EMD Gas Hydrates Committee
Annual Report

Timothy S. Collett, Chair
U.S. Geological Survey
Colorado School of Mines

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Executive Summary

Gas hydrate is a widespread naturally-occurring combination of water and natural gases. Gas hydrate is found in shallow sediments of deepwater regions of the continental margins and in areas of continuous permafrost. Global research on the potential commercial viability of gas extraction from gas hydrates continues, predominantly in Asia and in the United States, where current efforts focus on the controlled destabilization of highly-saturation deposits hosted in mostly sand-rich reservoirs.

Production tests in Arctic Canada (Mackenzie Delta) and Alaska have shown that gas can be produced from highly-concentrated gas hydrate accumulations in coarse-grained (i.e., sand rich) reservoir systems with conventional production technologies. Production can be achieved through the depressurization method and by more complex methods such as molecular substitution (e.g., CO_2-CH_4 exchange). In 2013, a gas hydrate production test was conducted in a marine setting in the offshore of Japan. An additional test was conducted in Japan in 2017 to further evaluate alternative well completion technologies. Also in 2017, China completed a 60-day gas hydrate production test in the Shenhu region of the South China Sea.

Introduction

Gas hydrate field production tests, laboratory studies, and computer modeling have documented the fact that gas hydrates hosted in sand-rich, conventional reservoirs systems, can occur at high concentrations and can be produced with conventional hydrocarbon production technologies (Collett, 2002; Boswell et al., 2017). Initially, gas hydrate production studies focused on well-known gas hydrate accumulations in onshore Arctic permafrost environments (Figures 1A and 1B). The Mallik site, in the outer Mackenzie River Delta of northern Canada, and the Eileen/Tarn Gas Hydrate Accumulations on the Alaska North Slope have each been the focus of several important field production tests. In 2013, the Government of Japan reached an important milestone by undertaking the first test of a marine gas hydrate accumulation in the Nankai Trough located along the southeastern margin of Japan. In 2017, a second gas hydrate production test was conducted in the Nankai Trough to evaluate various completion and production systems. Also in 2017, the Government of China completed the first production test of a marine gas hydrate accumulation in the South China Sea. The completed Arctic permafrost and deep marine gas hydrate production tests have confirmed that gas hydrate can be produced by simply depressurizing the hydrate-bearing reservoir; thus, allowing the gas released from the solid hydrate structure to be produced to the surface much like gas from conventional reservoirs. Additional gas hydrate production testing has been proposed and is being planned for offshore China, Japan, and India. Also, the initial phases of a new gas hydrate testing project located on the Alaska North Slope was started in late 2018 that is scheduled to include extended production testing operations (https://www.netl.doe.gov/node/8020).

This report reviews the results of several of the key Arctic permafrost and marine gas hydrate production studies with a focus on understanding the geologic and engineering controls on the occurrence and production characteristics of gas hydrates.

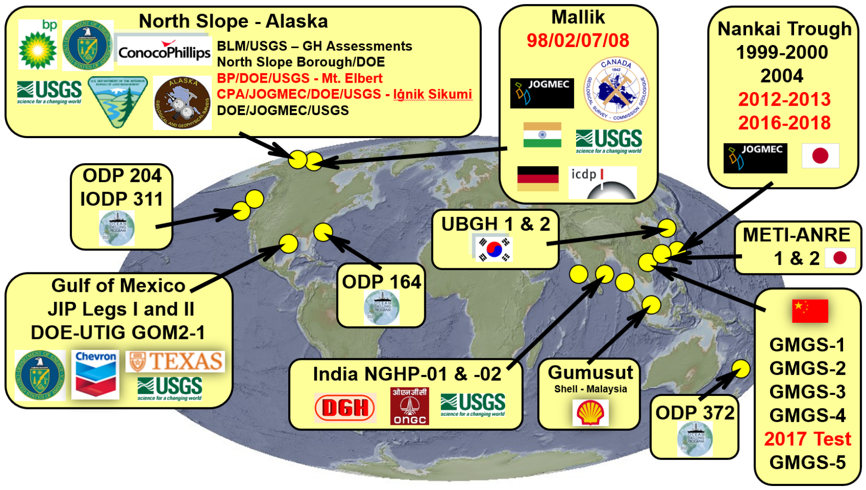

Figure 1A. Map of past scientific and industry drilling activities conducted by countries, private sector, government agencies, and academia that have helped to refine global gas hydrate resource estimates and characterize the energy resource potential of gas hydrates.

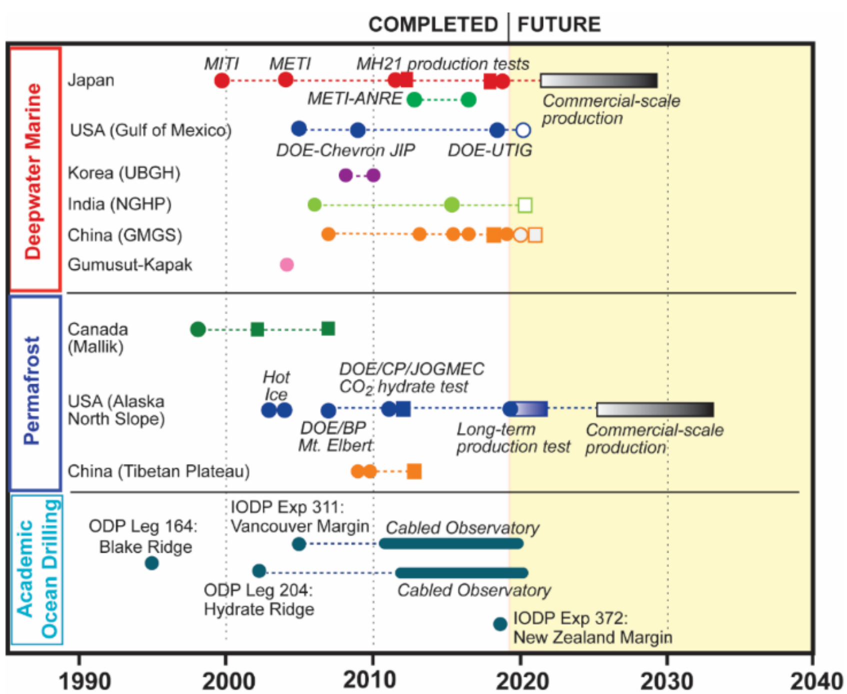

Figure 1B. Timeline of past scientific and industry drilling activities conducted by countries, private sector, government agencies, and academia that have helped to refine global gas hydrate resource estimates and characterize the energy resource potential of gas hydrates.

