HYDRATE PETROLEUM SYSTEM APPROACH TO NATURAL GAS HYDRATE EXPLORATION

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ABSTRACT
Natural gas hydrate is unique among both conventional and other unconventional hydrocarbons in that it is neither liquid, gaseous, nor adsorbed. Oceanic natural gas hydrate concentrations have crystallized a chemical reaction between gas and water molecules in the gas hydrate stability zone. Hydrate concentrations may develop at any level within the zone. Conventional hydrate petroleum analysis resembles that of conventional hydrocarbon systems but is different in a number of important respects. Its critical elements are: 1) gas sources, 2) migration pathways, 3) a gas hydrate stability zone suitable for natural gas hydrate to form, and 4) adequate concentration of dissolved natural gas in migrating pore fluids. There is no need to link particular deposits with particular source beds, there is no need to understand the entire thermal history of the basin, and there is no need for a geological trap. The hydrogeological system from below the GHSZ to the seafloor, and the geological disposition of the migration pathways into and within the GHSZ is a key to exploration for natural gas hydrate concentrations.

Keywords: gas hydrates, petroleum system, reservoir, gas resource, trap, unconventional gas

NOMENCLATURE
Natural gas hydrate (NGH)
Natural gas may be produced from converted hydrate.
Gas hydrate stability zone (GHSZ)
Gas hydrate production domain (GHPD)
Hydrate Petroleum System Analysis (HPSA).
Specifically for Oceanic NGH unless otherwise stated.
Bottom simulating reflector (BSR)

INTRODUCTION
Natural gas hydrate (NGH) is an unconventional gas resource that has yet to be commercialized. Although other unconventional gas resources, among them shale gas, tight gas, and coalbed methane have been commercialized, the process of converting NGH to its constituent water and gas (Max and Johnson, in press) and successfully recovering the gas commercially has not yet reached the point of being an industrially verified methodology.

NGH is unique among gas resources because in its natural state it is a solid crystalline material formed by digenetic crystallization. NGH forms spontaneously when certain gases contact water under suitable conditions of pressure, temperature, and concentration (Fig. 1). Gas hydrate is comprised of cage structures of water molecules having gas molecules within the voids in a stable crystalline structure. Naturally occurring gas hydrate is composed of mainly methane, with some minor amounts of higher density hydrocarbon gases where thermogenic gas is available. Formation of gas hydrate compresses gas within the hydrate crystalline structure as the
gas molecules are held closely together. Once gas hydrate has formed, it is stable in the natural environment and can only be converted by lowering pressure, increasing temperature, introducing a chemical inhibitor, or by gas molecule substitution.

Methane is the dominant gas in NGH. It occurs naturally in a gas hydrate stability zone (GHSZ) that is rarely more than 1 km thick in the uppermost marine sediments or permafrost regions in which temperature and pressure are suitable for hydrate to form spontaneously if there is sufficient gas flux. Pressure and temperature control the thickness of the hydrate stability zone,

Oceanic NGH is considered to hold 95% of the world’s NGH (Kvenvolden & Lorenson, 2001), although permafrost hydrate recognized to date in the Arctic were geologically trapped gas deposits before the uppermost part of some of these deposits were converted to NGH during intensification of glacial episodes. Permafrost hydrate associated with conventional trapping is known from conventional exploration practices and no special hydrate petroleum system model needs be erected for them. In order to optimize exploration for oceanic NGH, however, it is important to understand the nature of the location in which the NGH is most likely to be concentrated.

Although most gas hydrate occurs in distributed in a dispersed manner in muddy sediments, the greatest concentrations appear to occur in sands and more coarse beds, where the formation of hydrate is probably related to crystallization from pore water fluids (Max, 2003, Max et al., 2006). Hydrate contains an enormous amount of gas in different types of strata that may be of greater volume than is estimated to be in conventional gas deposits (Boswell et al. 2010). Consistent with other natural resources, the volumetrically least common strata is likely to contain the most concentrated NGH (Fig. 2). The methodology for locating oceanic NGH concentrations or ‘sweet spots’, which is the main topic of this paper, requires a petroleum system for NGH to be defined.

