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A case study of natural gas hydrates (NGH) in offshore NW Sabah: Identification, shallow geohazard implication for exploration drilling, extraction challenges and potential energy resource estimation

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Abstract: Natural gas hydrates (NGHs), sometimes referred to as "flammable ice", are crystalline solids, consisting of hydrocarbon gases with low molecular weight, such as methane, ethane and propane, bound with water molecules within cage-like lattices. The water molecules and low molecular weight NGH lattices are stable within a specific range of temperatures and pressures, and the source of the gases can be biogenic or thermogenic in origin. NGHs are common in the upper hundreds of metres of sub-seafloor sediments on the continental margins at water depths greater than about 500 m. Seismic reflection profiles and wireline well logs are common indicators used to identify the presence of NGHs, which are often encountered during offshore deepwater exploration drilling. They may cause geohazards such as slope instability, expulsion of the seafloor, shallow water flows and shallow gas if the stability of penetrated NGHs is disturbed and starts to dissociate. Methane gas hydrates represent a significant potential energy resource, as illustrated in this case study from offshore NW Sabah and may represent one of the world's largest reservoirs of carbon-based fuel, with some estimates suggest that the hydrocarbons bound in the form of NGHs may rival the total energy resources contained in other conventional hydrocarbon sources. Methane can be extracted from NGHs through three methods: depressurization, inhibitor injection and thermal stimulation. However, risk associated with NGHs extraction can contribute to environmental concerns such as global warming and a decrease in microbial communities associated with methane hydrate ecosystem. Presently, in many countries, national programs exist for the research and production of natural gas from NGH deposits. As a result, hundreds of deposits have been discovered, with a few hundred wells drilled and kilometres of NGH cores studied. Hence, in the future (pending improved gas price and extraction technology), methane gas hydrates could be a vast source of natural gas supply.

Key words: Natural gas hydrates (NGH), geohazards, methane, offshore Sabah, energy resource

INTRODUCTION

Natural gas hydrates (NGH), the "flammable ice" also known as clathrates, are crystalline solids that look like ice and consist of gases with low molecular weight, such as methane, ethane and propane, bound with water molecules within cage-like lattices (Figure 1). Methane gas hydrates are the most common form and were first observed by H. Davy in 1810 (Davy, 1811). The water molecules and low molecular weight gases are stable and do not easily dissociate within a certain range of temperatures and pressures (e.g., Shankar *et al.,* 2004). In addition, a small amount of carbon dioxide (CO_2) and hydrogen sulphide (H_2S) may also exist in the NGHs.

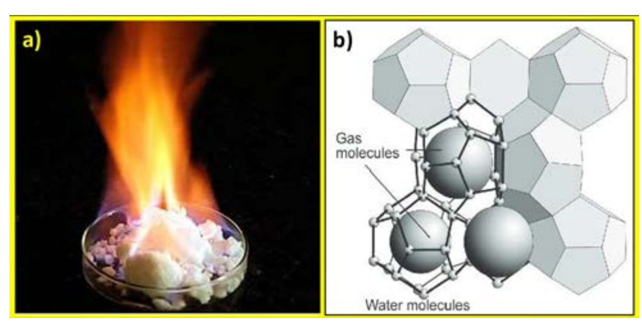

Figure 1: (a) Natural gas hydrates (NGH) – "flammable ice" (from Cox, 2008), (b) NGH lattices consisting of a cage of gas and water molecules (from Bohrmann & Torres, 2006).

In an ideal saturated methane hydrate the methane molecules fill all the cages, where the methane to water molar ratio is roughly 1:6. The interaction between the water molecules and gas molecules is through the Van der Waals forces (e.g., Petrucci *et al.,* 2007); there is no chemical bonding between the gas molecules and water molecules leaving the gas molecules free to move in the crystal lattices (Bohrmann & Torres, 2006). The source of gas can be biogenic or thermogenic. Biogenic gas commonly comes from the fermentative decomposition of organic matter, while the thermogenic gases are derived from the conversion of thermocatalytic organic materials (Behain, 2005; Spalding & Fox, 2014). The majority of the biogenic methane is found close to the Earth's surface, whereas most of thermogenic methane is derived from a deeply buried thermogenic source (Figure 2), at temperatures higher than the NGH stability zone (GHSZ) (e.g., SAARC Energy Centre, 2010).

OCCURRENCE AND FORMATION OF NATURAL GAS HYDRATES

NGH can be found in both terrestrial and marine depositional environments. The terrestrial deposits occur in polar regions and permafrost areas, while the marine deposits can be found within the upper 500 m hundred metres of sub-seafloor sediments on the continental margins and in deepwater areas worldwide (Primer, 2011) (Figure 2). Recent scientific drilling and evaluation programs suggest that NGH occur in abundance, primarily in marine settings, with about 1% of the global NGH distribution occurring in permafrost environments (UNEP, 2014). The primary factors that control or regulate NGH formation in the submarine sediments are temperature, pressure and the availability of water and gas (Shankar *et al.,* 2004), leading to significant differences in the depth of methane hydrate stability zones in permafrost areas compared to those formed in the ocean bottom (Figure 3). Because these factors vary significantly, even at a local scale, NGH occurrences are highly variable (Figure 2).

