Gas Hydrate and Associated Fras Accumulations in the Prudhoe Bay – Kuparuk River Area on the North Slope of Alaska"; NETL (2014), "Alaska North Slope Gas Hydrate Reservoir Characterization"

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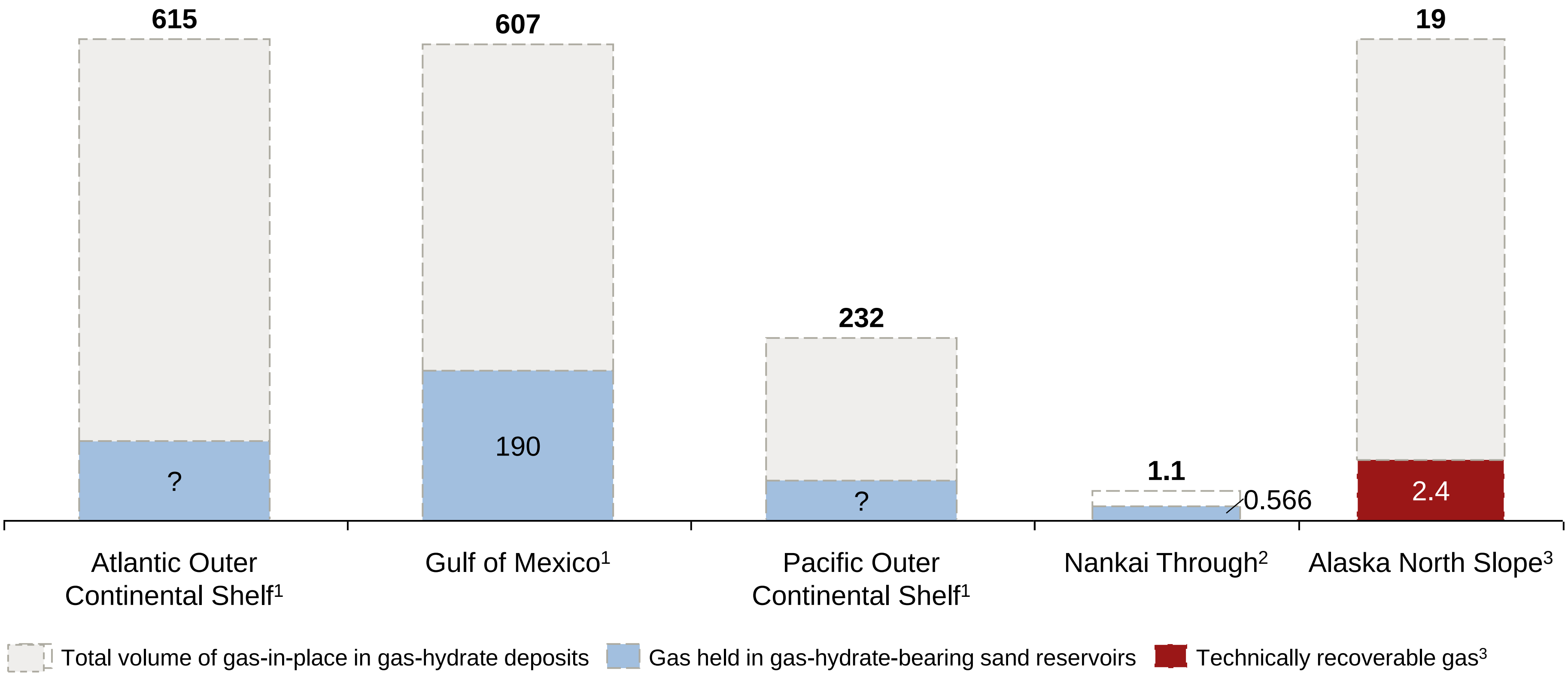
Appendix 9 – Estimated gas-in-place in selected areas

