Hydrate petroleum system approach to natural gas hydrate exploration

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ABSTRACT: Natural gas hydrate (NGH) is a solid crystalline material composed of water and natural gas (primarily methane) that is stable under conditions of moderately high pressure and moderately low temperature found in permafrost and continental margin sediments. A NGH petroleum system is different in a number of important ways from conventional petroleum systems related to large concentrations of gas and petroleum. The critical elements of the NGH petroleum system are: (1) a gas hydrate stability zone (GHSZ) in which pressure and temperature lie within the field of hydrate stability, creating a thermodynamic trap of suitable thickness for NGH concentrations to form; (2) recent and modern gas flux into the GHSZ along migration pathways; and (3) suitable sediment host sands within the GHSZ. These elements have to be active now and in the recent geological past. Exploration in continental margin sediments includes basin analysis to identify source and host sediment likelihood and disposition, potential reservoir localization using existing seismic analysis tools for locating turbidite sands and estimating NGH saturation, and deposit characterization using drilling and logging. Drilling has validated first-order seismic analysis techniques for identifying and quantifying NGH using rock physics mechanical models.

INTRODUCTION

Natural gas hydrate (NGH) is a potentially vast energy resource. A median global resource potential for high-grade NGH sands, based on a NGH petroleum system approach, indicates as much as 43 300 trillion cubic feet (TCF), of which perhaps 50% may be technically recoverable (Johnson 2011). This compares very favourably with combined resource and reserve estimates for coalbed methane of 9000 TCF, and tight gas of 7400 TCF (NPC 2007) and technically recoverable shale gas of 7299 TCF (Kuuskraa *et al.* 2013). The most recent evaluation of gas in place in NGH in the lower 48 States US offshore using a petroleum system approach is a statistical mean of 51 288 TCF (BOEM 2013).

While the volume of natural gas (NG) contained in the world's NGH accumulations may greatly exceed that of other NG resources (Collett 2002), a substantial proportion of NGH is present in low-grade accumulations (Boswell & Collett 2011) that are unlikely to be developed commercially (Moridis & Sloan 2007). There is, however, growing evidence that natural gas can be produced from high-grade NGH concentrations (Max *et al.* 2006) in coarse-grained sediments with existing conventional oil and gas production technology (Moridis & Kowalsky 2006).

Oceanic NGH is often regarded as a gas resource for the far future, and this may be the case for gas-rich regions such as North America. But for coastal states with little conventional natural gas, and high-cost imported LNG, NGH may be developed sooner. For instance, a technical production test was carried out on the 40 TCF Nankai NGH deposit during March 2013 by JOGMEC, as part of the MH21 plan for production by 2018 (JOGMEC 2013). It is very likely that the Japanese will be able to replace gas imports with indigenous production from NGH and this will stimulate other NGH development. In addition to the Japanese initiatives, Korean, Indian and Chinese national programmes have aggressive NGH exploration projects in which drilling and production tests were conducted in 2013 and are scheduled for 2014.

Recent development of shale gas in North America has provided a large gas supply that may delay the development of NGH there. In other countries that have NGH potential, however, development of indigenous gas supply is a national priority in order to obtain energy security. Understanding the physical chemical and geological attributes of the NGH petroleum system on its own merits is as important to exploration as understanding conventional petroleum systems has been.

NATURAL GAS HYDRATE AND ITS OCCURRENCES

NGH is a non-stoichiometric crystalline solid composed of water molecules that form cage structures and gas molecules that occupy almost all of the cages, because the stability of the adjacent cages induced by van der Waals bonding stabilize the cage structures as a whole. Energy density levels for dissociation may be somewhat lower if gas molecules do not occupy all of the cages, and undersaturated NGH is common (Sloan & Koh 2008). NGH spontaneously forms by crystallizing from mineralizing solutions when the right combinations of elevated pressure and low-temperature conditions exist (Fig. 1), and where there is a suitable concentration of dissolved NGH-forming gas and water.

NGH is found commonly within a NGH stability zone (GHSZ) that extends from near a cold surface in permafrost

Petroleum Geoscience, Vol. **20**, 2014, pp. 187–199
http://dx.doi.org/10.1144/petgeo2012-049
Published *Online First* on March, 21, 2014

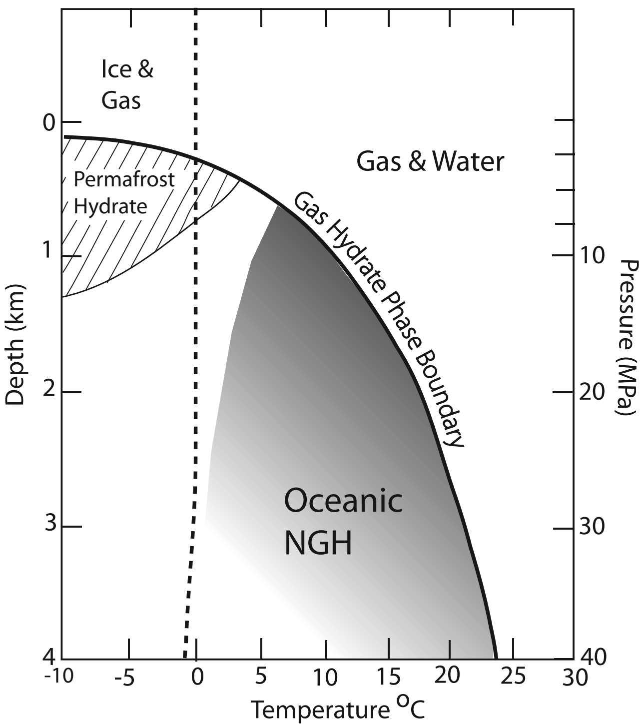

Fig. 1. Pressure–temperature diagram showing fields of permafrost and oceanic NGH concentration stability. Note that oceanic NGH may form at temperatures below 0 °C, such as in the Arctic Ocean, where salinity suppresses the formation of ice. ©Hydrate Energy International. Used with permission.

regions or, in oceanic sediments, from the seafloor downwards to some depth at which increasing temperature renders NGH unstable (Kvenvolden 1988*a*). Permafrost NGH is stable downwards from a depth of about 200 m. Oceanic NGH occurs at water depths greater than 500 m at mid to low latitudes. Colder seawater brings the minimum depth of the GHSZ to less than 300 m in the Arctic Ocean (Max *et al.* 2013). The thickness of the GHSZ varies with temperature and pressure, typically increasing with increasing water depth as a result of increasing pressure. As the geothermal gradient varies considerably, the thickness of the GHSZ varies on a global scale (Wood & Jung 2008; Wallmann *et al.* 2012). Rapid lateral changes in the thickness of the GHSZ are rare except near salt diapirs (McConnell & Kendall 2003).

NGH is an inert, physically stable, solid material in its ambient reservoir conditions, which differentiates it strongly from conventional liquid or from gas deposits that are usually highly pressurized and can release immense latent energy immediately when drilled. There are two principal attributes that are affected by the presence of natural gas in the form of NGH. First, drilling safety is affected because dispersed NGH may be expected close to the surface, immediately below the sulphate reduction zone, in which bacteria consume methane. If gas flux is high, the sulphate reduction zone can be very thin. If even 2% or 3% dispersed NGH occurs in surficial sediments, heating related to drilling and cementing, and other seafloor exploration activities can accidentally dissociate the NGH, which may substantially reduce sediment strength and cause mass transport flows. Circulation of cold seafloor water near exploration/production activities is sufficient to dramatically reduce the risk of NGH-induced sediment instability, and other refrigeration techniques are also used. Second, absence of overpressure reduces the blowout risk to approximately zero.

Because the crystalline cage structures closely pack the gas molecules, 1 m^3 of NGH will produce about 164 m^3 of methane at STP (1 kPa, 20 °C), equivalent to an energy density of at least 165 000 BTU/ft^3 and higher where heavier hydrocarbon gases such as ethane, propane and butane may be present. Crystallization of NGH is a highly reversible chemical reaction governed by diffusion mechanisms that are very responsive to physical surroundings. Because NGH occurs relatively close to the seafloor or the Earth's surface, climate exerts a strong control over its state of growth or dissolution. Also, because NGH sequesters natural gas early in the diagenesis of fine-grained sediments in which permeability may decrease considerably while NGH persists, NGH may be part of a gas conservation system in some shales (Max & Johnson 2012).