Along the continental margin, deep marine sediments are predominantly low permeability fine-grained muds and oozes. Because the pore spaces between and within the sediment grains are occupied by the upwelling methane gas migrating into the GHSZ (Lonero, 2008), coarser deposits are likely to have enhanced potential for NGH accumulation capacity and reservoir performance, such as the NGH-bearing sands discovered offshore Korea (Lee *et al.,* 2011; Moridis *et al.,* 2013). Since any higher permeability sand and gravel deposits are more favourable to NGH formation than fine sediments, lithologic indications may be used to highlight likely locations of NGH development (e.g., Garg *et al*., 2008; Boswell *et al.,* 2011) (Figure 4). However, it is noted that the occurrence of NGH itself within the reservoir can also influence the effective porosity and permeability parameters and if the reservoir is produced, effective porosity and permeability will change over time (Ritts, 2017).

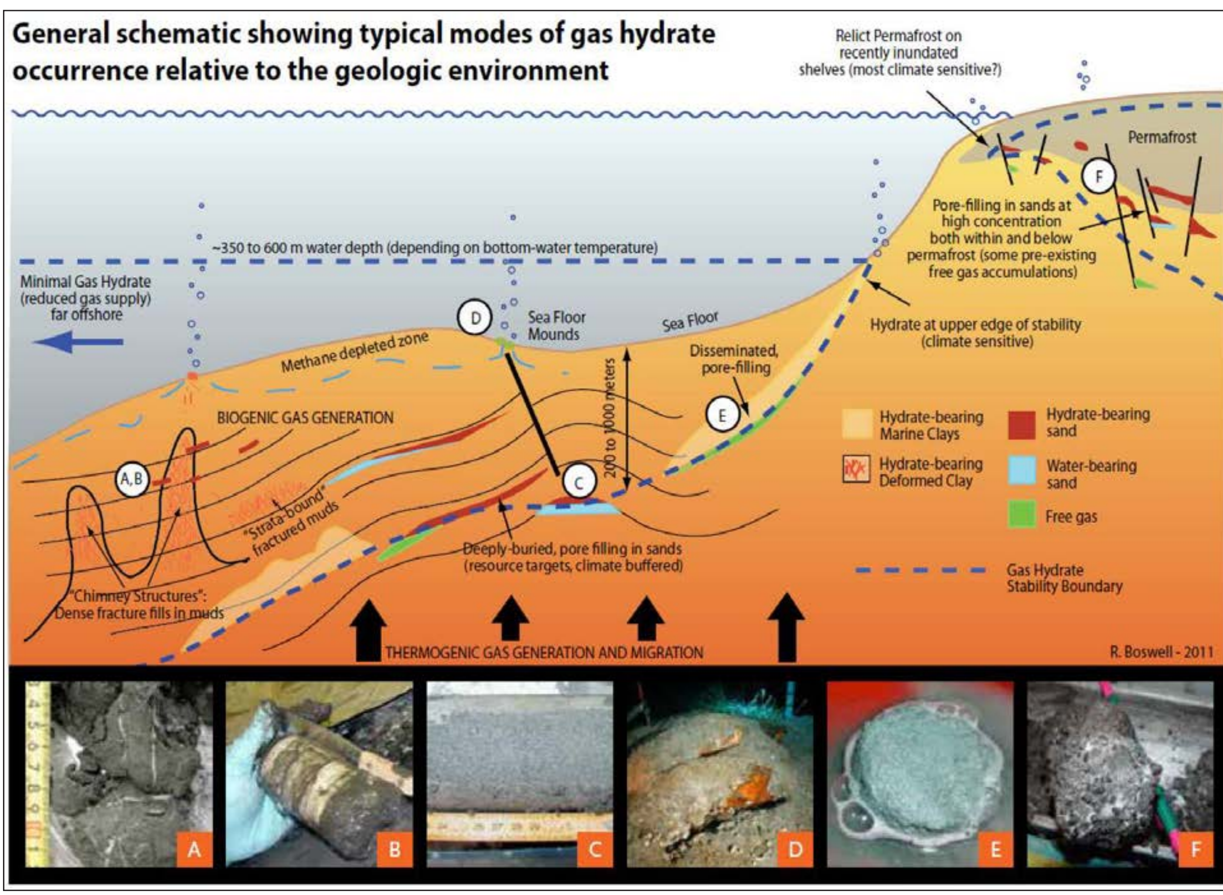

Figure 2: General schematic showing typical modes of NGH occurrence relative to the geologic environment. Thin (A) and thickly veined (B) sediment-displacing NGHs (white) in fine-grained sediment (grey); (C) pore-filling NGHs in sand; (D) NGH mounds on the sea floor (hydrate has an orange coating from oil and is draped with grey sediment); (E) disseminated NGHs (white specks) in fine-grained sediment (grey); (F) NGHs (white) in coarse sands (grey) (from UNEP, 2014 and adapted from Boswell, 2011).