Mallik (Canada)

The Mallik gas hydrate research site in northern Canada has been the focus of three important gas hydrate field tests (i.e., Mallik Gas Hydrate Testing Projects 1998, 2002, and 2007-2008). The Mallik 2L-38 gas hydrate research well (which was part of the 1998 Mallik Gas Hydrate Testing Project), was drilled to evaluate the geologic controls on the occurrence of gas hydrate and for the first time acquire specialized core and well data needed to characterize the reservoir properties of a hydrate-bearing reservoir system (Dallimore et al., 1999). With the successful completion of the 1998 Mallik Gas Hydrate Testing Project, the Mallik site became the focus of two new field studies that dealt with trying to produce gas hydrates for the first time, which included the Mallik 2002 Gas Hydrate Production Research Well Program (Dallimore and Collett, 2005) and the 2007-2008 JOGMEC/NRCan Mallik Gas Hydrate Production Research Program (Ashford et al., 2012; Dallimore et al., 2012).

The gas hydrate production testing efforts under the Mallik 2002 Gas Hydrate Production Research Well Program dealt with trying to heat and depressurize in-situ gas hydrate-bearing reservoirs (Dallimore and Collett, 2005). The production tests conducted in 2002 at Mallik were a series of controlled experiments that were designed to yield critical gas hydrate reservoir data and to further develop and test computer simulators that could be used to predict the response of gas hydrate reservoirs to both depressurization and thermal heating.

The Mallik 2002 gas hydrate depressurization tests included the deployment of a wireline conveyed formation testing tool that was used to test three hydrate-bearing reservoir units in the Mallik 5L-38 well. The response of the hydrate-bearing reservoirs during each test was similar to the pressure response of conventional reservoirs in that it was possible to produce water and gas from the reservoir during the depressurization phase, and the pressure in the reservoir rebounded to near the initial hydrostatic pressure conditions when the reservoir was “shut-in”. Transient analysis of the acquired pressure test data estimated that the permeability of the hydrate-bearing sand-rich reservoirs at the Mallik site range from about 0.001 to 0.1 mD (Hancock et al., 2005).

The Mallik 2002 field production test also include a thermal testing phase where a portion of the hydrate-bearing reservoir section was subjected to a borehole heat source of 50°C, which is approximately 40°C higher than the in-situ natural thermal condition of the reservoir being tested. As shown in Figure 2, over the duration of this 5-day long test, the rate of gas production from the well was highly variable with a maximum flow rate of 360 ft^3/day (Dallimore and Collett, 2005). Because of the reliance on only conductive heat exchange in this experiment, the overall observed gas production rate was low throughout.

In summary, under the Mallik 2002 project gas hydrate was produced for the first time by both depressurizing and heating the reservoir. It was also concluded that depressurization alone appeared to be the most feasible method for producing gas hydrates. However, because of the limited nature and duration of the Mallik 2002 gas hydrate depressurization tests, it was determined that to further advance our understanding of the producibility of gas hydrates, that a longer duration test would be required, the 2007-2008 JOGMEC/NRCan Mallik Gas Hydrate Production Research Program was designed to address this need.

As described by Ashford et al., (2012) and Dallimore et al., (2012), the 2007-2008 JOGMEC/NRCan Mallik Gas Hydrate Production Research Program was designed to conduct an extended duration depressurization test of a highly concentrated gas hydrate reservoir using conventional production technology to further characterize the production response of gas hydrate. The winter 2006 operations at Mallik dealt mainly with preparing the test site and well for testing in the winter of 2007. Because the Mallik site is only accessible by “ice-road”, all on-site operations are limited to about a four-month long winter operational window each year. In order to test borehole completion configuration, a 60-hour long flow test was completed in the Mallik test well at the end of the winter 2006 season. A 12-m-thick sand-rich hydrate-bearing reservoir was tested at a downhole flowing pressure of about 7.3 MPa, which is equivalent to a drawdown pressure (relative to an assumed hydrostatic gradient) of 3.7 MPa (Ashford et al., 2012). The apparent production of sand and pump control problems limited the duration of the winter 2006 test, which in the end produced about 830 m^3 (~29, 300 ft^3) of gas. Thus, again demonstrating the fact that gas hydrates can be produced by depressurization techniques. The winter 2006 Mallik operations included a six-day long depressurization flow (Figure 3), which was able the establish a sustained and stable gas flow rate averaging about 3,000 m^3/day (~105,000 ft^3/day). The total volume of gas and water produced over the duration of the test was about 13,000 m^3 (~460,000 ft^3) and 100 m^3 (~850 barrels), respectively (Ashford et al., 2012; Dallimore et al., 2012).

As summarized by Dallimore et al., (2012), the geologic, engineering, and production studies conducted over a decade at the Mallik site have provided critical insight into the geologic controls on gas hydrates in nature and for the first time direct information on the production response of hydrate reservoir systems. It was also concluded that longer duration production tests, under a wide range of reservoir conditions, would be required to fully assess the resource potential of gas hydrates.

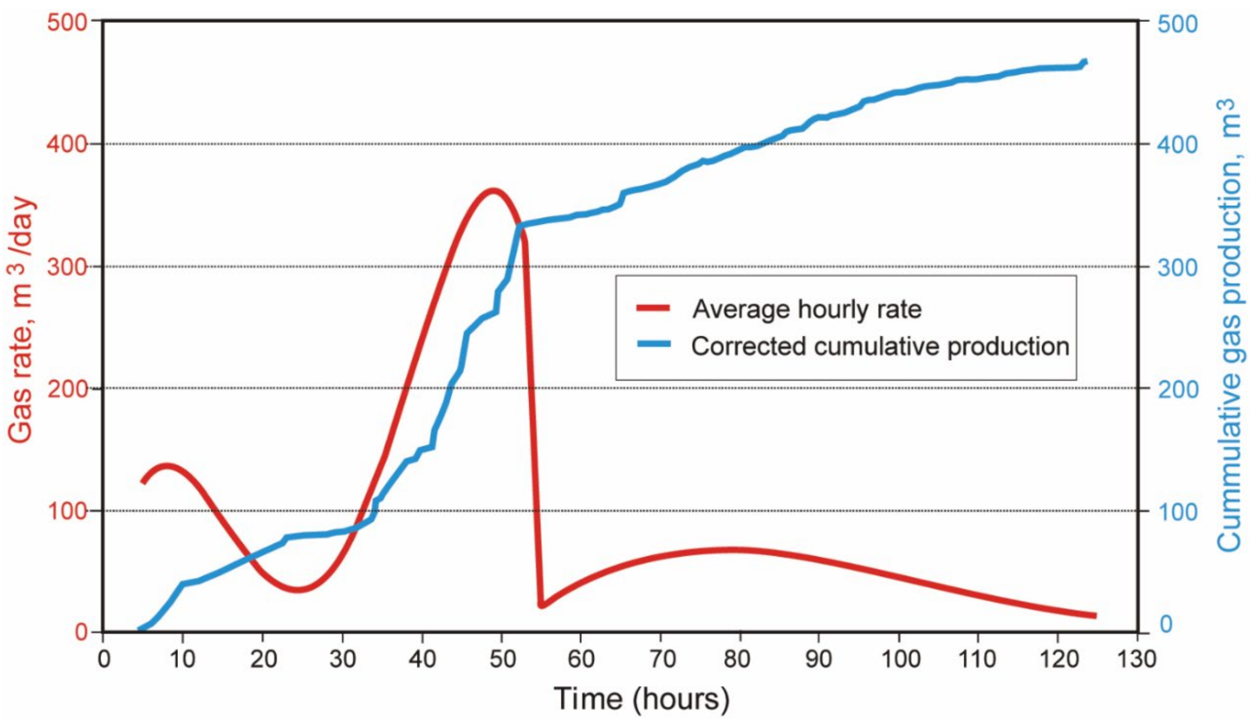

Figure 2. Gas hydrate production diagram showing the results of the thermal test in the 2002 Mallik 5L-38 gas hydrate production test well, depicted is the cumulative produced gas volume and the average hourly production rate (modified from Dallimore and Collett, 2005).