High-grade hydrate deposits are the primary NGH exploration objectives. These consist of large volumes of hydrate concentrated in relatively small volumes of reservoir rock. Hydrate concentrates in better bed-differentiated strata (sands and more course detritus) into which dissolved methane could be best transported by groundwater. In strata shown on a seismic section where a dipping stratigraphic sequence contains a number of porous beds, hydrate may form near the base of the GHSZ in each of the porous beds. In this case, the bottom simulating reflectors (BSR), which are a negative impedance contrast at the hydrate / subjacent gas stability boundary, 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 with a little gas down-dip in the in porous horizons as a ‘string of pearls BSR’. Each of the porous horizons has the potential to host high-grade hydrate deposits, and each constitutes a primary NGH exploration focus.
Closely spaced porous horizons have the potential to allow gas extraction from multiple horizons from a 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. Additionally, where a BSR occurs, the solutions were almost certainly supersaturated with respect to free gas formation from solution. These are first order exploration targets because there is the greatest likelihood of a relatively high gas flow and a high rate of hydrate crystallization over the longest distance in the porous horizon.

Even low in the GHSZ, however, hydrate concentrations can occur with no BSR observed (Paull, et al., 1998). The pore water solutions in the sediments immediately below NGH-enriched strata appear to have been undersaturated with respect to gas generation as no free gas is present. However, the saturation was apparently high enough to provide a driving force for hydrate crystallization once the solutions reached higher levels that were colder within the GHSZ. NGH concentrations higher in the GHSZ also can form from solutions that were relatively undersaturated with respect to hydrate formation until they have migrated to shallower depths. These are likely to be indistinguishable from deposits formed from solutions that already deposited hydrate lower in the GHSZ. These are second order exploration targets as they are likely to contain lower concentrations of hydrate, although they may still prove to be large enough to justify commercial recovery of natural gas.

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 BGHSZ and may extend over large areas. BSRs, whose importance has been overemphasized in the past, often constitute first order features on seismic sections. These well defined BSRs, such as are seen in the Blake Ridge area of the U.S. East Coast continental margin, are dramatic seismic features but are of limited exploration and economic value. The hydrate associated with these features often forms extremely large low grade deposits (Max et al., 2006) that have relatively small percentages of dispersed hydrate throughout huge volumes of fairly uniform muddy sediments. These do not constitute primary exploration targets.

**PETROLEUM SYSTEM ANALYSIS**

Petroleum system analysis is a systematic process that incorporates diverse geological information for petroleum and natural gas exploration, particularly in early stage evaluation (Ligtenberg & Neves, 2008), which is particularly applicable to continental deposits that were originally laid down in epicontinental shallow seas and in continental slope deposits along thickly sedimeted continental margins. Conventional petroleum system analysis is an attempt to understand and describe the temporal sequence of processes that lead to the formation of hydrocarbon accumulations. A petroleum system is, “a dynamic petroleum generating and concentrating physical chemical system functioning in a geologic space and time” (Demaison and Huizinga, 1994). An individual petroleum system can have very individual characteristics or history, and different petroleum systems can occur in the same basin, in which the geological history has varied over time.

The main elements of a conventional petroleum system can be summarized on an ‘events chart’ (Magoon, et al., 2001) that consists of: 1) suitable source rock, burial and thermal history, 2) reservoir rock, 3) seal rock, 4) overburden rock, 5) trap formation, 6) preservation, 7) the generation, migration, and accumulation of the hydrocarbon itself, and, 8) the critical moment in geological time when the deposit actually formed, which is essentially a function of #7 above.

The implication from conventional hydrocarbon system analysis is that once the geological background is set, the generation, migration, and accumulation of the hydrocarbon is accomplished in a relatively short space of geological time. Once the hydrocarbons have been trapped, they can remain in the trap and persist little changed in the reservoir for a very long time. 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. Because a geological basin matures over time, a wide range of geological ages of deposits and their depth in the basin, as well as their relationships with different source beds and migration pathways may be developed in geospatial proximity.

**NGH PETROLEUM SYSTEM**

NGH forms under very different conditions from conventional gas deposits. Whereas different
petroleum systems can develop in a sedimentary basin over time, with the character of source beds, reservoirs, trap and seals, overburden and preservation all differing through time, NGH deposits worldwide have a single set of critical factors that controls their development. And that critical set of factors has to be active in the present or very recent past for hydrate concentrations to form and persist.

Hydrate petroleum system analysis (HPSA) is much more direct than conventional petroleum system analysis, and is almost certainly a good deal less expensive to carry out. There are fewer critical factors and they all have to be acting synchronously (Fig. 3).