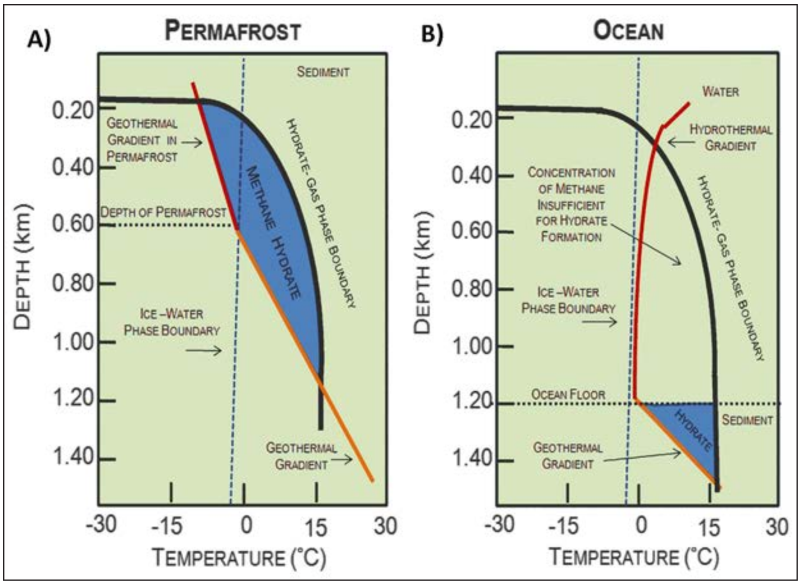

Figure 3: The methane gas hydrate stability zone (A) in permafrost, and (B) in ocean hydrate deposits (from Harrison, 2010).

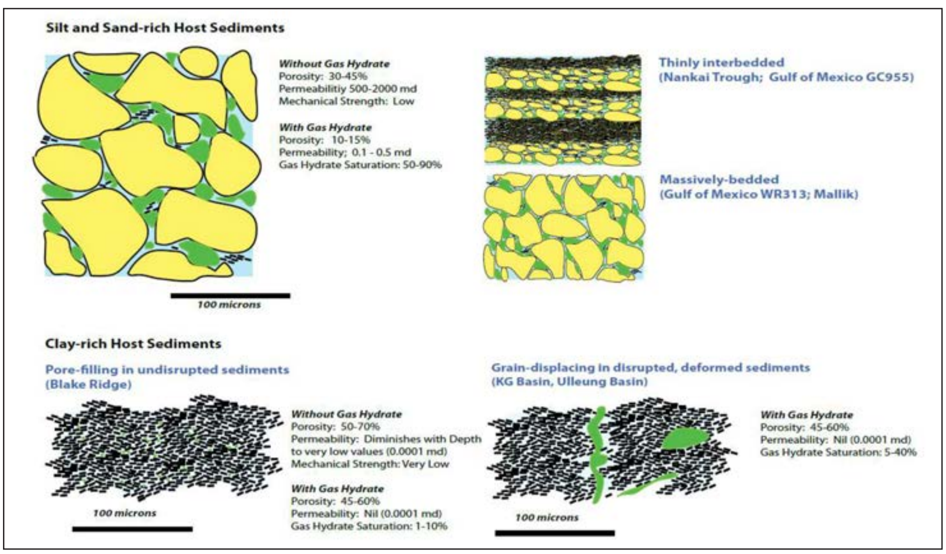

Figure 4: Lithologic influence on NGH accumulations where coarser silt- and sand-rich host sediments are more favourable over clay- and mud-rich host sediments with better reservoir properties (adapted from UNEP, 2014).

Within the GHSZ, three phases of methane are present: as a solid hydrate, dissolved in solution and as a free gas (Lonero, 2008). Due to the existence of these three phases, a triple point is formed at the GHSZ (Lonero, 2008; Worthington, 2010). The stability of the GHSZ can be disturbed when a small amount of salt (NaCl) is added into water, resulting in a phase boundary shift to the left, where temperature is decreased (Figure 5). On the other hand, when carbon dioxide (CO_2), hydrogen sulphide (H_2S), ethane (C_2H_4) or propane (C_3H_8) are added to methane, the phase boundary shifts to the right thus increasing the P/T stability field in which methane hydrate is stable (Kvenvolden, 1998, 1999; Lonero, 2008; Worthington, 2010) (Figure 5).

Phase boundary data indicates that in continental polar regions the water depth temperature is close to 0°C, while in the tropical regions, the temperature is approximately 3°C in water depths over 1000 m (Kvenvolden, 1998). With these observations, geothermal gradient of various geologic environments (see Figure 2), can be calculated from the depth at the lower limit of the GHSZ. Different and localized geothermal gradients alter thickness of GHSZ and the occurrence of NGH formation is also limited to the shallow geosphere where the amount of methane required for gas hydrate formation exceeds its solubility in water (Kvenvolden & Lorenson, 2001).