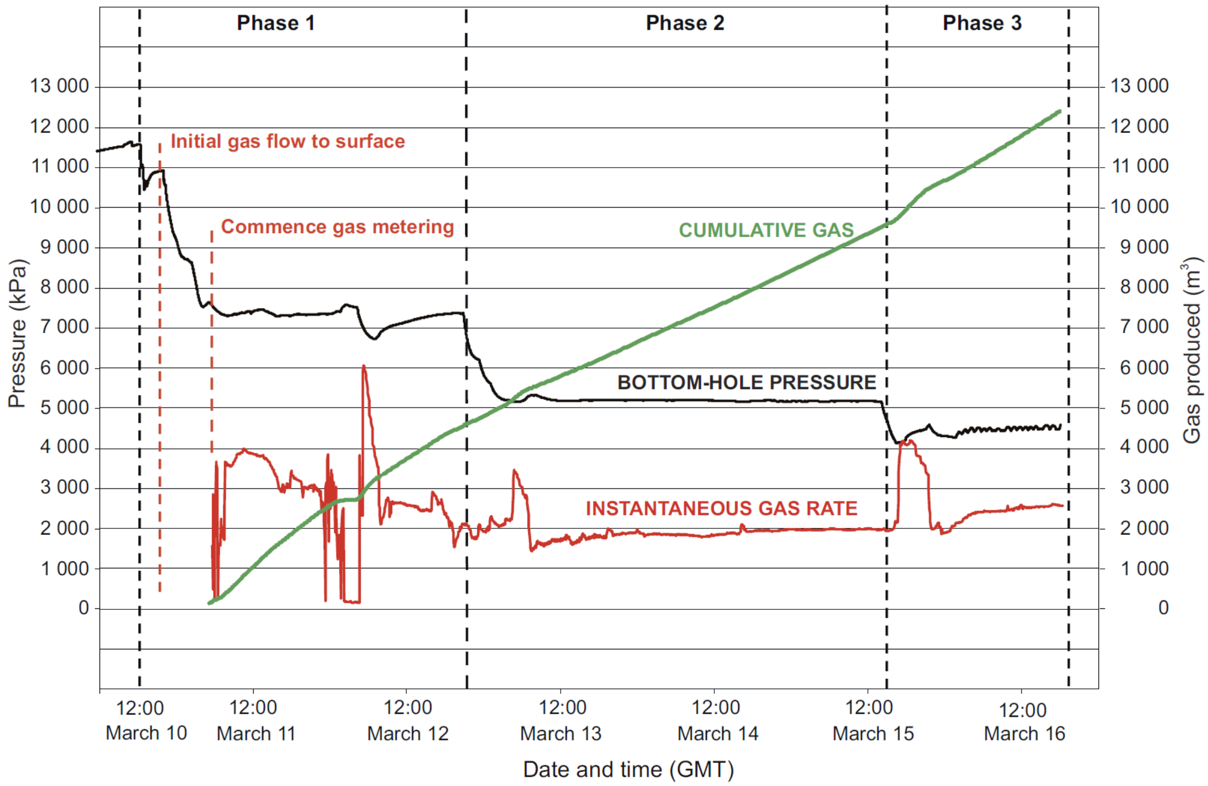

Figure 3. Downhole pressure, gas production rates, and cumulative gas produced during the depressurization production test of the 2008 Mallik 2L-38 well (modified from Ashford and others, 2012).

Alaska North Slope (USA)

The occurrence of gas hydrate on the Alaska North Slope (ANS) is closely associated with well-characterized petroleum systems (Collett, 1993). The U.S. Geological Survey Alaska Gas Hydrate Assessment Team (2013) through their assessment of the energy resource potential of gas hydrates in Alaska generated a series of maps showing distribution and thickness of the gas hydrate stability zone on the ANS. Physical evidence for presence of gas hydrate was established through the analysis of cores and downhole logs from an industry test well and two government sponsored gas hydrate test wells (the Mount Elbert, and Iġnik Sikumi wells) as drilled in the Prudhoe Bay and Milne Point oil fields. The analysis of log data obtained from more than 1,000 oil exploration and development wells have also been used to identify and map the distribution of various gas hydrate accumulations and prospects across the ANS (Collett, 2002). These studies have also indicated that most of the known gas hydrate accumulations on the ANS, and likely throughout the Arctic, were originally conventional free-gas fields that in response to the onset of cold Arctic conditions at the start of the Pleistocene were converted gas hydrate.

The Mount Elbert Gas Hydrate Test Well in 2007 was dedicated to coring, downhole logging and short-duration formation pressure tests, which provided the first comprehensive data collection on the geologic controls on the occurrence of gas hydrates in northern Alaska. The Mount Elbert project acquired a comprehensive set of advanced well surveys, more than 130 m (or 427 ft) of core, and MDT style formation test data (Hunter et al., 2011). The Mount Elbert MDT program included a series of "pre-flow tests" that were conducted under conditions that would allow for the analysis of in situ reservoir properties in advance of gas hydrate dissociation within the reservoir being tested. During the same tests, the pressure was eventually drawn-down below gas hydrate equilibrium conditions and the gas hydrate was allowed to dissociate; thus, producing gas and water. The MDT test results from the Mount Elbert well compared favorably with the results of similar tests in the 2002 Mallik 5L-38 well. The Mount Elbert and 2002 Mallik 5L-38 MDT results both show a mobile water phase within hydrate-bearing reservoirs even at very high gas hydrate saturations. Modeling work reported by Anderson et al., (2008), also concluded that the pore-space within two of the hydrate-bearing reservoirs tested at the Mount Elbert site on the ANS were characterized by mobile pore-water saturations as high as 15% (with in situ reservoir permeabilities as high as 0.17 mD). It is important to note that the recognition of the presence of a mobile water phase within gas hydrate reservoirs was an important development in that it provided the means, or pathway, to draw the pressure down on hydrate-bearing reservoirs; thus, allowing for the effective depressurization of gas hydrate reservoirs and the production of gas from these complex reservoir configurations.