Active Hydrate Petroleum System

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\text{Accumulation / Preservation (GHSZ)}
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\[
\text{Migration (Critical Moment)}
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\[
\text{Gas Generation}
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Figure 3. Schematic elements of the hydrate petroleum system.

The basic elements of the NGH petroleum system consist of:
1) Source(s) of gas
2) Migration pathways and active groundwater system
3) Zone of gas hydrate P-T stability
4) Dissolved natural gas concentration

The objective of hydrate petroleum system analysis remains the same as it is for conventional petroleum system analysis, which is to improve exploration for NGH concentrations so as to identify commercial sources of natural gas.

NGH petroleum system analysis focuses on the NGH zone of interest, which is usually confined to the upper 1 to 1.5 km of marine sediments in water depths greater than about 800 m; that is, deep continental margins from a water depth of about 700 m downwards. This zone of interest consists of the generally seafloor-parallel gas hydrate stability zone (GHSZ) in which hydrate 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 commonly are found, exploration and extraction costs for NGH-optimized practices that are in the process of being developed may be significantly lower than those of conventional hydrocarbon exploration. The cost factors should be particularly divergent when NGH is compared with deep, high temperature, high pressure conventional gas deposits.

NGH, in contrast, is essentially a more ‘modern’ deposit in which existing hydrate concentrations depend on existing and geologically recent gas and dissolved gas flow toward 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 geological gradient, and the height of sea level stand, whose changes have no effect on conventional hydrocarbon deposits exert a strong influence over the existence and persistence of hydrate and hydrate concentrations.

1) Gas sources

The superabundance of biogenic methane in oceanic NGH and its concentration in the uppermost seafloor sediments suggests that the thermal history of a basin over time may be of much less importance for NGH than for conventional hydrocarbons. Because not enough microbial methane is generated internally within the GHSZ to account for the gas content of most accumulations, a gas source outside and below is required. Also, 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 hydrate. Nonetheless, there appear to be huge amounts of hydrate (Kvenvolden and Lorenson, 2001). Hydrate is a natural buffer for oceanic methane production; hydrate captures the methane and holds it securely from entering the ocean or
atmosphere. It is likely that the majority of methane has been produced by bacterial activity in a broad area of sediments whose temperature did not even reach the kerogen stage of conventional hydrocarbon production, within which oil may be generated between 60 and 120 °C and gas will be generated between 120 and 225 °C through chemical processes (Selley, 1998).

The potential for gas generation in a province can be expressed in the same way as that for conventional hydrocarbons: Volume of hydrocarbon generated (V) = basin area (A) X average total thickness of source rock (T) X 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, especially in the biogenic ranges where huge volumes of marine sediments are capable of hosting methanogenic biota, but the transformation ratio may be different from the experience of conventional hydrocarbon assessment potential, as may the provenance and timeline for production of gas in hydrate deposits.

Because the sedimentary environments in which the petroleum system operates evolves over time, the relative timing of the thermal history and migration systems may be critical for conventional hydrocarbon production, migration and trapping. Gas hydrate is a more modern phenomenon and the thermal history of the basin is not of direct relevance for NGH petroleum analysis. 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. So long as the existing gas flux has been sufficient to allow the formation of hydrate concentrations, and is presently strong enough to sustain stable hydrate conditions, there is no reason to expend resources elucidating the long-term basin thermal history or in identifying a distinct source bed for hydrate concentrations.

Whereas conventional petroleum system analysis seeks to link a particular source with a particular hydrocarbon deposit, this is not a requirement for NGH analysis. The biogenic gas may well be drawn from a very large volume of sediments, especially in a passive continental margin having a thick sedimentary prism. Hydrate in an active margin is more likely to include thermogenic gas. These thermogenic sources are likely to be more distant than in a conventional petroleum system and related to a multitude of sources and source beds to the lower part of an accretionary prism.

2) Migration paths and groundwater systems
Methane in the hydrate system would have been carried from depth in ground water toward the surface in both primary and secondary porosity. Exploration for hydrate concentrations will literally ‘follow the water’ from a methane rich, subjacent groundwater source to a location within the GHSZ where spontaneous hydrate crystallization will take place. Tracking methane and groundwater source within a relatively short distance below the GHSZ to hydrate concentrations within the GHSZ is a fundamental aim of hydrate exploration. The groundwater system within marine sediments on deep continental margins and continental slopes is the driver of the hydrate system. In a passive margin the water drive is sediment compaction under gravity while in an active margin tectonism is likely to be more important than gravity alone.