STUDY OBJECTIVES

With an active and proven petroleum system in offshore NW Sabah, NGH can be a common occurrence and regularly encountered during deepwater drilling operations. They represent both a potential source of drilling geohazards and conversely a potential unconventional resource. Hence, the objectives of this case study, based on an NGH accumulation in Block X are:

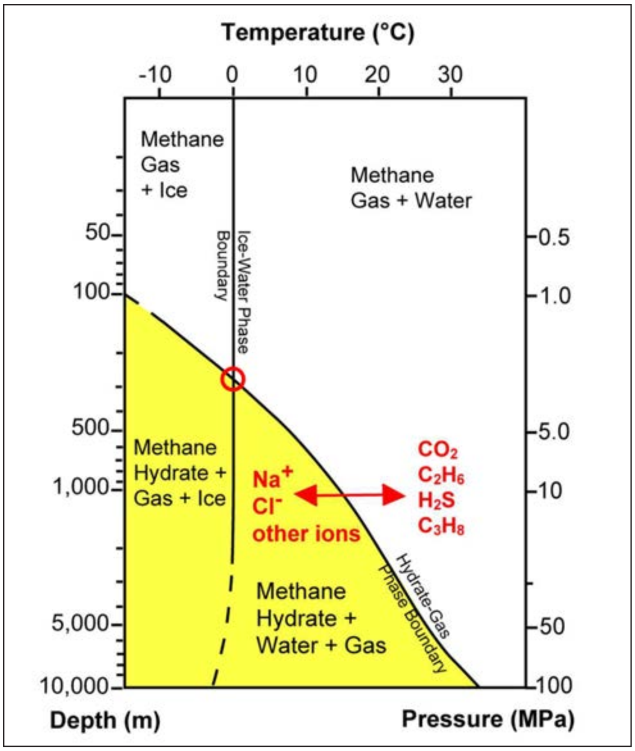

Figure 5: Three Phase diagram showing the boundary between methane hydrate (in yellow) and free methane gas (white) for a pure methane/water system. Addition of ions shifts the boundary to the left, decreasing the P/T stability field. The presence of gases like carbon dioxide, hydrogen sulphide or other high-molecular hydrocarbons shifts the curve to the right, thus increasing the P/T field in which methane hydrate is stable (from Bohrmann & Torres, 2006 and adapted from Kvenvolden, 1998). With the existence of the three phases, a triple point, as indicated by the red circle is formed in the GHSZ (see also Worthington, 2010).

a) To identify the presence of NGHs and to mitigate them as a drilling geohazard in an exploration block located in offshore deepwater Sabah area,
b) To investigate NGH as a potential future unconventional energy resource with the associated risk of extraction, and
c) To estimate the potential resource volume of an NGH deposit in the investigated exploration area.

GEOLOGICAL SETTING AND STRATIGRAPHY

The offshore NW Sabah Basin is a foreland basin associated with an active fold and thrust belt (Figure 6), where, from the latest Miocene to Holocene epochs, a consistent palaeo-shelf edge position has been established with a restricted narrow shelf area due to constant hinterland uplift and very rapid subsidence rates of the basinal area (Ingram *et al.,* 2004; Behain, 2005; Grant, 2005; Lambiase & Cullen, 2013; Jong *et al.,* 2014, 2016; Kessler & Jong, 2015; Khamis *et al.,* 2018a, b).

The East Baram Delta province where the study area of "Block X" is located (Siti Aishah Abdullah *et al.,* 2018), is a margin originating in the Eocene when the proto-South China Sea oceanic crust started subducting below the NW Borneo continental margin (Figure 7). The basin consists of a thick, clastic sedimentary succession deposited as a consequence of Miocene to Holocene uplift and rapid erosion of the Sabah land massif, which resulted in the NW progradation of regressive clastic deltas (Jong *et al.,* 2014; Khamis *et al.,* 2018a, b). The sediment input greatly exceeded accommodation space along the narrow shelf, triggering shelf-margin instability and resulting in episodic, massive slope failures with slumps and prolific turbidite deposition from the Middle