The analysis and modeling of the data from the Mount Elbert well, along with other available log data from existing industry wells in the area, led to the identification of the PBU L-Pad area as the most optimal site for the subsequent Iġnik Sikumi gas hydrate production test (Collett et al., 2011; Schoderbek et al., 2012, 2013; Boswell et al., 2017). Building on promising laboratory studies dealing with CH_4 hydrate CO_2 exchange technology, ConocoPhillips and the DOE entered into a cooperative research agreement in 2008 with the goal to develop a multi-year field trial to investigate CO_2 injectivity and the exchange potential of CO_2 with CH_4 in a hydrate-bearing reservoir on the ANS (Schoderbek et al., 2012). This project was a multidisciplinary effort that incorporated laboratory and computer simulation models to design the CO_2-CH_4 exchange field test. The criteria used to select the location of the test site included the consideration of the proximity to established infrastructure including roads and production gravel pads, and the occurrence of known hydrate deposits with multiple reservoirs at suitable temperature and pressure conditions. A site was chosen near the L-Pad in the Prudhoe Bay Unit; downhole log data from nearby wells indicated that the Eileen gas hydrate accumulation likely extended across the area of the proposed test site and the test well, named Iġnik Sikumi #1, would likely encounter three hydrate-bearing sandstone reservoirs within the depth interval from 115 to 735 m.

The 2011 Iġnik Sikumi field test involved the drilling of a single, near-vertical, test well and conducting wireline logging of targeted hydrate-bearing reservoirs. In 2012 the Iġnik Sikumi field testing program included a CO_2-CH_4 hydrate production test and an extended duration depressurization flow-back test. The Iġnik Sikumi gas hydrate test was performed in the same vertical well (total depth of 792 m; 2,597 ft) drilled in 2011 (Anderson et al., 2014). The first stage of the test consisted of the injecting 210,000 scf of a CO_2-N_2 mixture over a period of 13 days (Figure 5). Flow back of the well commenced following the reconfiguration of the surface equipment.

One of the most notable scientific accomplishments of the trial was the identification of a specific mixture of N_2/CO_2 gas that prevented the formation of secondary CO_2 hydrate in the reservoir, which in turn allowed for the injection of CO_2 into the reservoir being tested. After injecting 210 mscf of the N_2/CO_2 gas mixture, the well was flowed for a period of 37 days with gas production rates exceeding 175,000 ft^3/day (Figure 5). The final drawdown stage, which featured formation pressures below CH_4 hydrate stability, saw sustained gas production rates ranging from 20,000 ft^3/day to 45,000 ft^3/day. Most of the N_2 that was injected into the reservoir was recovered from the well during the backflow stage of the test; however, about 48 mscf (around half) of the CO_2 injected into the reservoir remained in the formation. The Iġnik Sikumi test successfully demonstrated that CO_2 could be injected into a water-bearing reservoir under conditions that would usually form secondary CO_2 hydrates, CH_4 was than produced from the reservoir, and N_2/CO_2 exchange technology was shown to be technically feasible (Schoderbek et al., 2012).

On 23-Janurary-2019, DOE in partnership with the Japan Oil, Gas and Metals National Corporation (JOGMEC), the U.S. Geological Survey (USGS), and Petrotechnical Resources-Alaska (PRA) announced the successful completion of a stratigraphic test well on the ANS that proved the occurrence of gas hydrates in two sand-rich reservoir sections that are suitable for potential future testing. It was reported that the location of a stratigraphic test well in the greater Prudhoe Bay Oil Field provides the necessary infrastructure to conduct field experiments of sufficient duration to reveal how gas hydrates release natural gas in response to reservoir depressurization. Currently such long-term testing cannot be feasibly done either offshore or in an undeveloped Arctic area onshore. This initial well, which is expected to be part of a three well pilot test site, was suspended with temperature and acoustic-monitoring devices that will allow it to serve as a monitoring well for future field experiments. Significant subsurface data was secured including a full suite of geophysical measurements and 39 sidewall pressure cores during the operation.

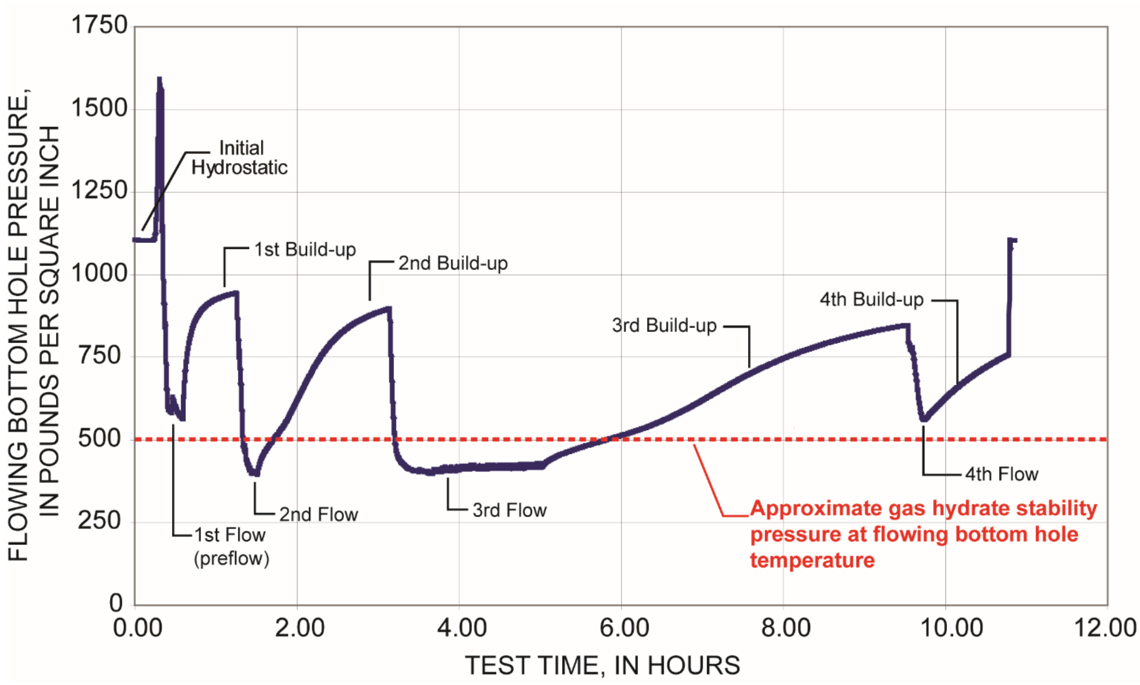

Figure 4. Downhole pressure data from MDT test C2 at ~656 m (2,151 ft) in the Mount Elbert test well. Plot shows three pressure drawdown-recovery sequences (modified from Anderson et al., 2008).