Estimates of global NGH abundance published during the past 30 years have pointed to an immense amount of NGH in place (Kvenvolden 1988*a*; Kvenvolden & Lorenson 2001; Boswell & Collett 2006), with over 95% estimated to be in oceanic sediments. Four general classes of NGH in different surroundings have been identified (Table 1). These classes are based on thermodynamic models that were used to estimate the costs of processes that are required to convert NGH to its constituent gas and water (Moridis & Kowalsky 2006). There are subtle but important differences in the petroleum systems related to each of these classes of NGH concentration.

There are three main types of permafrost NGH concentration, two of which are unique and one of which is essentially the same as the oceanic NGH petroleum system, which is hereafter referred to as 'the NGH petroleum system'.

PERMAFROST NGH

The three types of permafrost NGH are:

- Existing gas concentrations in geological traps in which some of the trapped gas has been converted to NGH, such as Mallik in the Mackenzie Delta of Canada (Dallimore *et al.* 1999), in the Alaskan North Slope (Collett *et al.* 2008) and, probably, also in the Messoyakha gas field (Collett & Ginsburg 1998), which may be representative of many other west Siberian NGH concentrations in the Yamal-Nenets Autonomous District and to the east. These have been found through conventional petroleum system exploration and do not require any special NGH-specific exploration techniques.
- Vein-type NGH formed by a gas–ice reaction when natural gas has been injected into ice permafrost. These have only recently been recognized in the Alpine permafrost of the Qinghai–Tibet plateau in western China (Lu *et al.* 2010). It is possible that they may constitute a new permafrost NGH play (Max & Johnson 2011*b*) but their potential is unknown. At present, drilling appears to be the primary exploration technique. This petroleum system is described in Max & Johnson (2011*a*).
- NGH in the compound ice-cryosphere–NGH GHSZ that is not associated with pre-existing gas concentrations in geological traps. From an exploration point of view, these may share many of the attributes of oceanic NGH paragenesis and have a strongly related petroleum system, but it is unlikely that the rocks and sediments in a permafrost area GHSZ will have the same weak geotechnical and permeability characteristics of shallow-marine sediments.

OCEANIC NHG

Oceanic NGH is the only NGH option for coastal nations with little or no permafrost terrain. Nations with major expanses of

Table 1. *NGH classification table. Revised from Moridis & Kowalsky (2006). © Hydrate Energy International. Used with permission (see also Worthington 2010 for image-based NGH Class descriptions)*

Class	Hydrate	Bounded	Materials in contact	Geological situation	System
1	Concentrated	Permeability boundaries/ geological strata	Gas over water	1a Oceanic	Open
				1b Oceanic, permafrost	Closed
2			Mobile water	Oceanic	Open
3			No gas or water	Dry gas trap (including vein-type NGH) (permafrost)	Closed
4	Dispersed	Few permeability boundaries	Pore water	Fine-grained marine sediments	Very open

permafrost – the United States, Canada and the Russian Federation – are all energy-rich. But most of the other nations in the world have an interest in identifying and exploring their NGH potential. Exploration for oceanic NGH has made remarkable strides in the last 20 years, particularly in the national programmes of Japan (Noguchi *et al.* 2011), the United States (Boswell *et al.* 2012), Canada (Dallimore *et al.* 1999), and India and Korea (Long *et al.* 2008). Although the NGH programmes of Canada and the United States were primarily driven by economic interest 10 years ago, other unconventional resources, including shale gas and oil sands, have reduced the imperative to develop NGH in North America as a near-term gas resource. In countries that have few indigenous energy resources, however, the political concerns to obtain a secure, local gas resource may be more important to development than the delivered gas price on imported resources.

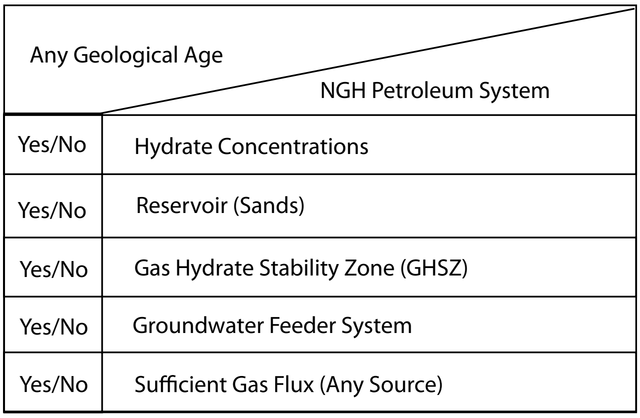

Fig. 2. Schematic diagram of the NGH petroleum system. All components need to be present for NGH concentrations to form. ©Hydrate Energy International. Used with permission.

THE NGH PETROLEUM SYSTEM

Petroleum system analysis is a process of incorporating diverse natural system information to assist petroleum and natural gas exploration (Ligtenberg & Neves 2008), especially in the early-stage evaluation of continental slope deposits (Okui *et al.* 2008). Classical petroleum system analysis comprises those factors that drive the generation, migration and accumulation of hydrocarbons. Accurate coordination of these elements and processes in time and space is critical to the exploration risk-assessment process and for look-back identification of missed opportunities. We follow Selley (1998) in regarding hydrocarbon accumulations as being originally of organic origin, although thermal processes that produce the gas and petroleum liquids are often involved, as well as biogenic processes. The organic origin of commercial hydrocarbon deposits means that organic-rich source beds must exist for each hydrocarbon deposit. There should be at least as many petroleum systems as there are thermally mature source rocks. For conventional hydrocarbon deposits there may be many different systems, whereas the NGH petroleum system is more uniform.

There are certain aspects of NGH that render concentrations very different from conventional gas and petroleum deposits and their histories. NGH petroleum system analysis, as we outline it here, focuses on those elements that are important to understanding where the natural gas originated, how it migrated and how it then concentrated through crystallization. The objective of NGH petroleum system analysis remains the same as it is for conventional petroleum system analysis, which is to improve exploration for NGH concentrations in order to identify commercial resources of NGH.

The main elements of a conventional petroleum system consist of: (1) the source rock, and its thermal and burial history; (2) the migration pathway; (3) the reservoir; and (4) a trap and seal. Generation, migration, concentration and accumulation in reservoirs all play a role in determining the formation of a deposit and the viability of economic recovery (Selley 1998). Most important, a critical moment in which gas and petroleum liquids migrate into a trap must exist. Once the hydrocarbons have been trapped, they can remain in the trap and persist relatively unchanged in the reservoir for a very long time. Hydrocarbon deposits that form subsequently in the history of the basin may be of different generation history, depth, and stratigraphic and structural setting, but all may persist once they are trapped. A wide range of geological ages of deposits and their depths in the basin, as well as their relationships with different source beds and migration pathways, may be developed in geospatial proximity.

In contrast, the superficially similar NGH petroleum system (Fig. 2) includes the same basic elements, but all of these have to be active or interactive at present and in the recent past. The critical moment for the petroleum system is geologically now. NGH is essentially an entirely ‘modern’ deposit in which NGH concentrations that currently exist are in a dynamic equilibrium with existing pressure and temperature conditions. NG migrates into the GHSZ, where some of it is sequestered as NGH, while unsequestered NG may migrate directly into the ocean. The reason why there appears to be so much natural gas sequestered in ‘transient’ NGH is that conditions of NGH stability are so widespread, being found along every continental margin and deeper continental shelf areas, including areas (such as Japan) that lack significant conventional gas accumulations but which have proven NGH accumulations. Worldwide, host sediments also appear to occur profusely (up to 25% in the Gulf of Mexico GHSZ, for instance: Frye 2008) within these GHSZs.

The dynamics of the system depend on existing and geologically recent gas and dissolved gas migration towards the surface of thick marine sediment, existing migration pathways and existing physical chemical conditions immediately below the seafloor. These elements may not have persisted in their present form for long in geological time, at least in the sediment section in which NGH may occur. NGH is very responsive to changes in environment conditions. Ocean seafloor temperature and the local geothermal gradient, and the height of sea-level stand, changes in which have no effect on conventional hydrocarbon deposits, may exert a strong influence over the existence and persistence of NGH concentrations owing to the resulting variations in pressure (Max *et al.* 2006).