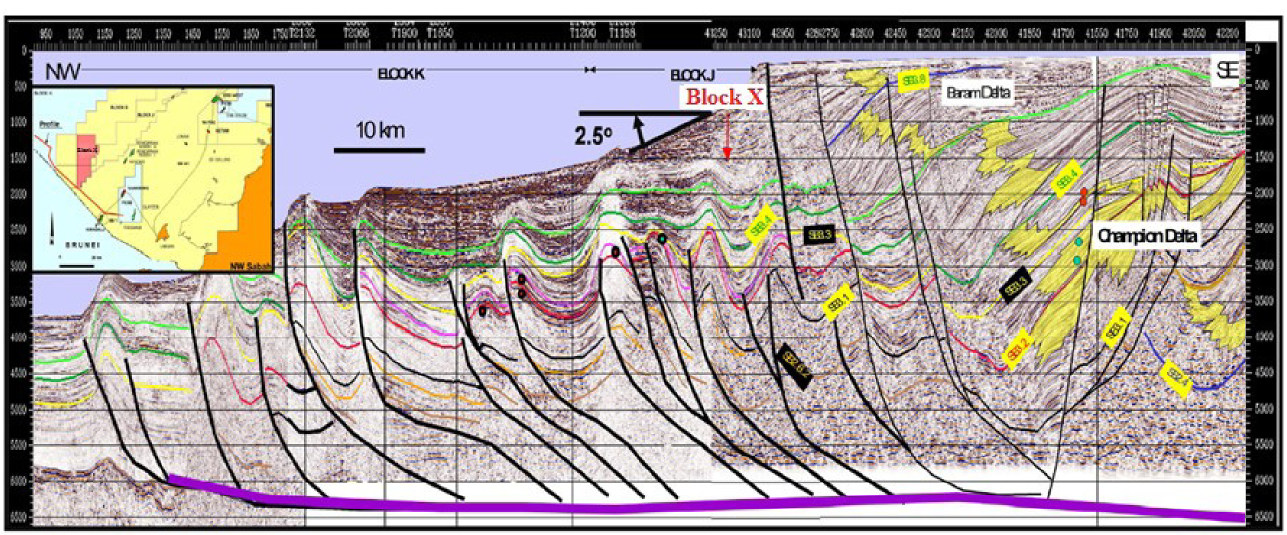

Figure 6: NW Sabah fold and thrust belt, the index map shows the line location with study area of "Block X" as indicated. As a result of uplift and erosion during Miocene to Holocene epochs, a NW prograding and regressive clastic delta is formed (from JX Nippon, 2014 and modified from Grant, 2005).

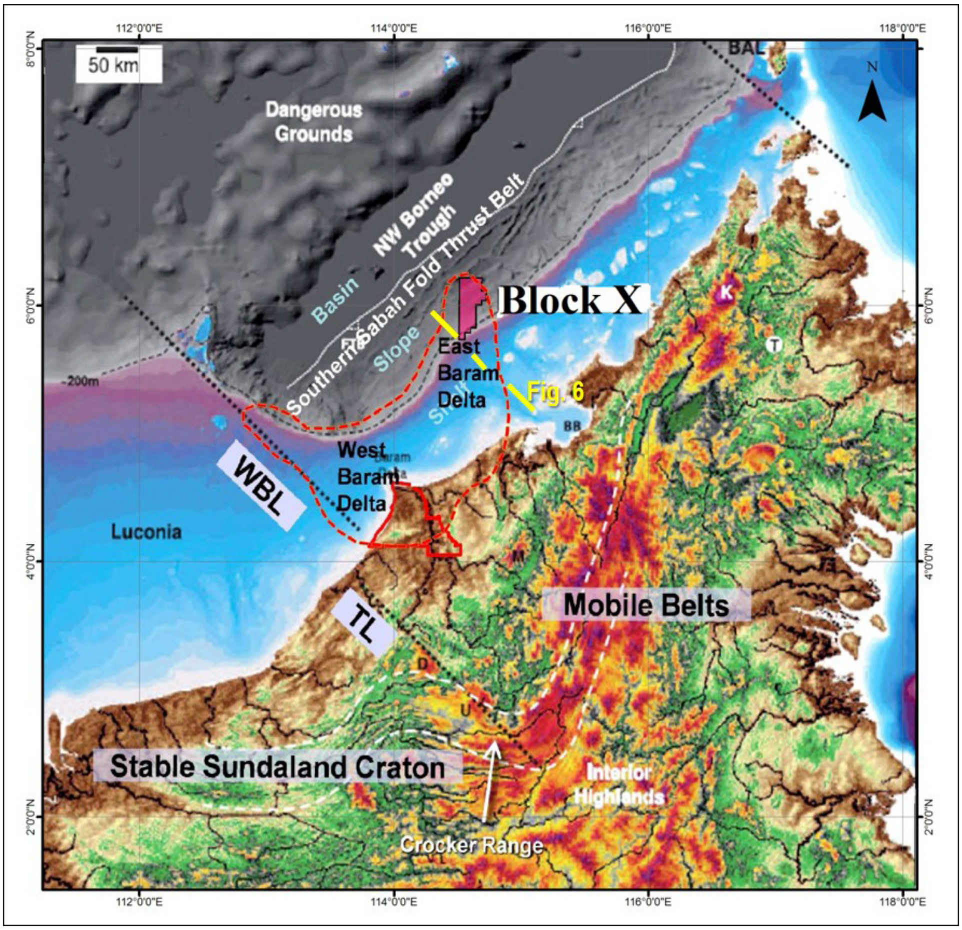

Figure 7: NW Borneo regional map, where the NW Borneo margin is transected by the West Baram Line (WBL) and Tinjar Line (TL). The study area of "Block X" is shown located in the East Baram Delta basin (from Jong *et al*., 2014 and modified from Cullen, 2010).

Miocene to Pliocene times. Sediment loading on the slope also caused activation of mobile shale at depth forming a belt of "toe-thrust" anticlines further outboard, creating the major hydrocarbon traps in the study area (Figure 6). The chronostratigraphic scheme of the study area is shown in Figure 8.