Gas-hydrate deposits: gas-in-place

Mean estimates in tcm

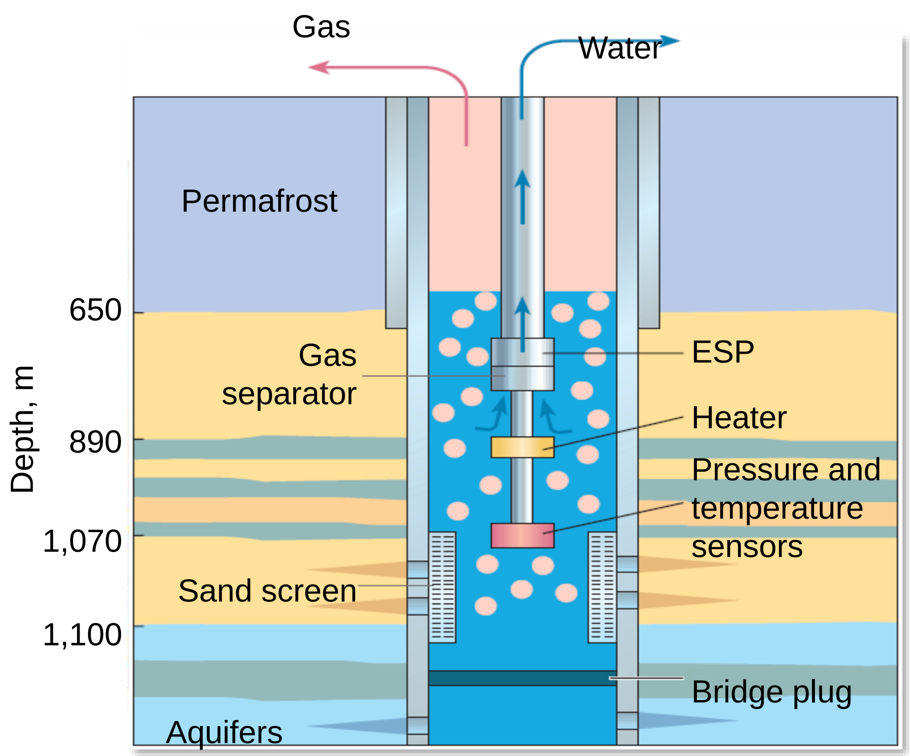


1. Released by the U.S. Bureau of Ocean Energy Management in 2008; at the time, there were insufficient data to assess sand-hosted resource volumes in Atlantic and Pacific Outer Continental Shelves; 2. Released by Japan's MH21 Program in 2008; 3. Study conducted by the U.S. Geological Survey in collaboration with the U.S. Bureau of Land Management in 2008. As of 2014, it is the only one to have assessed technically recoverable resources.

Source: Bureau of Ocean Energy Management (2012), "Assessment of In-Place Gas Hydrate Resources of the Lower 48 United States Outer Continental Shelf"; U.S. Department of the Interior Minerals Management Service Resource Evaluation Division (2008), "Preliminary Evaluation of In-Place Gas Hydrate Resources: Gulf of Mexico Outer Continental Shelf"; Fujii et al. (2008), "Resource Assessment of Methane Hydrate in the Eastern Nankai Trough, Japan"; USGS (2008), "Assessment of Gas Hydrate Resources on the North Slope, Alaska"

Appendix 10 – Gas hydrate depressurization process

Well completion for the Mallik 2008 Depressurization production test



- Depressurization is the most promising dissociation technique for sand reservoirs and will most likely be used for further production tests or medium-term commercial developments.
- During the 2008 Mallik production test in Canada, an electric submersible pump (ESP) installed above the perforations depressurized the formation by lowering the water level in the well. Sand screens prevented sand influx from the unconsolidated formation to the borehole. Hydrate dissociation produced gas and water. After gas-water separation, gas flowed to the surface, and produced water was sampled and reinjected in a separate water-disposal well.

Source Yamamoto and Dallimore (2008), “Aurora-JOGMEC-NRCan Mallik 2006-2008 Gas Hydrate Research Project Progress”; Birchwood et al. (2010), “Development in Gas Hydrates” in Schlumberger Oilfield Review, Vol. 22 Issue. 1