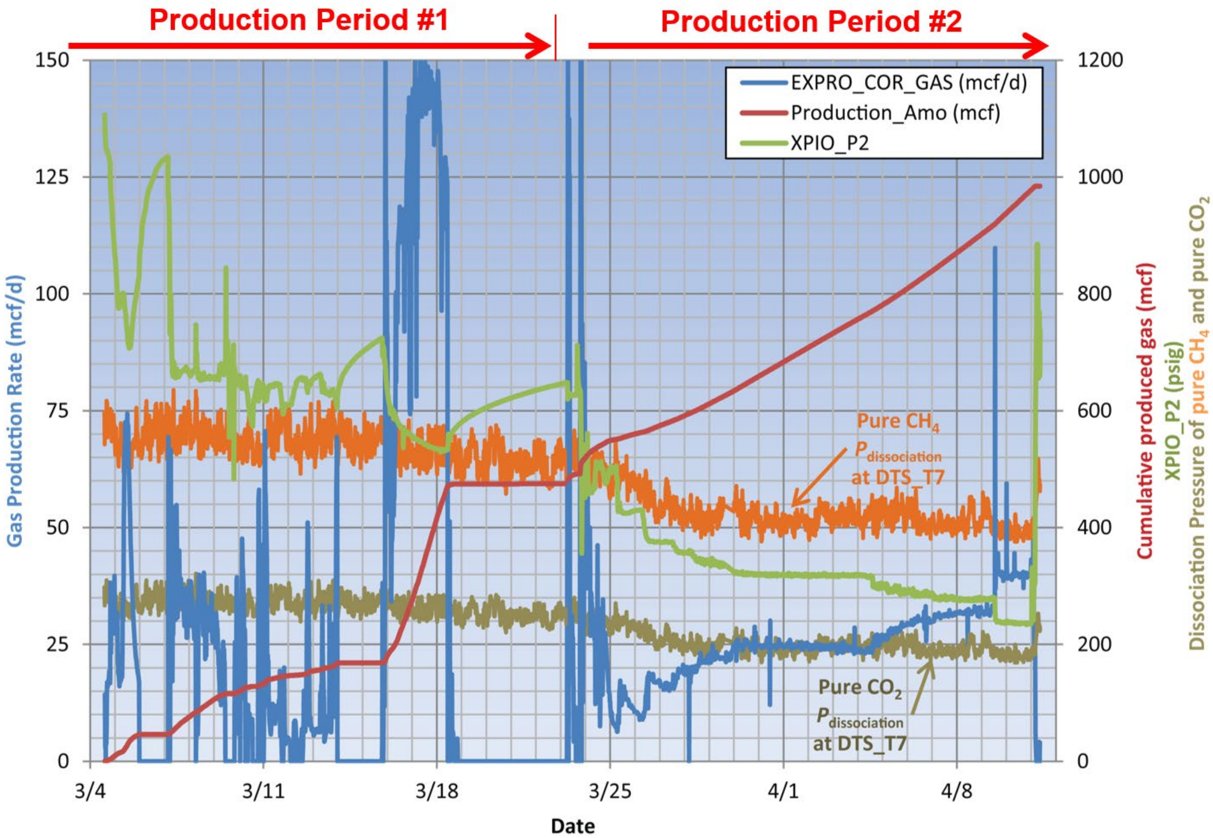

Figure 5. Results of the Iġnik Sikumi field production test (modified from Boswell et al., 2017). The light green line indicates wellbore pressure at the reservoir level. The blue line shows the gas production rate. The red line shows the cumulative gas produced during the test. The orange line represents the calculated pressure-temperature phase boundary for pure CH_4 hydrate. The dark green line represents the calculated pressure-temperature phase boundary for pure CO_2 hydrate. During "Production Period #1" the bottom hole flowing pressure never dropped below the phase boundary for pure CH_4 hydrate. During "Production Period #2" the bottom hole flowing pressure did drop below the phase boundary for pure CH_4 hydrate; however, it never dropped below the phase boundary for pure CO_2 hydrate.

Nankai Trough (Japan)

In 1994 the Petroleum Council of Japan recommended that the energy resource potential of gas hydrates in the offshore of Japan should be further assessed. In response, the Ministry of International Trade and Industry (now the Ministry of Economy, Trade and Industry: METI) developed plans for a gas hydrate exploratory drilling project named "Nankai Trough". The project was led by the Japan National Oil Corporation (now the Japan Oil, Gas and Metals National Corporation: JOGMEC) on behalf of METI. The focus of this effort was to assess the energy resource potential of gas hydrates inferred previously from the identification of BSRs on seismic lines from the offshore area off the Tenryu River in Shizuoka Prefecture (Tsuji et al., 2004, 2009). Early in 2000, JOGMEC led an effort to drill a gas hydrate prospect for the first time to confirm the occurrence of gas hydrate in the Nankai Trough (Figure 6A). Drilling, downhole logging, and coring at the 2000 Nankai Trough test site documented the presence several thick hydrate-bearing coarse-grained reservoir sections. The total thickness of the hydrate-bearing reservoir section encountered at the 2000 Nankai Trough test site was calculated at about 13 m; with downhole log-derived gas hydrate saturations exceeding 80% in several layers.

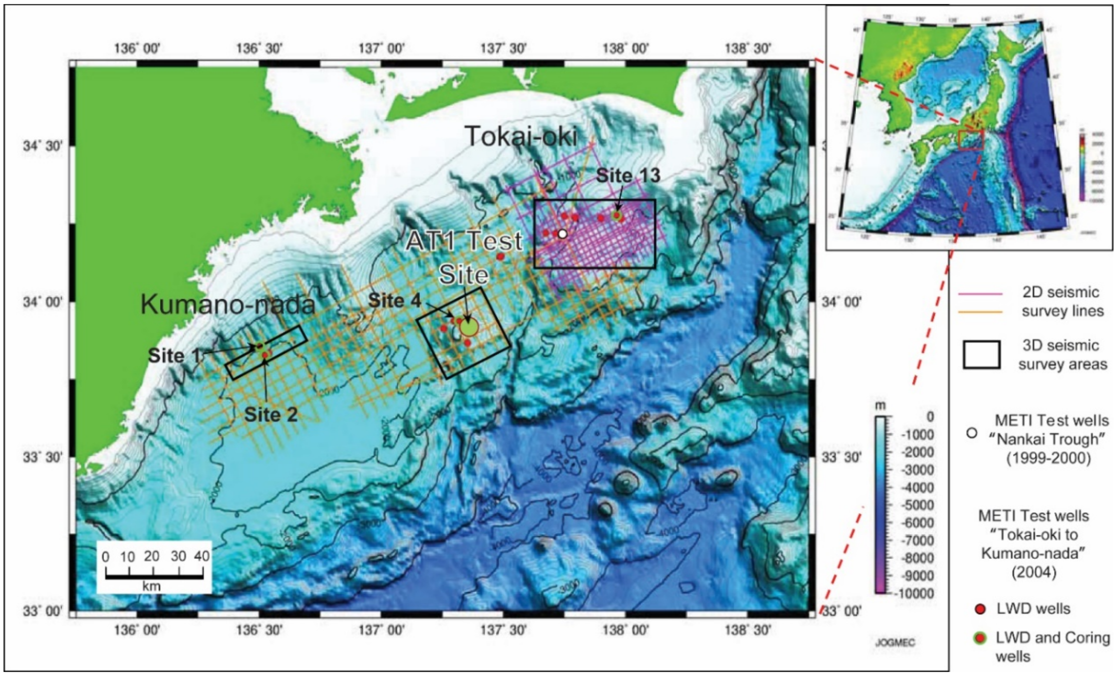

Figure 6A. Map of Nankai Trough region along the southeast coast of Japan. Shown are the locations of the 1999/2000 METI wells and the 2004 Tokai-oki to Kumano-nada wells along with the location of the 2012/2013 AT1 Test Site. Also shown is the location of the 2D and 3D seismic data used to select the location of the sites drilled during both field efforts (modified from Fujii et al., 2009).