Detailed studies of ancient migration systems that have concentrated conventional hydrocarbons can be important to the identification of deposits. In addition, geological analysis of a basin’s thermal and sedimentological attributes is part of petroleum system analysis because the conditions for hydrocarbon concentration, and the concentration process itself, can begin early in the history of a basin. Once a conventional hydrocarbon deposit has formed, it may persist for a very long time, even if the migration path for that system diminishes or ceases. Subsequent source and migration systems may further charge existing hydrocarbon reservoirs, or they may form entirely new ones, often in sediments that may not yet have been deposited when the older deposits were formed. Studies of ancient migration systems serve essentially no purpose in NGH exploration because the NGH system is dependent on existing supply of reactants and gas flux, whole history may not reach back much in geological time.

NGH concentrations that may contain enough gas to warrant extraction are similar to conventional gas concentration in two important ways. There have to be sources for the natural gas, and there have to be geological pathways through which the methane is transported, most commonly in pore water systems. It is not
necessary to know the sources of the gas. A continuous supply of dissolved methane in the groundwater now and in the immediate past is critical. If the concentration of dissolved methane in the pore water is high enough, hydrate will form and persist. Without a high enough continuing ‘gas flux’ methane hydrate will dissolve, even though the ambient conditions of pressure and temperature favor hydrate stability. Thus, one of the exploration tools vital to gas hydrate exploration is an understanding of pore water movements and its chemical character as part of a groundwater supply system. Water sources must be tracked into the GHSZ. Hydrate petroleum system analysis focuses (more or less) on existing groundwater systematics, as the longer geological history and ancient fluid movements are not an aid to hydrate exploration.

Conventional hydrocarbon reservoirs may be found at any depth in a petroliferous basin; almost always much deeper than hydrate concentrations, except in some isolated permafrost hydrate deposits. Thus, conventional hydrocarbon deposits may be hot, often above the boiling point of water, which may necessitate very careful handling. In contrast, hydrate concentrations are confined to the GHSZ, a zone that commonly parallels the seafloor and only extends to a certain depth from place to place, and which will move upward with continued sediment deposition. The ambient temperatures of hydrate deposits are also unlikely to be above 40 °C.

Geological traps do not generally bound oceanic gas hydrate concentrations, even though less permeable beds enclosing the more porous horizons might give the impression of a 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 hydrate-forming gas. Formation of hydrate itself may provide the trap. Potential hydrate-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 to their continuations or analogs at depth. Pressure and temperature are critical for the formation of methane hydrate concentrations. Conventional hydrocarbon accumulations are not dependent upon a narrow set of physical-chemical parameters whereas NGH concentrations are. The existing or modern groundwater hydraulic system, which may have a geological ‘tail’ of hundreds of thousands to millions of years, is critical to the existence of hydrate concentrations. Under the right circumstances, hydrate concentrations can develop relatively quickly.

3) The gas hydrate stability zone

NGH is unique among gas resources because in its natural state it is a solid crystalline material formed by digenetic crystallization. NGH thus has a number of analogues with mineral deposits, particularly low temperature stratabound deposits. Where NGH forms in porous sediment, very high pore fills can be achieved, which suggests that bulk crystallization within the pore water is favored over nucleation and growth on sediment grains, which would have the effect of blocking pore throats before porosity could become substantially filled. This indicates relatively slow growth, and hence, relatively slow supply of reactants.

NGH forms spontaneously when certain gases contact water under suitable conditions of pressure, temperature (Fig. 1), and concentration. NGH is composed of mainly biogenic methane, with some higher density hydrocarbon gases where thermogenic gas is available. Where more than one hydrate forming gas is present in a mixture, the compound hydrate that forms takes gas from the mixture in proportion to its preference (Max et al., 2006) so that the proportion of gases in the hydrate will be different than in the surrounding mixture of gases.

NGH is a transitory mineral deposit that forms in a highly reversible reaction that can cause the hydrate to dissolve or dissociate almost as rapidly as it can form. Although there may be a superficial similarity to coalbed methane that will effuse absorbed gas when pressure is lowered, this is fundamentally different from the process of converting NGH to its component water and gas through depressurization, which causes dissociation of the material itself.