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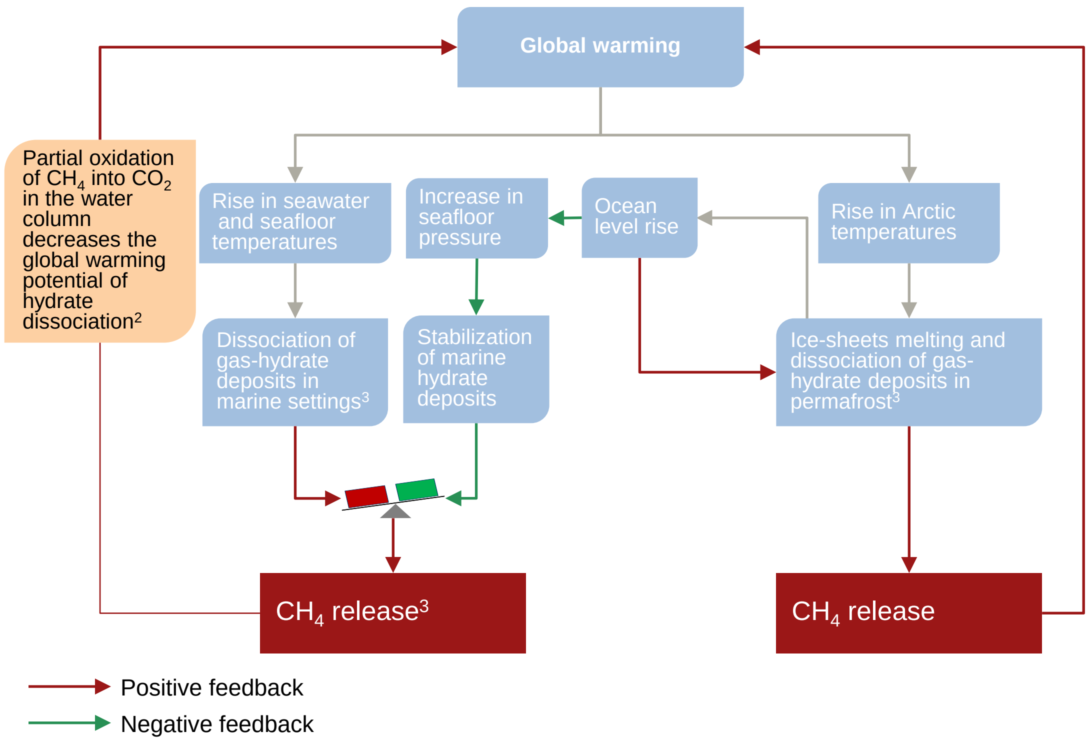
Appendix 11 – Climate change feedbacks and gas-hydrate resources

Description of gas-hydrate emission feedbacks[1]



- **The response of gas hydrates to climate change is still poorly understood.** Indeed, the response is affected by a combination of contradictory feedback mechanisms, both positive and negative.
- **Positive feedback.** A warming Earth will tend to destabilize terrestrial Arctic hydrates, leading to the release of methane. This effect is accelerated by rising sea levels, caused by the melting of glaciers. As water at 4°C covers the flat Arctic plain, it raises the temperature of the ground below it and tends to destabilize hydrate deposits.
- **Negative feedback.** Rising sea level results in an increase in seafloor pressure, which tends to stabilize marine gas-hydrate deposits.
- **It should be noted that all these effects are slow,** and while possibly important over geological timescales, are very unlikely to be significant over a century timescale.

1. Positive/negative feedbacks refer to feedback mechanisms that can accelerate/counterbalance a global-warming trend; 2. For more information about the relative global warming potential of methane and CO2, refer to slide 54; 3. As a result of thermal inertia, heat diffusion and permafrost melting take time and should be slow enough to insulate most hydrate deposits from expected anthropogenic warming over a century timescale. In addition, the fate of methane released is uncertain. For more information, refer to slides 55 and 56.

Source: IPCC (2013), “Carbon and Other Biogeochemical Cycles”; Reagan and Moridis (2007), “Oceanic gas hydrate instability and dissociation under climate change scenarios”; Maslin et al. (2010), “Gas hydrates: past and future geohazard?”