NATURAL GAS HYDRATE IDENTIFICATION

Seismic reflection profiles and wireline well logs in conjunction with core data (Figure 2), are commonly used as indicators to identify the presence of NGH (e.g., Paganoni *et al.,* 2016, 2018). The two key NGH identification parameters are briefly discussed below:

Seismic reflection profiles

On the seismic profiles, NGHs are typically associated with a Bottom Simulating Reflector (BSR) as shown in Figure 9. BSR represents the base of the GHSZ, a high amplitude zone comprising strong seismic wave reflectors, roughly parallel to the seafloor reflection. The BSR is a reflection interface between the high velocity NGH-bearing sediments and the underlying low velocity gas-bearing sediments (e.g., SAARC Energy Centre, 2010). BSR forms in water depths of more than 400 m, where phase boundaries governed by temperature, pressure, composition of gas and salinity of pore water may dissect other reflectors (Hyndman & Davis, 1992; Kvenvolden, 1993; Behain, 2005). BSR depth can be used to estimate geothermal gradient and heat flux in the NGH-bearing sediments (Bohrmann & Torres, 2006; McGiveron & Jong, 2018a). As such, the existence of BSR in seismic reflection data can be used to investigate the presence of marine or oceanic NGH deposits.

The signal intensity at the BSR is high and is produced by P-wave velocity inversion with increasing acoustic velocity (Behain, 2005). Reverse polarity is indicated in the seismic reflection from the base of the NGH causing a negative reflection coefficient. The seafloor topography is mimicked by the seismic reflection with increasing sediment and water depths (Shipley *et al.,* 1979; Kvenvolden & Lorenson, 2001). In the seismic profile, low reflection amplitudes in the zone above the BSR cause acoustic impedance to decrease (Behain, 2005). This is due to NGHs accumulating in highly-porous strata, causing a reduction of seismic velocity (Dillon & Max, 2000). The area of low reflection amplitudes is known as the "blanking" zone (Behain, 2005; Lin *et al.,* 2009) (Figure 10). Based on the