Oceanic NGH occurs naturally in the gas hydrate stability zone (GHSZ) that extends downward from the seafloor to some depth determined by increasing temperature (Max, 2003). Within this zone temperature and pressure are suitable for hydrate to form spontaneously. The GHSZ, which thickens with increasing water depth, may extend to about 1 km below the seafloor. Local geothermal gradients exert a strong influence on the thickness of the GHSZ, as
does water depth (pressure) and the seafloor temperature. Rapid lateral changes in the thickness of the GHSZ are rare except near salt diapirs. NGH deposits are thus restricted in time and space, in contrast to conventional hydrocarbon deposits whose locations are generally unrelated to the deeper geothermal temperatures.

Oceanic NGH is characteristically a very pure gas deposit, and will have about the same purity worldwide because NGH paragenesis is relatively simple. The gas in NGH is dominantly biogenic methane that has few contaminants. It is rarely associated with liquid petroleum, even when its gas has a thermogenic source. 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, SOx, CO2, and other contaminants that are often found in conventional deposits. Other contaminants, such as SOx, are preferred hydrate formers that have the potential to form below the methane hydrate stability region. This crystallization selectively extracts higher density hydrocarbon gases from the gas mixture and can act to produce a relatively pure reject methane gas. As a result of salt rejection and equilibration of water media during and after crystallization, almost pure water is produced when hydrate dissociates. Very high salinity brines are unlikely to be encountered in NGH extraction.

Gas hydrate formation and dissociation are both chemical reactions that produce heat upon formation and consumes 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 P-T space back toward the phase boundary. When NGH begins to dissociate, heat is consumed that also tends to drive the reaction point back toward the phase boundary, but in the opposite direction. NGH only dissociates at its margins with surrounding media (usually water), which may limit early dissociation, especially in a high grade deposit (Max et al., 2006). NGH does not have the potential to dissociate rapidly or 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. This inherent stability is self evident from many images of solid NGH being examined at upon core recovery, even if this has taken many hours. About the same maximum rate of dissociation may be obtained in an in-situ hydrate concentration under conversion, as when the hydrate may be grossly out of its stability field.

A great deal of early emphasis has been placed on the base of the GHSZ (BGHSZ) because it is relatively easy to identify if there is a well defined BSR. The BGHSZ is the greatest depth at which methane hydrate naturally occurs. It is often imaged on reflection seismic data. BSR has been used as a primary drilling target, despite the fact that BSR is an indication of dispersed gas being present in pore water below the BSR rather than it being an indicator of the presence of significant methane hydrate above the BSR (Max, 1990). In the simplest early models for formation of gas hydrate concentrations, most of the hydrate was expected to occur only immediately above the BSR. It is now known from drilling and down hole measurements and sampling that hydrate can occur anywhere in the GHSZ where there is suitable host and hydrate-forming gas supply.

It is also important to note, however, that hydrate may not be stable everywhere in the GHSZ, particularly in its upper part. A zone of sulfate reduction of methane near the seafloor can affect the depth of the upper limit at which hydrate concentrations will form (Borowski and Paull, 1996). Under certain conditions that favor an active sulfate reaction zone, the upper limit of hydrate development could be tens or even in rare circumstances, hundreds of meters below the seafloor, even though pressure-temperature conditions would be well within the pressure-temperature field of hydrate stability. The base of the sulfate zone, however, will almost certainly be shallower than the practical upper limit of hydrate recovery, which will be defined according to safety and other drilling factors. Above some depth, the risk factors of hydrate conversion and recovery activities will be too great. 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.

4) Gas concentration and its impact on hydrate crystallization

The formation of hydrate is a physical chemical process of crystallization that occurs when ascending fluids containing sufficient concentration of natural gas reach a location in the
GHSZ in which conditions are suitable for crystallization. Where crystallization from dissolved natural gas is the paragenetic cause of NGH formation, an open hydraulic system in which the groundwater at depth below a hydrate concentration is in continuity with the seawater through seafloor vents or seeps provides the optimum conditions for subjacent NGH formation. Deep towed or AAUV methane sniffers are an excellent way of establishing the presence of a groundwater system suitable for the formation of hydrate deposits.