The primary physical contrast to conventional hydrocarbon deposits is that NGH does not require a geological trap. When NGH crystallizes in a GHSZ, it comprises both the reservoir and the trap. Formation of NGH is the result of thermodynamic trapping in which dissolved natural gas crystallizes to a solid. Potential NGH pay zones can occur anywhere in the GHSZ, depending on the groundwater supply system.

NGH petroleum system analysis, which is our focus, concentrates on the GHSZ, which is usually confined to the upper 1–1.2 km of marine sediments in water depths greater than about 800 m; located on deep continental margins. This zone of interest is the GHSZ, in which NGH deposits will be found, and the porous beds and zones for some distance below the GHSZ that bring the natural gases up into the zone from depth. Although it is not known to what water depths possible NGH concentrations may occur, there will probably be some maximum depth below which exploration cutoffs will apply for either operational considerations or some aspect of NGH paragenesis.

Because the NGH zone of interest is much shallower than the deeper zones in which conventional hydrocarbons are found, exploration and extraction costs for NGH that are currently being developed may be significantly lower than those of conventional hydrocarbon exploration. These cost factors should be particularly more attractive when NGH is compared with deep, high-temperature, high-pressure conventional gas deposits. For example, high-resolution seismic data over the shallow GHSZ interval amplitude data have successfully been extracted at relatively low cost from existing two- and three-dimensional (2D and 3D) conventional seismic surveys acquired for the exploration of conventional hydrocarbons. Very few NGH-specific seismic surveys have been carried out. It is advisable, however, to archive digital data in two forms, with and without automatic depth compensation, so that higher-frequency data are preserved in the less processed shallow data. Higher-frequency deep-tow seismic surveys (Gettrust *et al.* 2005) yield higher-resolution data but these surveys are slow, 2D and are only useful if targeted upon suspected NGH concentrations rather than being used as a wide area exploration technique. In frontier regions where there has been little or no conventional hydrocarbon exploration, such as the High Arctic, much less expensive scientific surveys have revealed the likelihood of NGH.

In general, most of the gas in NGH has been produced either biogenically or thermogenically deeper in the basin before migrating upwards to the GHSZ. Migration pathways, along permeable beds, faults or a combination of these, need to connect the gas sources with the GHSZ. There has to be a thick enough GHSZ to sustain NGH concentrations over a relatively short geological time, along with suitable host sediments in which the NGH can concentrate. Finally, there has to be a sufficient concentration of dissolved or free gas in ascending pore water. In essence, the critical moment has to be at present (in a somewhat extended geological context that could be as short as tens or hundreds of thousands of years).

The geological age of oceanic sediment in which NGH concentrations may occur will be the most recent sediments deposited, as these will occupy the GHSZ. Along continental margins where there is a high rate of sedimentation, these tend to be Plio-Pleistocene in age. However, sediment deposition is rarely evenly distributed along a continental margin, which is a reason why understanding the one-time courses of rivers and shelf sediment redistribution systems may be important in identifying those regions of a continental margin that are liable to have the most favourable host sediments in which NGH concentration could form. In a region as limited in scale as the northern Gulf of Mexico, which has the Mississippi River as its principal source of sediment, the depocentre has shifted over time so that, while thick Plio-Pleistocene sediments occur off western Louisiana, NGH also occurs in sediments of Miocene age off eastern Louisiana where the Plio-Pleistocene section is thinner. While the older sediments containing NGH may have slightly different properties than younger sediments at the same burial levels simply because dewatering of the sediments is partially a time, as well as an overburden compaction, factor, they are likely to be more similar than sediments of similar age would be in permafrost environments.

Gas sources to drive sufficient gas flux

NGH is composed dominantly of biogenic methane, particularly in passive continental margins such as the Blake Ridge off the SE USA, where deep thermogenic sources do not appear to have been tapped, carbon isotope data indicate that biogenic methane dominates (Paull & Ussler 2001). Even in active margin areas, biogenic methane is much more common than thermogenic methane (Kastner 2001). Biogenic gas directly feeding the GHSZ has been observed in drill holes (Wellsbury *et al.* 2000; Wellsbury & Parkes 2003; Parkes *et al.* 2005). Of the many drill holes into oceanic NGH, only a few have more than a small percentage of thermogenic gas or traces of liquid hydrocarbons (Kvenvolden 1988*b*). Where deeper sources are tapped, often by deep faults, such as are common in accretionary margins such as Cascadia (Trehu *et al.* 2004), thermogenic gas may locally be a prominent component of the gas mixture along with traces of liquid petroleum. Natural gas liquids are not present so long as there is any water for them to react with because the heavier hydrocarbon gases have a strong preference for forming NGH, with respect to methane. Complete sequestration of higher-density hydrocarbon gases in compound NGH is the rule.

Oceanic NGH in the subsurface has thus far been proven by drilling and sampling to be relatively pure biogenic methane. It appears to have about the same purity worldwide, which implies a single or related set of processes. In addition to the basic hydrate-forming component, any chemical or dissolved ionic material migrating with the dissolved gas that is not a hydrate-former is rejected from the crystallizing NGH into the pore water where it will dissolve and be carried away. This is particularly true for salt, for which low-salinity zones were one of the primary indicators for the presence of dispersed NGH in the Blake Ridge (Paull *et al.* 1996, 1998).

The superabundance of biogenic methane in oceanic NGH and its concentration in the uppermost seafloor sediments suggests that the thermal history of basins over time is of much less importance than for conventional hydrocarbons. Not enough microbial methane is generated internally within the GHSZ to account for the gas content of most accumulations, although thick muddy sediments with up to 10% organics could generate enough gas to form dispersed NGH locally. Therefore, a gas source outside and below is necessary (Max *et al.* 2006). In the very large volumes of marine sediments on continental margins that provide a suitable habitat for methanogenic deep biota, huge amounts of methane will be produced (Dickens *et al.* 1997), of which only a relatively small proportion may be captured in NGH. NGH is a natural buffer for oceanic methane production; NGH captures some of the methane and holds it securely from entering the ocean or atmosphere. It would appear that the majority of methane has been produced by bacterial activity in sediments whose temperature did not attain the kerogen stage required for conventional hydrocarbon generation (oil may be generated between 100 and 120 °C, gas is generated between 120 and 225 °C: Selley 1998).

The potential for gas generation can be expressed in the same way as that for conventional hydrocarbons: volume of hydrocarbon generated (=) basin area (×) average total thickness of source rock (×) transformation ratio. In the conventional petroleum system, the transformation ratio is the ratio of the petroleum actually formed to its genetic potential. The same relationship can be applied to gas feeding NGH, whether the source is thermogenic or biogenic. However, in the case of biogenic methane, the transformation ratio may be different from the experience of conventional hydrocarbon assessment potential, as may the provenance and timeline for production of gas that is present in NGH deposits (Kvenvolden & Lorenson 2001).

Because the sedimentary environments in which the petroleum system operates evolve over time, the relative timing of the thermal history and migration systems may be critical for conventional hydrocarbon production, migration and trapping. In addition, gas often does not have the same level of geochemical indicators as petroleum, and there may be little or no chemical linkage with a distinct source bed. As long as the existing gas flux has been sufficient to allow the formation of NGH concentrations and is presently strong enough to sustain stable NGH conditions (Ruppel & Kinoshita 2000), it is not essential to expend resources on elucidating the long-term basin thermal history or in identifying a distinct source bed for NGH concentrations.

Migration pathways and active groundwater feed system

Methane in the NGH system is carried from depth in groundwater towards the surface in both connected primary and secondary porosity. Exploration for NGH concentrations will literally ‘follow the water’ from a methane-rich, subjacent groundwater source to a location within the GHSZ where spontaneous NGH crystallization will take place. Tracking methane and groundwater sources within a relatively short distance below the GHSZ to NGH concentrations within the GHSZ is a fundamental aim of NGH exploration. The groundwater system within marine sediments on deep continental margins and continental slopes is the driver of the NGH system. In a passive margin, the water drive is predominantly due to sediment compaction under gravity; while, in an active margin, tectonics are likely to be more important than gravity alone.