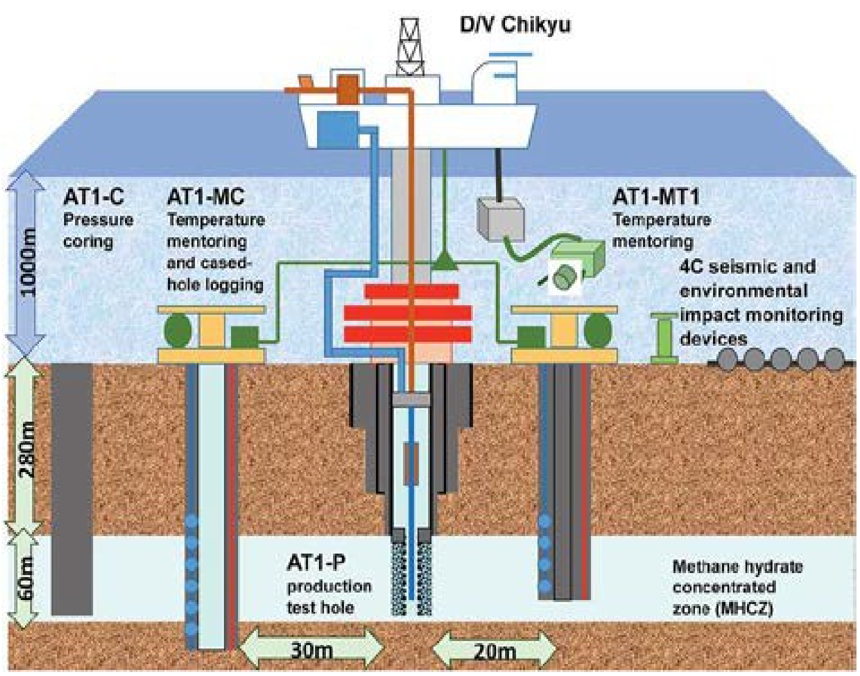

Figure 6B. Schematic view of the Nankai Trough 2012/2013 AT1 gas hydrate production test site, including production test hole (AT1-P) and two monitoring holes (AT1-MT1 and AT1-C) (modified from Yamamoto et al., 2014). A coring hole and seafloor monitoring devices (ocean bottom cable for multi-component seismic survey and environmental-impact-monitoring sensors with methane sensors and a precise pressure gauge for subsidence measurement) were deployed around the production test holes. Temperature sensors were also deployed in some of the boreholes as shown.

After the success of the 2000 Nankai Trough Project, in 2001 METI launched a new project titled "Japan's Methane Hydrate Exploitation Program," under the direction of the Methane Hydrate 2001 Consortium (also known as MH21), with the goal to assess the energy resource potential of gas hydrates in the offshore of Japan, much like the goals of the previous Nankai Trough project. However, this project was intended to go much further, with the goal to develop the technology required to commercially produce gas hydrates. The multi-well "METI Toaki-oki to Kumano-nada" drilling project was conducted in early 2004 (Fujii et al., 2009; Tsuji et al., 2009). A total of sixteen sites (32 wells) were established in water depths ranging from ~700 to ~2,000 m (Figure 6A). The occurrence of pore-filling gas hydrate in turbidite sand reservoirs were confirmed from the analysis of downhole logs and cores as collected during the Toaki-oki to Kumano-nada exploration project. The acquisition and recovery of high quality downhole log data, new seismic data, and both conventional and pressure cores were used to estimate the volume of gas associated with the gas hydrate accumulations in the Nankai Trough. These same data were used to develop computer simulations to predict the production characteristics of several of the gas hydrate accumulations discovered in the Nankai Trough.

The MH21 program in 2013 completed the first ever test of gas production from marine gas hydrates (Yamamoto, 2015; Konno et al., 2017). The drilling vessel *D/V Chikyu*, was used for drilling and coring operations to establish the MH21 Nankai Trough 2012-2013 test site, named the AT1 site (Figures 6A and 6B). At the AT1 site, a production test well (AT1-P), two monitoring wells (AT1-MC and MT1), and a core well (AT1-C) were established in 2012. An extensive LWD and wireline-logging program was conducted in the AT1-MC well to characterize gas hydrate reservoir properties and to select the stratigraphic section to be tested in 2013 (Yamamoto, 2015). The AT1-MC encountered a 60-m-thick turbidite sand section with well log inferred reservoir sections ranging in thickness from a few centimeters to a few meters. Well log correlations between the AT1-MC and MT1 wells, which are offset by a distance of 40 m, exhibit good lateral continuity within the targeted test sand section. To obtain additional reservoir and seal property data from the AT1 test site, the Hybrid Pressure Coring System was used to acquire cores at near in-situ conditions from the AT1-C well and the recovered cores were processed through the Pressure Core Analysis and Transfer System (PCATS) lab at in-situ conditions to obtain critical reservoir engineering data.

The gas hydrate production flow test was conducted at the AT1 site in the spring of 2013. The AT1 production test started on 12-March-2013 and was completed on 19-March-2013, which was earlier than originally planned, because of sand production problems and deteriorating weather conditions. The cumulative volume of gas and water produced during the 6-day test at AT1 was estimated at ~120,00 m^3 and ~1,300 m^3, respectively (Figure 7) (Yamamoto, 2015; Konno et al., 2017). Based on the results of the 2013 AT1 test, a second test was designed and executed in 2016 to acquire additional quantitative data for the assessment of various gas hydrate production completion technologies.

In June of 2017, METI announced the completion of the second gas hydrate production test in the Nankai Trough (http://www.meti.go.jp/english/press/ 2017/0629_001.html). It was reported that the Agency for Natural Resources and Energy (ANRE) launched a new production test in the Nankai Trough, commissioned to JOGMEC, to test gas hydrate production in the offshore area between Atsumi Peninsula to Shima Peninsula (Daini Atsumi Knoll). It was further reported that the test was complete on 28-June-2017.

The ANRE and JOGMEC led second gas hydrate production test was designed to test new completion technologies designed to deal with sand production issues experienced in the first marine production test in 2013. During the 2017 test, one of the two production test wells experienced significant sand production problems; however, it was reported that the second well yielded sustained production over several operational flow periods (Yamamoto et al., 2019). It was also reported that they "could not clearly confirm an increase in the production rates at either of the wells, leaving challenges in establishing gas production technologies unsolved." The amount of gas produced from the first well during the 2017 Nankai Trough gas hydrate production test was approximately 35,000 m^3 in a total of 12 days; the second well produced approximately 200,000 m^3 of gas in a total in 24 days (Figure 8A-B).