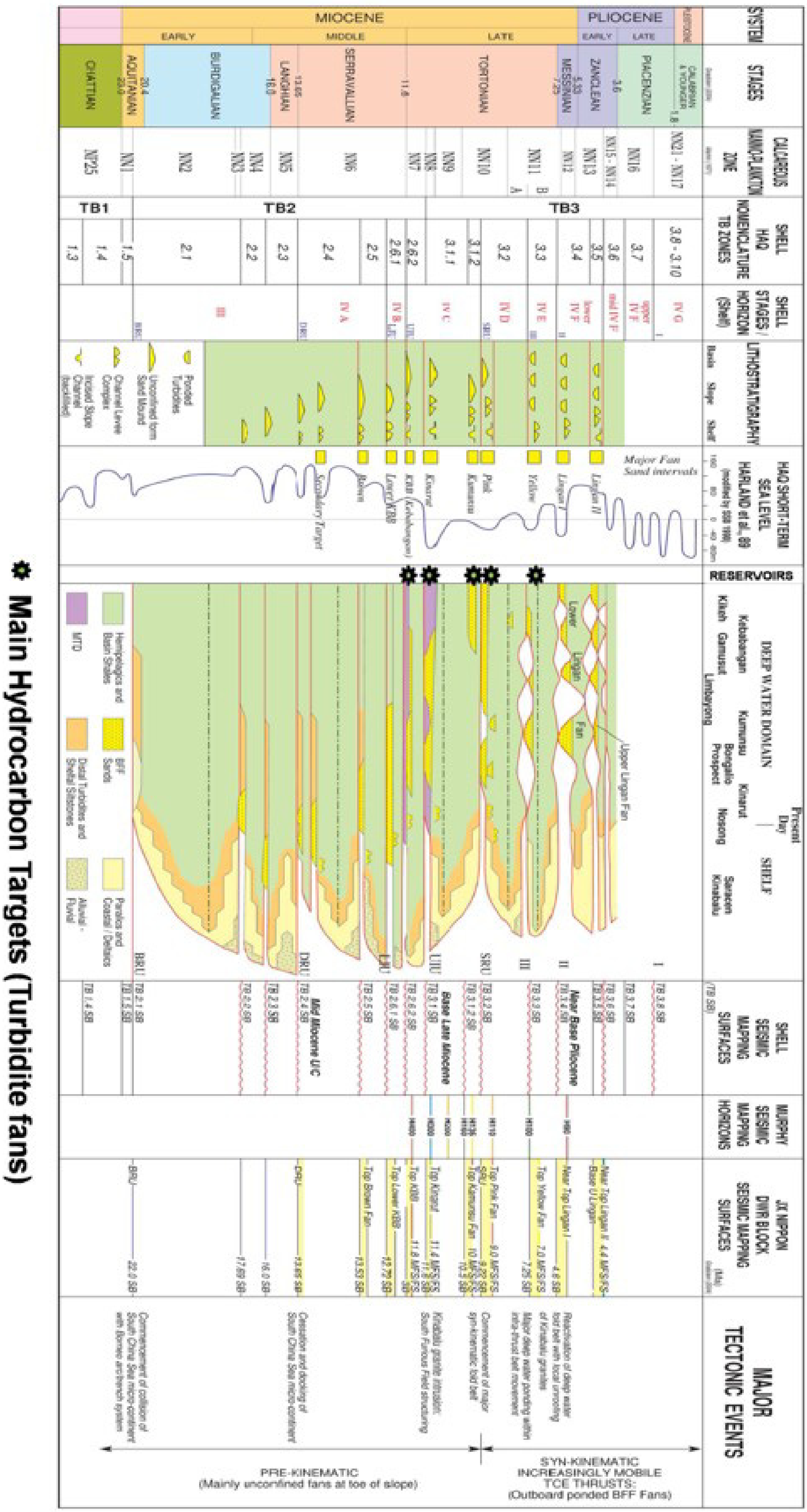

Figure 8: Sabah "Block X" chronostratigraphic scheme (from Jong *et al.*, 2014).

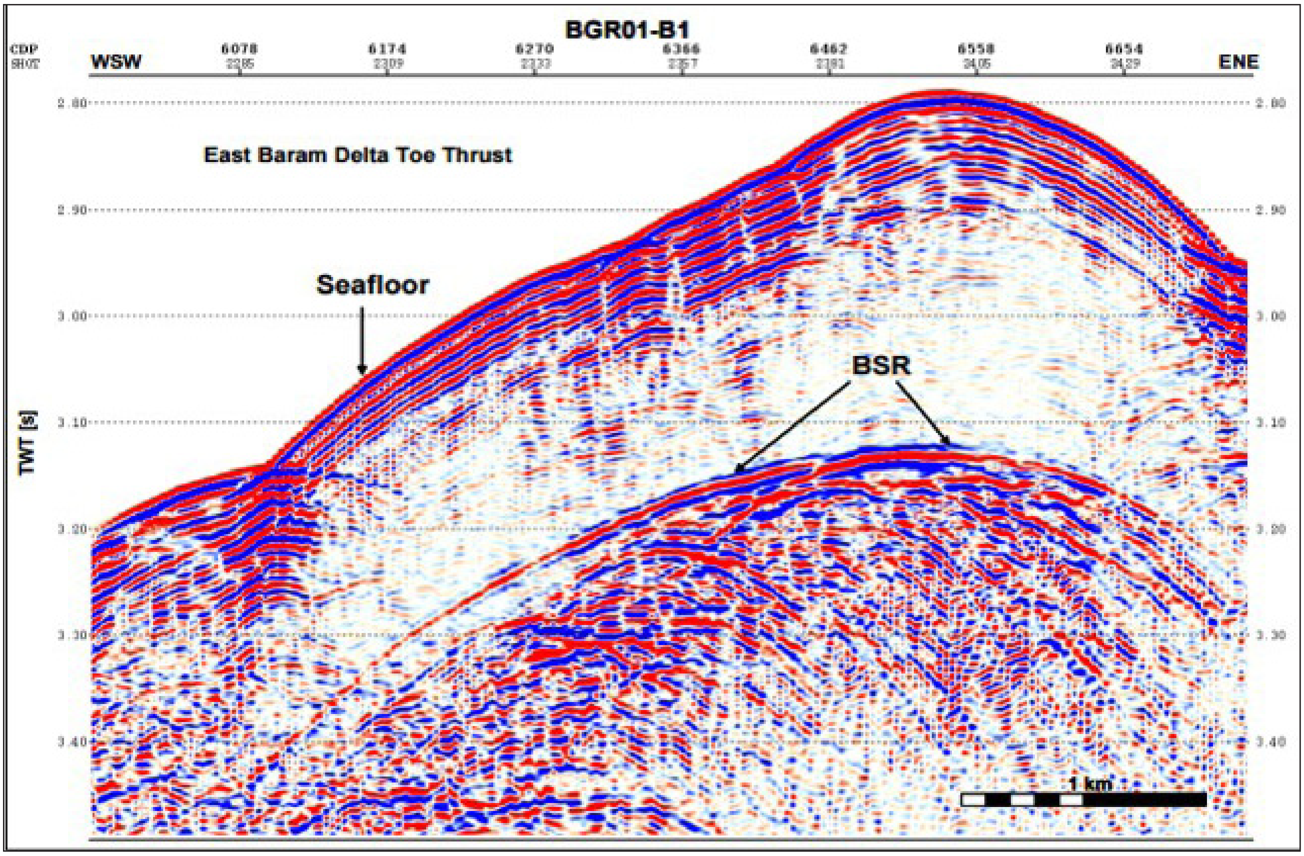

Figure 9: Detection of BSR in the seismic profile example from NW Sabah (from Behain, 2005).

studies by Dillon & Max (2000), Behain (2005) and Lin *et al.* (2009), the extent of the blanking zone can be used to estimate the quantity of NGH in the sediments.