NGH concentrations that may contain enough gas to warrant extraction are similar to conventional gas concentration in two important ways. There must be sources for the natural gas, and there must be geological pathways through which the methane is transported, most commonly in pore water systems. But with existing NGH concentrations, the sources of the gas are much less important than the existence of a sufficient supply of methane in the groundwater now and in the immediate past. If the concentration of dissolved methane in the pore water is high enough, NGH will form and persist. Thus, one of the exploration tools vital to gas NGH exploration is an understanding of pore-water movements and its chemical character as part of a groundwater supply system. Water sources should be tracked into the GHSZ, and mapped with fracture systems and the orientation of geological strata to provide a predictive capability.

NGH concentrations

Geological seals and traps do not generally constrain oceanic gas NGH concentrations, even though less permeable beds enclosing the more porous horizons might give the impression of a stratigraphic trap. There does not have to be a host or ‘reservoir’ that is in any way different from sediments and fracture zones suitable for migration of the NGH-forming gas. Formation of NGH itself provides both the reservoir and trap. Potential NGH-forming groundwater solutions passing into the GHSZ are likely to begin crystallization in strata or in fracture zones that are no different in any way from their continuations or analogues at depth. Conventional hydrocarbon accumulations are not dependent upon a narrow set of physical–chemical parameters, whereas NGH concentrations are. The existing or modern near-seafloor groundwater hydraulic system, which may have a geological ‘tail’ of hundreds of thousands to millions of years, is critical to the existence of NGH concentrations. Under the right circumstances, NGH concentrations can develop relatively quickly.

NGH crystallization and the GHSZ

As NGH is unique among gas resources because in its natural state it is a solid crystalline material formed by diagenetic crystallization, it is analogous to mineral deposits rather than to conventional gas deposits. Initial heterogeneous or homogeneous nucleation and growth in the bulk phase (suspended in pore water) will produce NGH grains that will behave as sediment grains. This appears to be more common than growth by adhering to the surface of sediment grains (Max *et al.* 2006, Chapter 2) because pore throats appear to remain open to fluid migration until very high NGH pore fill (60% common and 80% observed) and NGH grain and sediment intergrowth is achieved (Boswell *et al.* 2012). If NGH crystallized preferentially on sediment grain surfaces, it would tend to block pore throats. Fluid movement through the sediment would appear to be too slow to physically force very small NGH particles to physically block pores. To what extent high concentrations of NGH remain polycrystalline aggregates or whether annealing crystallization will produce fewer, larger crystals through a process of grain surface area reduction is not known but could be important to conversion of NGH for NG production.

Once NGH has formed, it is stable within its field of pressure and temperature, provided that the dissolved gas concentration remains sufficiently high. NGH is a transitory mineral deposit that has a highly reversible physical chemical reaction. If NG flux should drop below the level required to keep NGH from dissolving, then over time NGH concentrations will disappear. Although there may be a superficial similarity to coalbed methane in which solid matter can effuse absorbed NG when pressure is lowered, this is fundamentally different from the process of converting NGH to its component water and gas through a dissociation process. When NGH completely converts, no solid matter remains.

NGH concentrations tend to be very pure. The process of crystallization excludes many chemicals and dissolved ionic materials that are often found in gas and petroleum deposits. In particular, NGH has little nitrogen, sulphur compounds, CO_2 and other contaminants that are often found in conventional deposits. Other contaminants, such as sulphate compounds, are preferred hydrate formers that have the potential to form below the methane hydrate stability region. This ‘pre-crystallization’ at depths greater than the methane hydrate stability zone acts to purify the methane before it reaches the (methane) GHSZ. In addition, almost pure water is produced when hydrate dissociates; very-high-salinity brines are unlikely to be encountered in NGH extraction. When compound NGH dissociates, however, natural gas liquids (NGL) will be produced if the pressure on the dissociating NGH is high enough. We do not regard this as NGL in association with NGH but, instead, produced from it.

NGH formation and dissociation are both chemical reactions that produce heat upon formation and consume heat during dissociation. This introduces a natural buffering that acts to slow reaction rates. For instance, when hydrate begins to spontaneously form, heat is produced that drives the reaction point in pressure–temperature space back towards the phase boundary (Fig. 1). When hydrate begins to dissociate, heat is consumed that also tends to drive the reaction point back towards the phase boundary, but in the opposite direction. Hydrate only dissociates at its margin, which may limit early dissociation, especially in a high-grade deposit (Max *et al.* 2006). NGH does not have the potential to explosively decompress to its component gas and water, even if suddenly removed to pressure–temperature reaction points in which the NGH is very unstable. Although this is self-evident from many images of solid NGH examined at the sea surface after being recovered, it may not be understood that about the same maximum rate of dissociation may be obtained in an *in situ* NGH concentration under conversion as when the NGH may be grossly out of its stability field.

A great deal of early emphasis was traditionally placed on the base of the GHSZ (BGHSZ) because it is often easy to identify. The BSHSZ marks the greatest depth at which the NGH occurs naturally. It is often imaged as a prominent seismic reflector as it is a negative impedance contrast that reflects the top of free gas (Max 1990). It is especially prominent when it cuts across strata. The bottom-simulating reflection (BSR) has been used as a primary drilling target in early drilling when it was assumed that relatively high NGH levels of saturation generally overlay it. Drilling through a BSR on the Blake Ridge, however, proved relatively low values (up to 10% but more commonly <7% of bulk: Holbrook 2001) dispersed through very large volumes of sediment, but similar NGH was also drilled where there was no BSR. BSR is an indication of dispersed gas being present in pore water below it rather than being an indicator of the presence of significant NGH above.

Apart from gas that can be observed naturally venting from the seafloor, the presence of BSRs on seismic sections constitutes first-order evidence for significant NG production and retention. However, BSRs give little direct evidence for the potential for NGH concentrations, and are only useful in the very early stages of exploration. Where an inclined permeable horizon crosses into a GHSZ, it is common to find gas pooled below NGH in pore space. Depending on the thickness of the permeable horizons, velocity analysis can be used to estimate both the NGH saturation and the gas–water relationship (Max 1990; Frye 2008; Lee *et al.* 2009). Estimates of leakage at the seafloor combined with gas and NGH in-place will allow estimates of gas flux to be made. A first-order approximation for adequate gas flux, however, will be provided by the existence of the NGH itself. If gas flux were not high enough, then no NGH concentration would exist.

In lower-grade deposits that tend to be finer grained (muddier) and less well bed-differentiated, continuous BSRs often occur at approximately the location of the base of the GHSZ and may extend over large areas. The NGH associated with these features often forms extremely large, low-grade deposits (Max *et al.* 2006) that have relatively small percentages of between 3 and 8% NGH in diffusely defined horizons throughout huge volumes of fairly uniform muddy sediments. These do not constitute primary exploration targets.

It is also important to note that NGH may not be stable everywhere in the GHSZ, particularly in its upper part. A zone of sulphate reduction of methane associated with biosystems near the seafloor can affect the depth of the upper limit at which NGH concentrations will form (Borowski *et al.* 1996). Piston coring is a useful tool to investigate this, as the absence of sulphate in near-surface sediments may indicate that the methane flux is sufficient for deeper NGH formation. Under certain conditions that favour an active sulphate reaction zone, the upper limit of NGH development could be tens or even, in rare circumstances, hundreds of metres below the seafloor, even though pressure–temperature conditions may be well within the pressure–temperature field of NGH stability. The base of the sulphate zone, however, will almost certainly be shallower than the practical upper limit of NGH recovery in any area in which the GHSZ is thick enough to host NGH concentrations. It is likely that some general minimum depth in the GHSZ will be defined as the effective top of NGH gas recovery for safety reasons.

Suitable host sediments (reservoir sands)

It is theoretically possible to host commercial quantities of NGH either dispersed or in fracture zones in muddy sediment reservoirs (McGee *et al.* 2009) in which drilling results indicate that substantial quantities of NGH occur (Boswell *et al.* 2011, 2012). These are not regarded as primary exploration targets because seismic exploration for them is less certain than for sand hosts, and production from them is problematic because of reservoir instability during NGH conversion. The lack of a production model (Boswell & Collett 2011) means that these deposits are of secondary economic importance. Although most NGH occurs dispersed or in veinworks in muddy sediments, the greatest concentrations that have economic potential occur in sands and coarse-grained sedimentary strata (Max *et al.* 2006; Boswell & Collett 2011; Boswell *et al.* 2011, 2012). Thus, high-grade NGH deposits in sand hosts are the primary NGH exploration objectives (Max *et al.* 2006). These deposits consist of large volumes of NGH concentrated in relatively small volumes of reservoir and are similar in many ways to conventional gas deposits.