NGH forms from water in which a concentration of dissolved hydrate-forming gas is high enough so that hydrate will form spontaneously. A single phase system consists of water carrying dissolved gas. A two-phase system occurs when NGH and water with dissolved gas are present. A three-phase system occurs when free gas is present with water and hydrate (Fig. 3). In a gas-saturated system, gas will dissolve in the water as gas molecules are incorporated in hydrate crystal lattices. In a closed system, gas will be consumed while NGH forms until the vapor pressure of the gas concentration is about that in the hydrate, at which point no further reactions or solution changes will take place. In the GHSZ, the occurrence of a three phase methane system results in a disequilibrium condition in which dissolved gas is being extracting from water media by accreting hydrate while atwater-gas contacts, gas is dissolving. Dissolution in the presence of gas, diffusion and/or physical mixing, and reduction of dissolved gas concentration at a hydrate-water contact are rate-controlling steps. A three phase system may also indicate metastable conditions such as occur along the hydrate phase boundary.

The concentration of dissolved methane in pore water media is normally higher than the vapor pressure of gas (methane) in the hydrate in order for methane hydrate to accrete (Fig. 3). Therefore, continued supplies of high concentrations of dissolved methane in the pore water are the best way to insure the existence of a hydrate deposit in a porous zone open to source and to the surface. In situations where flux is about equal to groundwater flux, the maximum conditions for growth are present, although the presence of very buoyant gas micro-bubbles has the potential to drive the water transport system faster. Where groundwater is quiescent, in the absence of migrating gas micro-bubbles, much slower diffusion in the groundwater may be the only means of migration of dissolved hydrate-forming gas. Also, where solid hydrate or other mineralization sufficiently tightens the porosity, methane can only move through solid or liquid diffusion processes, which are much slower. Hydrate in contact with a solid diffusion barrier, such as a sediment grain, may persist for considerable periods of time without methane-saturated water in contact, although the natural tendency for hydrate to reject foreign material may cause a solid bond with a sediment particle to dissipate over time.

![Figure 3. Generalized concentration diagram showing regions of hydrate growth and dissolution. Courtesy of HEI.](image)

Because a geological trap is not required for the formation of a deposit, both sands and fracture zones within the GHSZ have the potential to contain significant NGH concentrations. Once a hydrate deposit has formed, especially in a concentration in an open hydraulic groundwater system, it will not have the same degree of permanence of a conventional gas deposit. Methane monohydrate formation and dissolution is controlled by a highly reversible reaction in a transitional or metastable zone in which either dissociation or dissolution is possible depending on slight changes in ambient pressure or temperature. Hydrate formation and dissolution will take place along the same hydrate phase boundary so that if conditions change even very slightly, hydrate that had been crystallizing may begin to dissociate.
Once gas hydrate has formed, it is stable within its field of pressure and temperature so long as gas concentration in the surrounding media remains higher than that in the NGH metastable zone. If the gas concentration in the water media falls below a certain level, the hydrate will begin to dissolve regardless of the pressure and temperature conditions in which hydrate is stable. Thus, the concentration of the hydrate-forming gas dissolved in the contact water media is a critical factor in concentrating hydrate that is often overlooked. Supersaturation to the level of free gas in a three phase system is commonly assumed.

Even where there may be supersaturation of groundwater or gas micro-bubbles propagating from depths into the GHSZ, however, formation of hydrate near the base of the GHSZ leaves the residual groundwater with the capability to possibly form hydrate higher in the GHSZ where it may be much colder and only slightly lower pressure. When a solution passing into the GHSZ is high enough to allow for spontaneous crystallization immediately upon attaining suitable pressure - temperature conditions, hydrate will form in the lower part of the GHSZ. Where the GHSZ is sufficiently thick for pressure to vary significantly, hydrate-bearing zones may develop at multiple depths, all crystallized from the same hydrate-forming solution. Results of the drilling program on the Cascadia margin of North America (Trehu et al, 2004), for instance, show hydrate concentrations in porous horizons occurring at multiple levels within the GHSZ.

In contrast to a fully saturated groundwater solution that may localize hydrate concentrations near the base of the GHSZ, solutions that do not have a sufficiently high concentration of hydrate-forming gas will not begin to form hydrate immediately upon reaching the GHSZ. As the solutions pass upward 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. Thus, solutions that may have too low a concentration of dissolved gas for free gas to form, may still have the potential to form hydrate once they attain the GHSZ, or some higher level within it.