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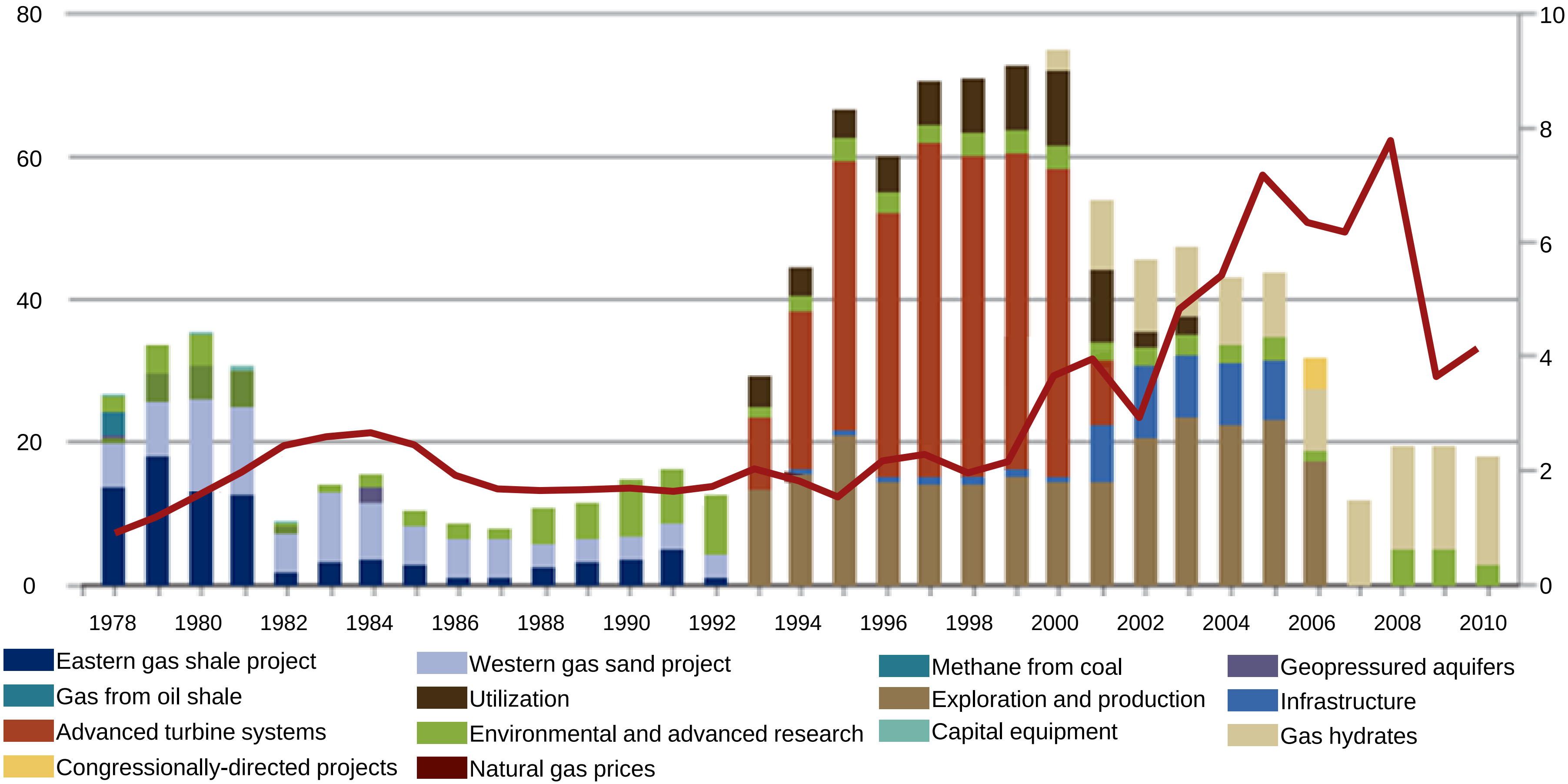
Appendix 12 – U.S. Department of Energy Gas Research & Development

U.S. DoE Natural Gas Research Funding History vs. natural gas price

Spending in millions of nominal $ (left) and natural gas price in $/Mcf nominal (right)



Source: MIT (2011), "The Future of Natural Gas"