There is emerging agreement that sand reservoirs containing NGH are the primary exploration objectives, not only because they appear to host most of the high-grade NGH concentrations (Ruppel 2011), but also because the geotechnical performance of the sand during NGH conversion to its constituent gas and water is almost certainly going to be more predictable and trouble-free than fracture-fill reservoirs in fine-grained sediments. In a sand, the orientation of the body in which the gas will flow and concentrate is much more predictable from analysis of seismic data than a fracture system in which the manner of interconnectivity is more difficult to evaluate. In addition, when NGH converts to gas and water, the overall strength of the reservoir decreases. However, because sands are framework-supported beds, they might be expected to undergo minor compaction regardless of the degree of grain cementation or overgrowth by the NGH, especially where the host sands had been somewhat compacted prior to the formation of NGH. Converting NGH in a muddy horizon may cause sediment mass movements and unpredictable gas movements.

Turbidite system sands are prominent constituents of continental margin sediments, often hosting deeply buried conventional gas and petroleum accumulations. They are also the primary host sediments for NGH, generally for the same reasons that they provide reservoirs for conventional hydrocarbon deposits: relatively high porosity and high permeability. Further, they will retain their permeability and porosity even when compacted because the sediment grains are part of the framework that supports the beds. Existing seismic analysis methods are sufficient for delineating these in the GHSZ (Frye 2008).

Gas concentration and NGH crystallization

A single-phase NGH feeder system consists of water carrying dissolved gas. A two-phase system occurs when NGH and water

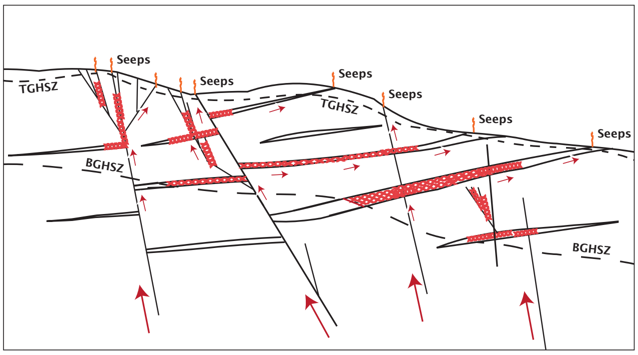

Fig. 3. Schematic diagram of a complex system of primary and secondary porosity paths, and projected locations of NGH concentrations. BGHSZ, base of the GHSZ; TGHSZ, top of the gas hydrate stability zone based on sulphate reduction in oceanic hydrate and the minimum pressure level for NGH stability in permafrost NGH. The arrows show gas/fluid movement. The red pattern indicates NGH in strata and fractures. ©Hydrate Energy International. Used with permission.

with dissolved gas are present. A three-phase system occurs when free gas is present with water and NGH. In a gas-saturated system, gas will dissolve in the water as gas molecules are incorporated into NGH crystal lattices. In a closed system, gas will be consumed while NGH forms until the vapour pressure of the gas concentration is about that in the NGH, at which point no further reactions or solution changes will take place. Within the GHSZ, the occurrence of a three-phase methane system indicates an unstable condition in which NGH is either growing or dissociating. A three-phase system may also indicate metastable conditions such as occur along the NGH phase boundary.

If pressure or temperature conditions alter even slightly so that the position of a NGH deposit changes from one side of the phase boundary to the other (Fig. 1), the NGH will tend to adapt to the new conditions by crystallizing or dissociating. However, there is an important third control governing NGH that is often overlooked. The concentration of dissolved methane in pore water must be higher than the concentration of methane in the NGH in order for methane NGH to nucleate and grow (Max & Johnson 2011*b*). When the concentration of NGH-forming gas in pore water is equivalent to that within the NGH, it is in equilibrium with its surroundings. When the concentration in the bounding pore water is greater, growth is promoted, with the growth dynamic (chemical potential) increasing with increasing concentration. When the concentration falls below the dynamic equilibrium level between the NGH and the bounding pore water, diffusion of NGH-forming gas from the NGH into the bounding pore water takes place with dissolution of the NGH even though pressure and temperature conditions may still be within NGH stability. The concentration of the NGH-forming gas in the pore media in contact with NGH is a primary control of the dynamic equilibrium that determines growth or dissolution. This is often overlooked because supersaturation is commonly assumed when NGH is detected.

Maintenance of high concentrations of dissolved methane in the pore water promotes the existence of NGH deposits within suitable strata within the GHSZ. Normally, gas flux will be about equal to groundwater flux as the water percolates through porous and permeable beds, although the presence of very buoyant gas micro-bubbles has the potential to drive the system faster. Even where there may be supersaturation of groundwater or gas micro-bubbles propagating from depths into the GHSZ, however, formation of NGH near the base of the GHSZ leaves the residual groundwater with the dissolved NG potential to form NGH higher in the GHSZ where it may be much colder and at only slightly lower pressure. When a solution passing into the GHSZ has a high enough concentration to allow for spontaneous crystallization immediately upon attaining suitable pressure–temperature conditions, NGH will form in the lower part of the GHSZ. Where the GHSZ is sufficiently thick for pressure or temperature to vary significantly, multiple depth-level NGH zones may develop, all crystallized from the same NGH-forming solution. Results of the drilling programme on the Cascadia margin of North America (Trehu *et al.* 2004), for instance, showed NGH concentrations in porous horizons occurring at multiple levels within the GHSZ.

In contrast to a fully saturated groundwater solution that may localize NGH concentrations near the base of the GHSZ, solutions that do not have a sufficiently high concentration of natural gas will not begin to form NGH immediately upon reaching the GHSZ. As the solutions pass upwards within the GHSZ, however, temperature decreases and pressure falls but, because the phase boundary is steep (Fig. 1), temperature is relatively more important at depth. In addition, dissolved gas concentration increases and with it the likelihood for spontaneous NGH crystallization. Thus, solutions that may have too low a concentration of dissolved gas for free gas to form may still have the potential to form NGH once they rise within the GHSZ.

NGH concentration characteristics

In conventional petroleum system analysis, accumulations of different materials (e.g. water, oil or gas) separate and occupy different portions of a wide variety of traps. In a contiguous reservoir, gas will overlie oil, which will overlie water. Water is the media in which gas and oil can be transported, separated and concentrated, even though the water itself may not move up-dip towards the reservoir/trap. Oceanic NGH concentrations of a commercial character may not be underlain or associated with free gas deposits and they will almost never be associated with more than traces of condensates or liquid petroleum. They can occur anywhere in the GHSZ where the right combination of factors exists (Fig. 3). Seismic response of NGH-bearing sediments relates to the higher bulk and shear modulus introduced by the NGH rather than to the gas or liquid response associated with conventional hydrocarbon deposits, except at the base of the GHSZ where underlying gas may be in contact with NGH.

NGH system analysis, after establishing that an area is a NG/active groundwater province, focuses on identifying porous horizons or zones that can act as conduits for migrating pore water or gas with high concentrations of dissolved methane which migrates from a warmer zone at depth to the colder GHSZ flanking the seafloor. The hydrogeological framework is one of fluid expulsion from the sediment prism, which is tied to a general reduction of permeability in the marine sediments. The path of the migrating methane-rich pore water need not always have been upwards. Pore water moves down pressure gradients that may occasionally be inverted in a folded or faulted porous horizon. Water movement may also be driven in any direction by dissociating NGH (Max & Clifford 2000).

The base of the GHSZ will move upwards as a response to sedimentation in order to maintain the thermodynamic balance (e.g. nearly constant GHSZ thickness with respect to the seafloor). In addition, lower pressures related to lowering sea level or geological uplift, or seafloor warming, gas overpressures are likely to develop at the BGHSZ where NGH, that has been abandoned by the upwards-migrating GHSZ, begins to dissociate. Overpressured gas also has the potential to drive pore water and can radically accentuate buoyant uplift of gas/water masses that may create their own zone of secondary porosity. At the extreme, a natural blowout or venting to the seafloor may develop (Dillon *et al.* 2001).