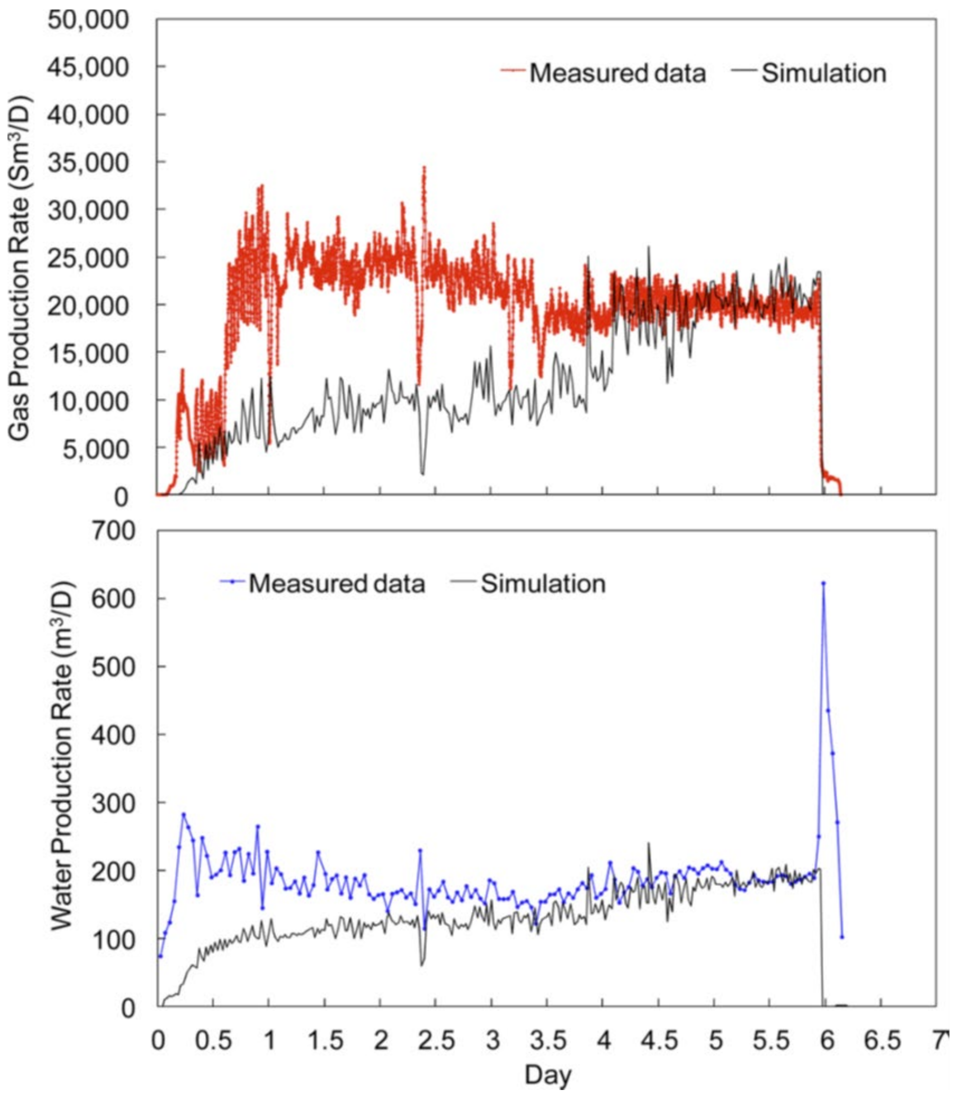

Figure 7. Measured and simulated (computer production model derived) gas and water production rates associated with the 2013 Nankai Trough Production Test (modified from Konno et al., 2017).

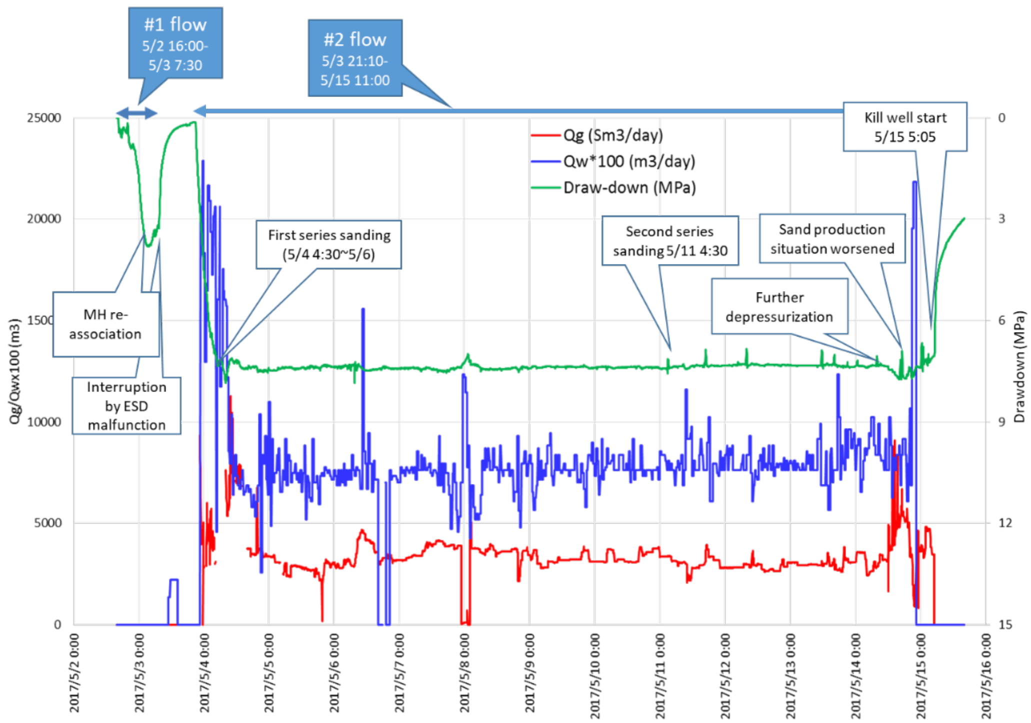

Figure 8A. Measured gas and water production rates associated with the 2017 Nankai Trough Production Test in the AT1-P3 well (modified from Yamamoto et al., 2019).