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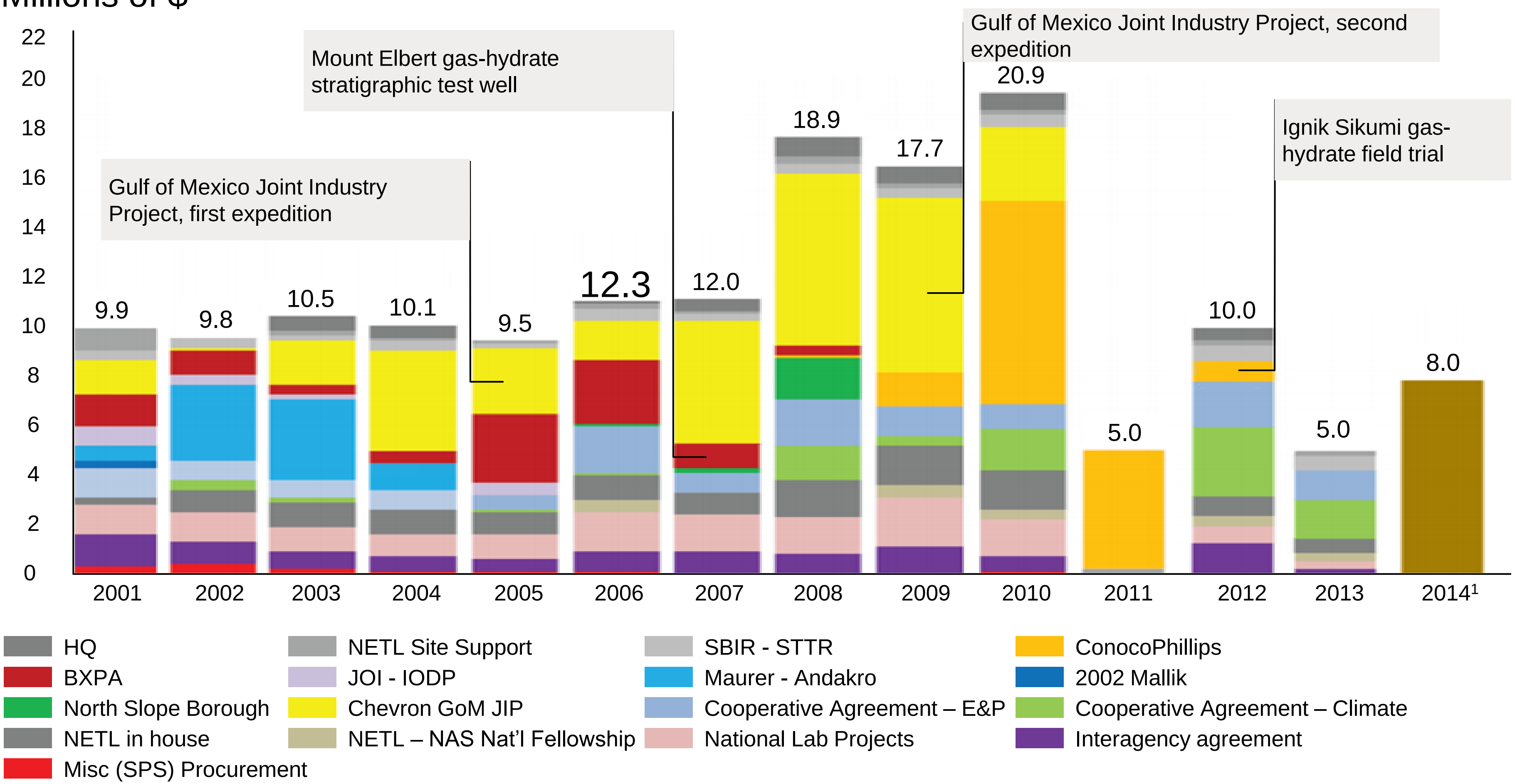
Appendix 13 – U.S. Department of Energy Gas Research & Development

U.S. DoE Gas Hydrate R&D program spending history

Millions of $



Source: U.S. DoE (2014), "DOE's Natural Gas Hydrate Program"