Primary exploration objectives are high-grade NGH deposits. These consist of large volumes of NGH concentrated in relatively small sediment volumes. NGH is more easily concentrated in bed-differentiated strata (sands and more coarse detritus). In strata shown on a seismic section where a dipping stratigraphic sequence contains a number of porous beds, NGH may form near the base of the GHSZ in each of the porous beds. In this case, the BSR will rarely be a strong continuous feature, in contrast to the more continuous BSR in more muddy, less well bed-differentiated sediments. We have termed these discontinuous BSRs that reflect the existence of NGH in porous horizons with often very little gas below as a 'string of pearls BSR', which is often difficult to identify. Each of the porous horizons has the potential to host high-grade NGH deposits, and each constitutes the primary NGH exploration focus. Closely spaced porous horizons have the potential to allow NG extraction from multiple horizons from a single network of horizontal wells.

High-grade NGH deposits immediately at the base of, or low in, the GHSZ strongly suggest that mineralizing solutions had a high concentration of dissolved methane prior to reaching the GHSZ. These are first-order exploration targets because there is the greatest likelihood of a relatively high gas flow and a high rate of NGH crystallization in a number of permeable horizons.

ECONOMIC ATTRIBUTES OF NGH EXPLORATION AND EXPLOITATION

NGH has a number of attributes that should make it less expensive in both exploration and extraction than conventional hydrocarbons. When practices are optimized for NGH, there is a potential for further cost savings that would lower the wellhead break-even price of natural gas recovered from NGH.

Geology below upper 1.5–2 km

NGH is more restricted in time and depth than are conventional hydrocarbon deposits. In particular, NGH is confined to the GHSZ worldwide, whereas conventional gas deposits can be found through a much greater vertical distance in marine sediments. Therefore, oceanic NGH targets will be found much shallower below the seafloor than conventional hydrocarbons in the same section. Type 1 permafrost NGH will be associated with pre-existing gas deposits but will occupy the upper part of joint gas–NGH deposits. There will usually be no requirement to carry out very deep seismic or other remote sensing surveys such as are necessary for conventional gas and oil. Lower-powered, higher-resolution surveys can be carried out, and smaller, less expensive vessels may be used.

Geophysical data analysis

The primary geophysical method for NGH exploration is the same as that for conventional hydrocarbons, both in data acquisition (with preservation of shallow high-frequency data in the 50–250 Hz range) as outlined by Haines *et al.* (2013*a*) and acoustic inversion processing techniques based on the geotechnical character of the solid, high-pressure and shear-wave acoustic velocity NGH (McConnell & Zhang 2005), whose acoustic parameters are quite different from liquid or gas hydrocarbons. Geotechnical parameters have been determined from downhole logging while drilling (LWD) (McConnell *et al.* 2009). Industry analytical techniques (such as attribute analysis, elastic inversion and spectral decomposition) developed for identifying sandy units in a continental slope environment, and for determining a wide variety of seismic anomalies, are directly applicable to identification of NGH concentrations.

Multi-channel 2D or 3D surveys with workstation processing of the digital data using standard seismic analysis software and hardware are being successfully used in the northern Gulf of Mexico (Frye 2008; Boswell *et al.* 2011, 2012), in the Nankai deposits off SE Japan (Noguchi *et al.* 2011) and off SE India. Relative and absolute pressure wave velocity and amplitude anomaly full waveform analysis (Bachrach *et al.* 2004), incorporating both measured and estimated physical properties of NGH, as have been summarized by Worthington (2010) among others, has been used to identify drilling targets and provide NGH saturation estimates in the northern Gulf of Mexico (Frye 2008; Boswell & Collett 2011). Although improvement to exploration seismic acquisition and processing continues (Haines *et al.* 2013*a*, *b*, 2014), drilling verification of processing based on NGH and reservoir host response indicates that seismic analysis techniques are sufficient for NGH characterization and valuation.

LWD, in our opinion, returns the best rock physics information from NGH concentrations that are relevant for seismic analysis techniques. No matter how carefully controlled drilling is carried out, altering the temperature and salinity conditions in the hole is inevitable. Nonetheless, minimization of the NGH perturbation effect can be achieved. This is important because any perturbation of NGH from its ambient conditions may cause substantial recrystallization, formation of an ice phase during dissociation or under supercooling conditions in pressure cores, and alteration of the fine fabric of microscopic watercourses that may remain in natural high-grade NGH concentrations. LWD takes place so soon after the ambient conditions of a NGH concentration are encountered that alterations affecting logging responses within the NGH and its 'rock' + NGH fabric are minimal. The *in situ* character of permeability is especially important because NGH deposits should have a certain minimal permeability to allow for initiation of widespread controlled dissociation (Max & Johnson 2011*b*). The highly reversible reaction of the NGH system, and its interaction with the ice phase upon dissociation or the alteration of pressure–temperature conditions, argues for downhole measurements rather than captured samples 'read' geophysically after a much longer span of time.

Riedel *et al.* (2010) and Waite *et al.* (2012) have summarized physical properties relevant to full waveform processing of NGH, and have also compared processed data estimations of NGH saturation to cores and artificially fabricated NGH. In particular, Spence *et al.* (2010) have modelled the pressure and shear-wave seismic effects of NGH concentrations to provide volumetric estimation models. The precise workflow used by different groups is presently not available, or only available on a proprietary basis, and is still under development. Nevertheless, drilling has validated the predictive accuracy of geophysical processing techniques by confirming not only the location of NGH concentrations but also the saturation estimates (Boswell *et al.* 2011, 2012). These techniques have reached an adequate base level and are ready to support exploration of NGH as the next major unconventional gas resource.

In potentially high-grade focused flow deposits in which NGH forms in a permeable sand at or near the base of the GHSZ (Fig. 4), the presence of NGH and gas can be detected and volumetrically estimated using acoustic propagation effects. First, the sands are distinguished by their higher V_p, but on a smaller scale by their upper positive and negative lower reflection coefficient, and by their amplitude. In the sand below the base GHSZ, V_p will be low and attenuation high; while, in the NGH-enriched section in the GHSZ, V_p will be higher and

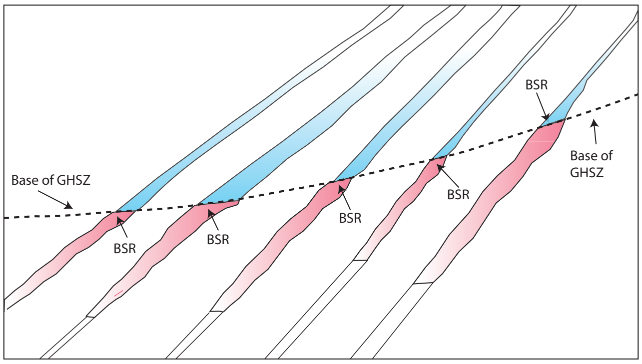

Fig. 4. Diagram of focused flow in permeable horizons showing the relationship of trapped gas below NGH at the base of the GHSZ. Note the non-continuous or 'string-of-pearls' BSR. The diagram is based on figure 11 of Boswell *et al.* (2011*b*). The extent of NGH up-dip may be exaggerated. The angle of intersection of the base GHSZ and permeable bedding is exaggerated. Shading indicates gas becoming less common down-dip and the NGH concentration more pronounced in the lower part of the GHSZ. ©Hydrate Energy International. Used with permission.

attenuation will generally be lower. Relative velocity amplitudes have been successfully used to estimate NGH saturation. In addition, relative V_p and attenuation alteration along the sand on either side of the base GHSZ will vary, with V_p decreasing upwards in both the gas and the NGH-enriched zone, and with a pronounced negative reflection coefficient at the junction between the gas and NGH-enriched zones.

Basin thermal history

The older geological history of the basin or sedimentary prism generally has no direct bearing on NGH concentrations. Therefore, there is no need to study the detailed sedimentation and thermal history. The possibly periodic generation and trapping of conventional hydrocarbons that may now be at depth are unlikely to be of direct relevance to NGH concentrations that may have commercial significance, unless they are leaky and the source of gases to the superjacent NGH. Deep stratigraphic drilling and downhole measurements do not need to be made for NGH exploration, and considerable savings should result from not having to carry out this work. Deep stratigraphic exploration wells are not required.

Geological traps

Structural analysis may not have to be carried out to the same level in conventional hydrocarbon exploration and, where done, need only be performed on the NGH zone of interest. In any case, because NGH is the result of crystallization in the GHSZ, the trap is of a physical chemical nature that need not require a conventional geological trap. Thus, even when no conventional traps occur, there may be significant concentrations of NGH with the potential for commercial development.