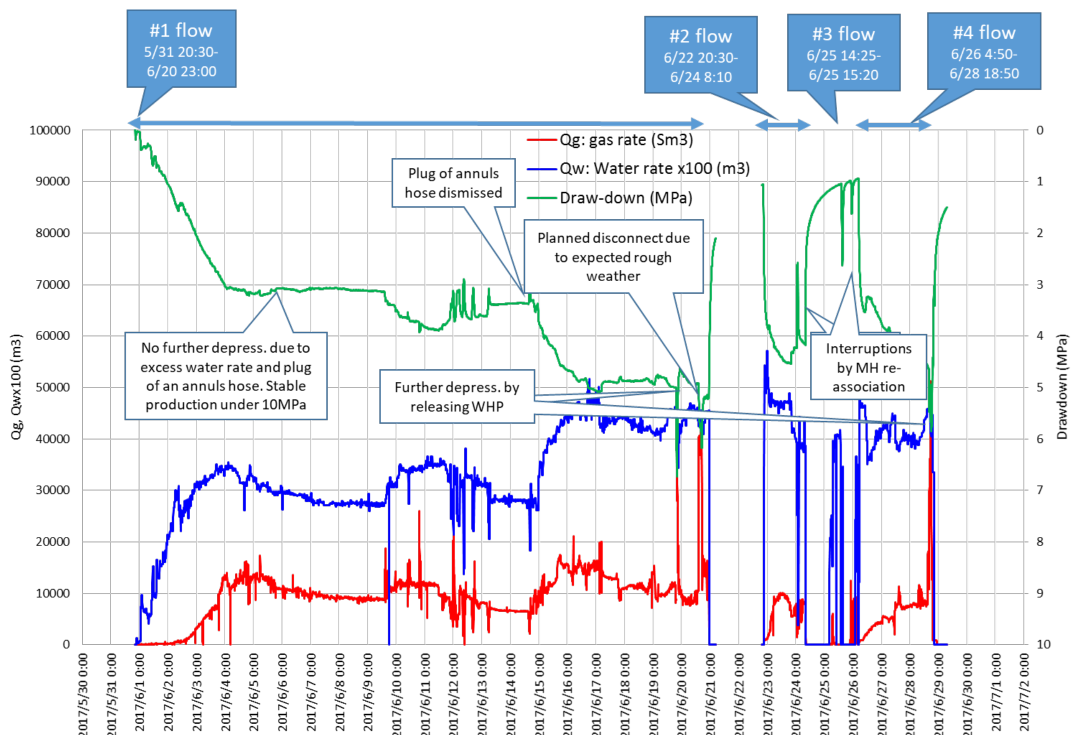

Figure 8B. Measured gas and water production rates associated with the 2017 Nankai Trough Production Test in the AT1-P2 well (modified from Yamamoto et al., 2019).

South China Sea (China)

The Guangzhou Center for Gas Hydrate Research was established in 2004 to conduct energy focused laboratory and field studies in the offshore of China. In June 2007, the Guangzhou Marine Geological Survey (GMGS) successfully completed a deepwater gas hydrate drilling and coring program (named GMGS1) in the South China Sea (Zhang et al., 2007; Yang et al., 2008; Wu et al., 2008). In 2015 and 2016, two additional geoscience expeditions (GMGS3 and GMGS4) were conducted in the Shenhu gas hydrate province. Both drilling expeditions featured logging-while-drilling (LWD), with 19 sites drilled in the Shenhu area during GMGS3 and 11 during GMGS4. A subset of these sites was also revisited for coring (Yang et al., 2008).

During GMGS3, pore-filling, strata-bound gas hydrates were discovered above the bottom simulating reflector (BSR) at a site named Site W17 in the South China Sea; this site ultimately became the location of the marine gas hydrate production test conducted in 2017 (Li et al., 2018). The Shenhu area is located in the Pearl River Mouth Basin, which is a region of active conventional hydrocarbon exploration. Locally, the Shenhu drilling area is characterized by a migrating canyon system and recent sedimentation is dominated by active downslope processes that have led to the deposition of mass transport deposits, submarine fans, contourites, and turbidity channels. In the Shenhu area, structure I and structure II pore-filling gas hydrate occurrences with variable saturations (up to ~65%) and reservoirs thicknesses have been identified with acquired cores, downhole well logs, and seismic data (Zhang et al., 2007; Wu et al., 2009a, b; Wang et al., 2011; Paganoni et al., 2016; Liang et al., 2017). The occurrence of relatively higher gas hydrate saturations at Site W17 and other similar sites in the Shenhu area are controlled by contribution of thermogenic gas sources, gas migration into the gas hydrate stability zone from below, and the physical properties of the sediments hosting the gas hydrates, which appear to have a slightly elevated coarser grain sediment fraction (mostly silt to fine-sand grain sizes) leading to the formation of pore-filling gas hydrate accumulations.

In May and June of 2017, the China Geological Survey conducted an industrial pilot gas hydrate production test in the Shenhu area (Li et al., 2018). The water depth at the test site 1266 m, and hydrate-bearing reservoir section is at a depth of 203-277 m below the seabed (mbsf). The production testing phase started on 10-May-2017 by decreasing effective bottom hole pressure in the well. The production test lasted for a total for 60 days, recovering 309,046 m^3 of gas, at a mean daily production rate of 5,151 m^3 per day. After the test, the production test string was recovered, and the well was abandoned (Figure 9A-B).

Figure 9A. Images of the 2017 gas hydrate production test in the South China Sea: The drilling platform *Bluewhale #1* (modified from Li et al., 2018).

Figure 9B. Images of the 2017 gas hydrate production test in the South China Sea: Gas flare as fueled by the gas hydrate production test (modified from Li et al., 2018).

Summary and Challenges

Gas hydrate energy resource studies being conducted in Korea, India, Canada, China, Japan, and the United States have made significant contributions to our understanding of the geologic controls on the occurrence of gas hydrate in nature and the assessment resource potential of gas hydrates. Scientific and industrial drilling in both Arctic permafrost and deep marine environments have confirmed that gas hydrates are an abundant potential resource. However, to fully understand the role that gas hydrates may play as a future energy resource will require more work.

Listed below are some of the major technical challenges and potential opportunities that will need to be dealt with on the path to the commercial production of gas hydrates:

Gas Hydrate Resource Characterization

- There is a need to refine current gas hydrate resource assessments, with a focus on moving from mostly in-place gas volume assessments to technically recoverable assessment and eventually to reserve estimates.
- Advance the development and integration of gas hydrate system modeling, laboratory studies, and field surveys.
- Develop, test, and deploy new field characterization tools to address important gas hydrate research requirements, along with the development of new gas hydrate prospecting procedures.

Gas Hydrate Production Technology

- Advance the development of new gas hydrate production models that incorporate advanced macro- and pore-scale mechanical models.
- Conduct laboratory, modeling, and field scale analysis of reservoir stimulation techniques that may enhance gas hydrate production.
- Review and apply to gas hydrate production, existing and new completion technologies, including horizontal completions, multi-lateral drilling, etc.
- Characterize potential drilling, completion, and production concerns associated with producing gas hydrates.
- More effort is required to assess the impact of gas hydrate production on the physical and mechanical properties of gas hydrate reservoir systems (i.e., properties of the reservoirs, the associated seals, etc.)

Market and Regulatory Challenges

- The emergence of other unconventional gas resources and more traditional sources of energy represents a significant challenge to the goal of commercial production of gas hydrates.
- In most settings the potential volume of gas associated with a given gas hydrate accumulation is unknown and the technology to produce gas hydrates is unproven.
- Gas hydrates generally occur in deep marine and Arctic environments, where high operational cost represent a significant challenge to the commercial production of gas hydrates.

- Limited economic modeling has shown that the commercial production of gas hydrates may be possible; however, we are still dealing with many unknowns.
- The impact on gas hydrate commercialization of specific national interests and local motivations need to be considered, including (1) taxation and climate change policies, (2) development of industry and government partnerships, (3) the design of purpose-built gas hydrate drilling and production systems, (4) local industrial use of produced gas, and (5) access to other energy resources.

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