HYDRATE: THE MOVING RESERVOIR

Conventional gas and petroleum deposits generally stay in their geological reservoirs once they have formed. That is, the structural or stratigraphic trap the hydrocarbon is in is a mechanically strong sealed system that may become more deeply buried or even moved relative to other reservoir rocks by tectonic forces. Yet, if the reservoir and trap system is not disrupted so that leaking might occur, the trap-reservoir geology tends to remain the same regardless in the change to their physical conditions.

NGH deposits, in contrast, can move from one geological host to another. The can reconcentrate and redeposit while incorporating newly-arrived gas. For instance, when a BGHSZ moves upward in response to continued sedimentation, lower pressures related to lowering sea level or geological uplift, or seafloor warming, NGH will naturally begin to convert. This is the result of conditions for hydrate stability have migrated upward. This may produce overpressured gas that will have the potential to drive pore water. At the extreme, a natural blowout or venting to the seafloor may develop.

CONVENTIONAL GAS ISSUES NOT OF FIRST ORDER IMPORTANCE FOR NGH SYSTEM ANALYSIS

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

Full geology & structure

Deep Seismic and other remote exploration methods below the upper 1.5 – 2 km of marine sediment are probably unnecessary. NGH is more restricted in time and space than are conventional hydrocarbon deposits. NGH is confined to the GHSZ worldwide. All NGH targets will be much shallower than conventional hydrocarbons. Because it is necessary to only understand the geology and hydrogeological system within the hydrate zone of interest, which will extend to some depth below the GHSZ that encompasses the groundwater feeder system into the GHSZ, there will usually be no requirement to carry out very deep seismic or other remote sensing surveys such as may be done for conventional gas and oil. Thus, lower powered, higher resolution surveys can be carried out. Smaller, less expensive vessels may be used. Considerable savings should result.
Computer analysis techniques 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. Therefore, little cost need be incurred in developing new computer capabilities. These costs are already amortized.

Basin thermal history
The older geological history of the basin or sedimentary prism generally has no direct bearing on the existence of hydrate 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 be now at depth are of no importance to the existence of hydrate concentrations that may have commercial significance. 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.

Geological Seal & Trap
Structural analysis may not have to be done to the same level in conventional hydrocarbon exploration, and where done, need only be done for the NGH zone of interest. In any case, because NGH is the result of crystallization in the GHSZ, the trap may be of a physical chemical nature and a conventional geological trap is not required. Thus, even where no conventional traps occur, there may be significant concentrations of NGH.

Tie to source beds
It is not necessary to determine the individual gas sources to NGH deposits. The only thing that matters is whether there has been adequate gas flux reaching back from the present into the recent past for long enough to form an economic NGH deposit. The geological feeders of mineralizing solutions to the lower part of the GHSZ are of importance, but identifying the precise deeper sources that provided the gas to the feeders are essentially irrelevant to NGH exploration.

Hydrocarbon available as free gas
NGH crystallizes from groundwater solutions that pass into the GHSZ. Significant amounts of hydrate can crystallize from a two-phase solution of hydrate and groundwater bearing adequate concentrations of dissolved methane. Free gas does not need to occur for NGH deposits to form. But free gas below the GHSZ may indicate that groundwater passing into the GHSZ is saturated with methane, which could be important to NGH exploration. In addition, the free gas itself could be a recoverable commodity and the effect on the geomechanical situation before, during, and after gas extraction are also important. But remote sensing can focus on the volume within and immediately below the GHSZ. This allows for greater resolution and potentially less expensive surveys.

Reservoir security and gas flow
In addition to the issues concerning hydrate conversion and the rate at which controlled conversion can proceed, there are two other issues that are important to hydrate.

Reservoir integrity
The mechanical properties of the sediment mass change when NGH is induced to begin conversion. In order to recover gas from NGH safely, it will be necessary to integrate the geomechanics in and around the hydrate resource.

Because NGH is essentially in equilibrium with its chemical environment and pressure and temperature of its ‘reservoir’, it must be converted to its component gas and water prior to recovering the gas. Hydrate extraction must begin with one or more of a number of methods that would be considered to be secondary recovery technique in conventional hydrocarbon recovery. For hydrate conversion, these ordinarily secondary techniques must be employed from the outset. All extraction models should minimize the amount of free gas in the NGH reservoir; hydrate conversion (Max et al., 2006, Max and Johnson, in press) should be matched to gas extraction.