Free gas

Free gas does not need to occur for NGH deposits to form.

Tie to source beds

It is not necessary to tie the individual gas sources to NGH deposits. The geological feeders of mineralizing solutions to the lower part of the GHSZ are of importance, but the source of gas into the feeder system at any level below the GHSZ is essentially irrelevant to NGH exploration.

Heavy (expensive) drilling capability

Because NGH is confined to the uppermost marine sediments, and these have approximately the same mechanical character worldwide, a narrow range of drilling capability will be sufficient. The heavy drilling capability required for drilling holes many kilometres deep, and the engineering requirements for casing and completing conventional hydrocarbon wells, are simply not required. In addition, because pressures in NGH 'reservoirs' during gas extraction will be lower and the amount of gas in the reservoir, with respect to stable NGH, will be far less at any one time during the extraction operation, blowout preventers (BOPs) can be much smaller, lighter and less expensive. Due attention will have to be given to cementing the casing in a zone above any NGH-bearing sand. This is already done in deep-water development for conventional hydrocarbons. Refrigeration using heat exchange with cold seafloor water is also possible. In addition, lighter drilling capability utilizing smaller vessels and lighter drilling apparatus, such as coiled tube drilling, should also be much less expensive than that required for conventional hydrocarbon recovery operations.

Flow assurance

NGH is stable only at relatively cool temperatures, measured thus far at no more than 35 °C and more commonly below 25–30 °C (Max 2003). Gas produced from NGH is unlikely to be higher than 40 °C, even following heating that may be part of the conversion methodology. The temperature differential between the produced gas and the ambient temperature on the seafloor, on which the wellhead and close-by transmission pipelines will be located, can be anticipated to be no more than 40 °C. Therefore, the crystallization driving force and water vapour pressures in a NGH-produced gas will be less conducive to unwanted NGH crystallization. Where existing conventional gas infrastructure is used to transmit the gas, it will already be insulated or have other provision for flow assurance. Only a small part of the existing flow assurance capability will be necessary to ensure gas flow assurance. Where new infrastructure is used, it can be 'lighter' and amenable to innovative flow assurance measures of much lower cost than that used with conventional flow assurance.

PHASED APPROACH TO OCEANIC NGH EXPLORATION

Conventional hydrocarbon exploration in deep water usually utilizes deep seismic data in order to identify drilling targets. The shallower information is usually ignored because conventional hydrocarbon deposits do not occur at these shallow depths, although some of the data can be used to control drilling risk. Other remote methods (e.g. electrical resistivity) can be more relevant through shallow depths into sediment. In contrast, NGH exploration and NGH petroleum system analysis need only be carried out in the upper 1.5–2 km of a stratigraphic sequence, and the lower part will only be useful for identifying gas flow courses rather than NGH concentrations. Exploration for NGH concentrations will follow a process similar to that of conventional petroleum system analysis, beginning with general characteristics and focusing on individual prospects.

Bathymetry and seafloor morphology

Bathymetry is critical because water depth is one of the primary controls, along with heat flow or geothermal gradient, of the thickness of the GHSZ and its location in 3D space below the seafloor. High-resolution bathymetry, which is now routinely being achieved using multibeam apparatus, has the potential to reveal first-order seafloor stability conditions, such as a mass flow or geologically passive character. In addition, seafloor vent features and gas venting itself indicate excess natural gas, a sequestered portion of which will occur in NGH within the GHSZ, which has to be traversed.

Potential reservoir identification

Evaluation of basin stratigraphy and sequence stratigraphy will establish the likelihood of clastic strata (usually turbiditic sands) in the continental shelf sequence that occurs within the GHSZ. Although secondary porosity zones with NGH-filled fractures are known (Sassen *et al.* 2001*a, b*; Boswell *et al.* 2012), current industry practices for conventional gas recovery can be used directly for natural gas converted from NGH. Fracture-zone NGH may be an economic target in the future, along with dispersed NGH, but NGH-enriched sands similar in almost every way to conventional gas reservoir host strata will be the first oceanic NGH play. The objective is to locate sands and the depositional systems that have brought them into the sediment pile. An evaluation for these host sediments would be comparable to the current practice of reservoir host analysis.

Depositional–mineralization framework

Reflection seismic survey is the most important tool for establishing not just the geology but also the gas and groundwater access to and through the GHSZ. Pressure and temperature, with due regard for salinity of the pore water, control the presence of GHSZ, but a gas flux is the essential feature for the development of NGH concentrations. Mineralizing solutions must be able to transit into the GHSZ. Identification should be made of at least key entry points of porous horizons that control migration of natural gas into the GHSZ targets potential NGH zones. Seismic analysis techniques developed in the northern Gulf of Mexico for predicting NGH and subjacent gas drilling targets (Frye 2008; Shelander *et al.* 2012) have been confirmed by drilling. Active vent sites should be mapped, and measurements made on natural gas and tracers. It is not necessary to make a full hydrogeological assessment of the basin prior to engaging in more detailed seismic analysis, such as using ocean bottom seismology (OBS) and shear-wave analysis to more clearly define NGH concentrations (Haines *et al.* 2013*b*). The ultimate source of the NGH mineralizing solutions is relatively unimportant compared to identifying the porous strata along which they enter the GHSZ.

NGH economic zone

NGH only occurs within the GHSZ, and large concentrations are likely to be located in preferred host sediments in the lowermost part of the GHSZ. The NGH economic zone may not be the same as the thickness of the GHSZ, however, because the depth of the sulphate–methane transition below the seafloor may mean that no NGH will occur on the seafloor or for some distance below it. The base of the GHSZ is initially calculated from seafloor temperature, pressure and geothermal gradient (Wallmann *et al.* 2012). This provides a model depth that is useful for examining reflection seismic records and locating evidence of BSR, from which an accurate geothermal gradient can be calculated.

NGH concentration characterization

Reflection seismic data are used to create digital structural contour maps on porous strata bases and tops, and to show the depositional system in the same manner as used for conventional hydrocarbon resource assessment. Existing workstation software has been successfully applied using the geotechnical parameters applicable for NGH and its effect on the host sediment. In contrast to defining a closure of reservoir strata, however, direct mapping of NGH concentrations within the strata is made. Where the NGH is concentrated at the base of permeable strata passing into the GHSZ, the concentration will continue up the strata, in which it will generally terminate diffusely. Other mineralized zones may occur at shallower depths in the same or other strata in the GHSZ (Max *et al.* 2006). Isopach maps of both NGH and subjacent natural gas can be constructed.

Higher-frequency geophysical data may often be extracted from seismic surveys acquired for deeper conventional objectives or from special deep-tow apparatus optimized for GHSZ exploration (Rowe & Gettrust 1993). However, a more rapid technique for producing a higher-quality seismic analysis can be obtained by deploying OBS in order to capture shear-wave information that can be convolved with the reflection seismic data to produce much a higher resolution of the NGH concentrations (Haines *et al.* 2013*b*).

NGH petroleum system analysis requires a good model for the detailed geological character of NGH concentrations. This and the associated pore-water character and nature of the gas flux into the GHSZ both have a direct impact upon NGH nucleation and growth, resulting in NGH concentrations, as well as conversion and gas recovery scenarios. According to Boswell *et al.* (2011, 2012), the initial results of the Gulf of Mexico Hydrates Joint Industry Project Leg II successfully proved the geophysical basis for turbidite sand location within the GHSZ, and the drilling assessment validated geophysical predictions of NGH saturation and gas-in-place estimates.

Once a potential concentration has been identified, direct examination through drilling is the vital next step in establishing that an exploration target may have economic potential. Logging and sampling provide a higher-quality resolution for geotechnical parameters that can be used for extent and valuation of gas-in-place. An economic geological method for cell valuation is necessary to estimate grade, reserves and value, rather than the full-porosity method used for conventional liquid and gas.

At this point, the 3D shape of the NGH concentration, its internal porosity and permeability, NGH saturation, and gas-in-place can be used to estimate technically recoverable and commercially recoverable gas.