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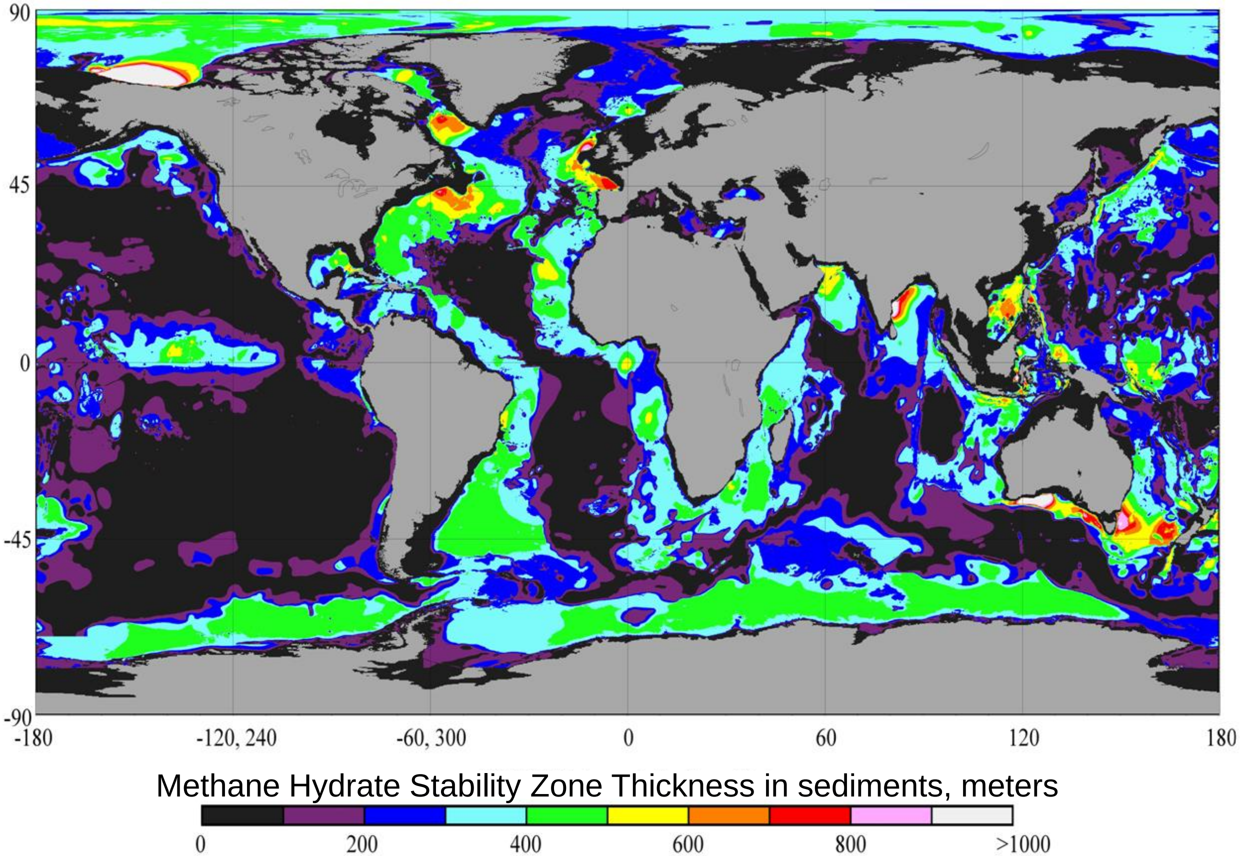
Appendix 14 – Gas hydrate stability zone thickness

Estimated global methane hydrate stability zone thickness in seafloor sediments



Source: Wood and Jung (2008), "Modeling the Extent of Earth's Marine Methane Hydrate Cryosphere"

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Acronyms (1/2)

bcm: billion cubic meters
boe: barrel of oil equivalent
BOEM: Bureau of Ocean Energy Management
BSR: Bottom simulating reflector
Btu: British thermal unit
CAGR: Compound annual (average) growth rate
CAPEX: Capital expenditures
CBM: Coalbed methane
CCS: Carbon capture & storage
CH4: Methane
CO2: Carbon dioxide
CSEM: Controlled source electromagnetic methods
DTS: Distributed temperature sensing
DWPI: Derwent World Patents Index
EIA: Energy Information Administration
EJ: Exajoule
ERR: Economically recoverable resource
GH: Gas hydrate
GHG: Greenhouse gas
GHOZ: Gas hydrate occurrence zone
GHSZ: Gas hydrate stability zone
GIP: Gas-in-place
GMGS: GuangZhou Marine Geological Survey
GWP: Global warming potential
H2S: Hydrogen sulfide
HEI: Hydrate Energy International
IEA: International Energy Agency
IIASA: International Institute for Applied Systems Analysis
IODP: Integrated Ocean Drilling Program
IPCC: Intergovernmental Panel on Climate Change
IPC: International patent classification
JIP: Joint Industry Project
JOGMEC: Japan Oil, Gas and Metals National Corporation
LNG: Liquefied natural gas
LPG: Liquefied petroleum gas
m: meter
MBtu: Million British thermal units
Mol: Mole
MPa: Mega Pascal
N/A: Not applicable
N2: Nitrogen
NETL: National Energy Technology Laboratory
NGHP: National Gas Hydrate Programme
NGL: Natural gas liquids
NGU: Norwegian Geological Survey
NMR: Nuclear magnetic resonance
NASA: National Aeronautics and Space Administration
NOAA: National Oceanic and Atmospheric Administration

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Acronyms (2/2)

NOC: National oil company
O&G: Oil & Gas
OBE: Ocean-bottom electric
ODP: Ocean Drilling Program
OECD: Organisation for Economic Co-operation and Development
OPEC: Organization of the Petroleum Exporting Countries
R&D: Research & development
R,D&D: Research, development and demonstration
RTD: Resistance temperature detector
TRR: Technically recoverable resource
UBGH: Ulleung Basin Gas Hydrate
U.S.: United States of America
USBL: Ultra-short baseline
USGS: United States Geological Survey
WIPO: World Intellectual Property Organization
WTP: Willingness-to-pay

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Picture credits

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