There are four main methods for hydrate conversion, all of which can be accomplished using existing or emerging technology. These include thermal, inhibitor, and depressurization dissociation, dissolution, and chemical exchange. Each approach has advantages and disadvantages related to operating expense, attainable flow rates, and volumes of produced water, but none have yet been proven in a commercial environment. Determination of the optimal approach will depend on specific reservoir and drilling conditions for each deposit. The variables that can be controlled to drive hydrate conversion are
temperature, pressure, chemistry of the aqueous media, and concentration of the hydrate forming gas.

Perhaps the major reason why hydrate development is lagging is that the material properties of oceanic natural gas hydrates, especially those rock mechanical properties important to the conversion of the hydrate to its constituent water and gas and the extraction of the gas, are not known with the engineering certainty necessary to provide for reservoir safety throughout a gas extraction operation.

Characterization of NGH concentrations that are the primary exploration targets was originally based on the alteration to rock and acoustic and magnetic properties caused when hydrate forms in pore and fracture space, and increase acoustic velocity, Vs, Vp along with bulk and shear modulii. Petrofabrics have been the key to natural gas hydrate exploration, with calibration of techniques produced by drilling. Although techniques for exploration for natural gas hydrate have not yet been fully implemented, combining an increased knowledge of how hydrate develops in concentrations with natural gas hydrate petroleum models, has allowed for a much more coherent approach to be developed.

Rock mechanics and the determination of geotechnical properties of hydrate concentration domains are the keys to successful commercial extraction of oceanic natural gas hydrate. This is because the hydrate that has formed has considerable mechanical strength, whether or not it cements sediment grains. Because sweet spot hydrate concentrations that contain enough natural gas to be of interest for commercial extraction appear to be developed predominantly in coarser grained sediments and sands, the risk of sediment collapse is relatively low since these sediments are grain supported. Some compaction can be anticipated but thixotropic flow conditions that might develop in muddy sediments with hydrate conversion are unlikely so long as gas conversion and extraction rates are kept below certain limits. More muddy sediments adjacent to and for some distance below a potential hydrate reservoir, and between the reservoir and the surface, however, are also of concern if they contain diffuse hydrate that may also be converted, as these sediments are mechanically weaker.

We propose referring to this critical volume as a ‘natural gas hydrate concentration domain’ (HCD). Within this volume a unified geomechanical model will be erected for the commercial extraction of gas from the standpoints of optimal gas production and reservoir security. The HCD is defined as all the elements of the geomechanical system important to reservoir security during exploration, extraction, and following shut-in. The HCD consists of the concentration itself, whether in primary or secondary porosity, and all geological strata and structures that could be affected mechanically by the conversion of hydrate and migration of gas and water during recovery. The objectives of understanding the mechanics of this volume are preventing blowouts from overpressured gas, cave-in or subsidence, and the prevention of triggering of any mass flows.

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 will be no more than 40°C. Therefore, the crystallization driving force and water vapor pressures in a NGH produced gas will be less conducive for 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. 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.

CONCLUSIONS
The paragenesis of oceanic NGH is now understood well enough to establish a hydrate petroleum system model to be used for resources exploration. This NGH petroleum system differs considerably from conventional petroleum systems and must be understood on its own terms. However, NGH petroleum system analysis has fewer geological issues with which to deal, and a much more restricted geological target as the
GHSZ lies within about 1 km of the seafloor and is composed of similar sedimentary materials worldwide.

In contrast to conventional gas deposits that may have had their ‘critical moments’ of formation at any time in the geological history of a petroliferous basin, NGH is essentially a modern deposit in that if the conditions for hydrate deposition that may have pertained in the recent past have ceased, it is likely that the deposit will naturally reconvert to its component gas and water. If a NGH concentration does not have conditions of hydrate formation or maintenance, it will not persist.

The critical elements of the NGH system are: an adequate gas supply from any source, a permeable migration path in either primary or secondary porosity, and a GHSZ into which the hydrate forming gas is brought at sufficient concentration to spontaneously crystallized when it reaches the suitable conditions of pressure and temperature in the GHSZ.

REFERENCES