NGH RECOVERY ISSUES: DISCUSSION

Because NGH is stable and effectively inert in its 'reservoir', it must be converted to its component gas and water prior to recovering the free gas. NG extraction must begin with one or more of a number of methods that would be considered to be a secondary recovery technique in conventional hydrocarbon production. There are five main methods for NGH conversion, all of which can be accomplished using existing or rapidly emerging technologies. These include thermal, inhibitor and depressurization dissociation, dissolution, and chemical exchange (Max & Johnson 2011*b*). Each approach has advantages and disadvantages related to operating expense (Max *et al.* 2006), attainable flow rates and volumes of produced water, but none has yet been proven in a commercial environment. Determination of the optimal approach will depend on specific reservoir and drilling conditions. The variables that can be controlled to drive NGH conversion are temperature, pressure, chemistry of the pore water and concentration of the NGH-forming gas.

In addition to the challenge of dissociating the NGH into its component gas and water, other aspects of NGH reservoirs provide technical challenges (Fekete Associates Inc. 2010). Owing to the shallow depths of NGH deposits, the reservoir sands tend to be poorly consolidated, and thus sand control is imperative during production. Fortunately, petroleum industry technology for dealing with this issue is well established and may be adapted for the development of NGH concentrations (Carlson *et al.* 2013; Schlumberger 2013). These reservoirs also have low reservoir pressures, and sustaining commercially viable gas flow rates will necessitate energy input during production through depressurization and/or thermal stimulation. This has a negative impact on development economics. Further impacting economics, most gas NGH deposits are remote from markets, requiring the establishment of additional infrastructure.

The most important safety factor in any recovery scenario of the marine NGH system is that not only is solid crystalline gas NGH physically stable within the GHSZ at the ambient pressure at which it occurs, but if either the pressure or temperature conditions are changed to those of instability, the natural buffering of the reaction system tends to slow dissociation reactions. Because NGH is normally stable, even if a natural or man-made pathway to the seafloor or the surface is made so long as it remains at ambient pressures and temperatures, no gas will be converted from the NGH. Moreover, because NGH conversion can only take place following the imposition of NGH instability conditions, removal of these artificial conditions, combined with the natural buffering of the reaction system, will slow free gas generation and even tend to reintroduce conditions of NGH stability in which gas molecules will again begin to be incorporated in NGH.

Until NGH is converted by one of a number of stimulation methods (Max & Johnson 2011*b*), there will be little or no free gas that could result in uncontrolled venting. Because dissociation is a surface-effect phenomenon – that is, the dissociation takes place only where diffusion drives NGH-forming gas from the NGH crystalline structure and allows the water cage structure to collapse – the surface area of the NGH is crucial to reaching high rates of dissociation. Ideally, substantial permeability will exist and dissociation rates will be high. If the surface area of NGH exposed to pore water is too small, it may be necessary to create higher surface area.

Depressurization has a more general effect through a NGH concentration with sufficient permeability in that it acts more or less uniformly across a broad area owing to hydraulic transfer of force. Heating may produce a more limited dissociation effect because only NGH grains within the range of the heating will dissociate. Extraction models that minimize the amount of free gas in the NGH during production will minimize the amount of gas that could leak. As there are very rarely any liquid hydrocarbons associated with NGH above the level of traces, there is a very low risk of oil pollution, especially during exploration drilling because gas in the GHSZ is present in the form of solid NGH and stable at ambient pressures.

Because NGH is a relatively shallow drilling target below the seafloor and the strata that will be drilled are liable to be similar worldwide, a lighter drilling capability than is currently used for deeper conventional hydrocarbon deposits is possible. We suggest that new NGH-specific drilling practices using existing technology, consisting of a light drilling capability using a combination of a mudboat or light drilling ship and coiled tube or some other lighter drilling method, be employed to reduce costs. Lighter drilling capability may be used because the NGH is a solid, crystalline material that is stable in its ambient environment and is very unlikely to cause blowouts when appropriate drilling practices are followed.

The cost of NGH exploration and recovery could be less than conventional hydrocarbons because only relatively shallow geophysical methods are required, and drilling targets and conditions are likely to be similar worldwide and no more than 1 km beneath the seafloor. In addition, NGH gas production-system temperatures will be relatively low, almost certainly below 40 °C, in contrast to conventional hydrocarbons that may have elevated temperatures that require substantial and costly handling that induce higher levels of risk. Because the temperature and pressure differentials will be lower in NGH recovery than found in deep conventional hydrocarbons, flow assurance will probably be easier to manage and less costly.

Drilling programmes conducted in Arctic locations in Canada and Alaska, and in offshore India, South Korea, China and especially Japan in the Nankai Field off Tokyo, and in the United States in the northern Gulf of Mexico during the past decade have begun to confirm the magnitude of the recoverable NGH resource potential. These programmes have proven the effectiveness of remote and subsurface exploration tools, especially seismic analysis, and have validated exploration models. While technical challenges remain, the field programmes have provided insights that will allow these challenges to be addressed.

During the early 1990s, there was speculation that a sand extending across the BHSZ (containing NGH up-dip and free gas down-dip) would allow depressurization to be used most effectively to convert the NGH and produce the free gas. Extraction of the gas results in depressurization of NGH in hydraulic continuity within the reservoir. This leads in turn to dissociation of the NGH, which would then continue to feed into the free gas zone (Dillon *et al.* 1993). This approach is favoured for permafrost NGH deposits, especially where reservoirs are isolated in geological traps, often by faulting. However, the down-dip gas legs observed thus far for marine NGH deposits appear to be of limited extent. Removal of the gas might not have a significant effect on reservoir pressures, although it could provide the basis for applying a depressurization conversion technique without thermal stimulation (Max & Johnson 2011*b*).

The current projected cost of producing NGH is based on conventional resource development costs but the spatial setting and nature of oceanic NGH offer many opportunities for lower-cost exploration and development technologies. In addition, there is an extremely low environmental risk associated with NGH exploration and production (Max & Johnson 2012). We consider it possible that if capital expenditure can be lowered through application of new exploration, drilling, and production technology and practices, NGH may become competitive with other gas resources on a produced cost basis.

CONCLUSIONS

The NGH system describes natural gas (mainly methane) from any source rising from source beds along primary or secondary porosity systems into a GHSZ, where the gas and pore water react to form the solid crystalline material, NGH, in porous and permeable sediment hosts.

NGH concentrations of possible commercial merit are confined to GHSZs. Turbidite sands, which are the primary targets for NGH concentrations in continental margin GHSZs, are the same types of reservoir systems that host conventional deepwater hydrocarbons in older, more deeply buried strata. A NGH petroleum system to guide exploration involves the acquisition of less information than conventional petroleum system analysis. Existing industry seismic and other remote sensing exploration, and drilling and logging, tools developed for conventional hydrocarbon exploration and production can be applied to NGH exploration without expensive and time-consuming development of new technology. NGH exploration in continental margins has been successful using NGH petroleum system approaches. NGH exploration in other marine depositional environments and in permafrost regions, and in NGH concentrations other than in continental margin turbidite systems, are currently second-order objectives that are likely to be achievable over time. Seismic processing techniques exist to estimate NGH saturation of host sands and to identify drilling targets.

Conventional petroleum system analysis is applicable to permafrost NGH that forms in the upper part of shallow conventional gas traps. The oceanic-type NGH resource has a very different but common paragenesis and localization worldwide: exploration need only follow a narrow set of practices.

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Received 10 July 2012; revised typescript accepted 3 December 2013.

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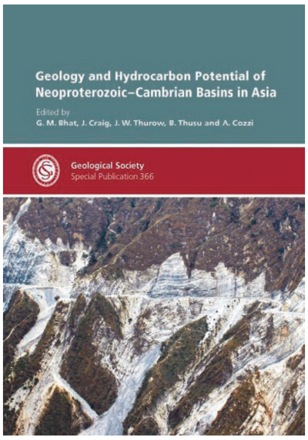

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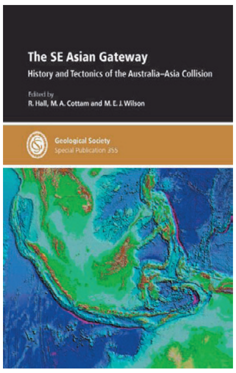

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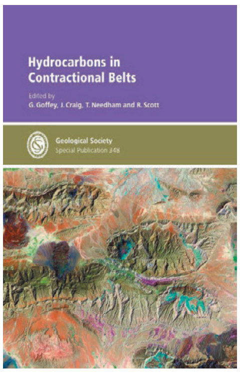

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