In general, geophysical methods hold great promise for the remote detection and quantification of NGH deposits because of the strong changes in the physical properties that are induced by the presence of NGHs (UNEP, 2014). However, some authors have cautioned that NGH concentration cannot be inferred from the intensity of a BSR alone, nor can the lack of a BSR be interpreted as indicating that NGHs is not present. Further progress in developing exploration technique for NGHs had to incorporate the existence of a working petroleum system having a sufficient gas flux (as indicated by gas chimneys), and a suitable GHSZ with porous and permeable strata that would allow focused flow of gas and gas-enriched mineralizing solutions into the GHSZ (e.g., Max & Johnson, 2017).

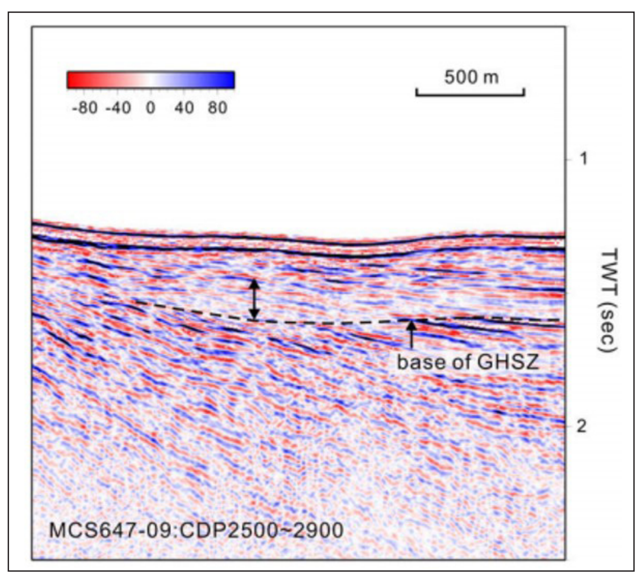

Figure 10: The blanking zone, as indicated by the double headed arrow can be used to estimate the quantity of NGH deposit in the sediments (from Lin *et al*., 2009).

Wireline well logs and core data

In conjunction with BSR, NGHs can also be detected by wireline logs such as spontaneous potential and resistivity logs (Goodman, 1980; Bigelow, 1992; Kvenvolden & Lorenson, 2001; Goh *et al.,* 2017). When NGHs are present, the electrical resistivity log records higher values, while spontaneous potential readings are lower. Neutron porosity readings for NGH-bearing sediments will increase, while density and acoustic transit time will decrease (Collets & Ladd, 2000). According to Pearson *et al.* (1983), sonic velocity and resistivity logs are strongly influenced by the presence of NGHs. High sonic velocity gives a qualitative indication of the presence of NGHs, while resistivity can provide a semi-quantitative measurement of the amount of hydrate present by measuring the resistive intervals. Therefore, resistivity and sonic velocity log readings are important parameters that can be used to assess NGH deposits. It is noted that one dataset that is currently best acquired through wireline logging that has effective application to NGH studies is the nuclear-magnetic resonance (NMR) tool (Kleinberg *et al.*, 2005). At present, NMR provides the best available information on both sediment permeability and the distribution of various pore-filling constituents, including mobile liquid water.

With reference to Figure 11, the entire logged section is comprised of sand/silt (HGSZ section), while the interval below GHSZ is dominated by shale. The resistivity and velocity spikes correlate to the sandy intervals for the methane hydrate-filled sand, with resistivity readings higher than 100 ohm.m, as well as high sonic velocity, while density is generally lower in the GHSZ. Similarly, in the massive methane hydrate-filled sandy interval, the sonic velocity and resistivity is high and the density is low. In the example shown in Figure 12 from an NGH exploration well drilled in the northern Gulf of Mexico, the wireline log data obtained show two sand-rich reservoirs enclosed in an overall clay-rich system that are fully saturated with NGH, which recorded high resistivity and sonic readings in the NGH-filled zones.

Traditionally, the scientific expeditions designed to investigate the occurrence of NGHs come with specialized drilling vessels and dedicated field programs such as coring and logging-while-drilling (LWD) campaign that can test many locations. NGH and free gas concentrations, as well as the reservoir facies and parameters can be identified through core analysis (Figure 2), and by downhole logging (Behain, 2005) (Figure 11). Furthermore, downhole logging and core derived porosities can also be applied to compute the total water content of the sediments (Collets & Ladd, 2000). However, it is noted that in conventional oil and gas exploration drilling as in the case for Block X, the upper wellbore section where NGHs could be potentially penetrated is usually not logged, nor cored.

In dedicated scientific expeditions, standard coring is conducted that recovers sediment from NGH-bearing intervals, although the reduction in pressure and increase in temperature as the core sample is retrieved often result in the dissociation of all but the most massive hydrates. Nonetheless, the dissociation of NGHs and release of nearly pure water into the original saline pore fluids results in a unique chemical signal called freshening, which can be exploited to infer the presence and concentration of NGHs (Kastner *et al.*, 1995; Hesse, 2003). The dissociation of NGHs due to the endothermic nature of the reaction also results in a cooling of the surrounding sediments. This phenomenon was first used systematically to infer NGH

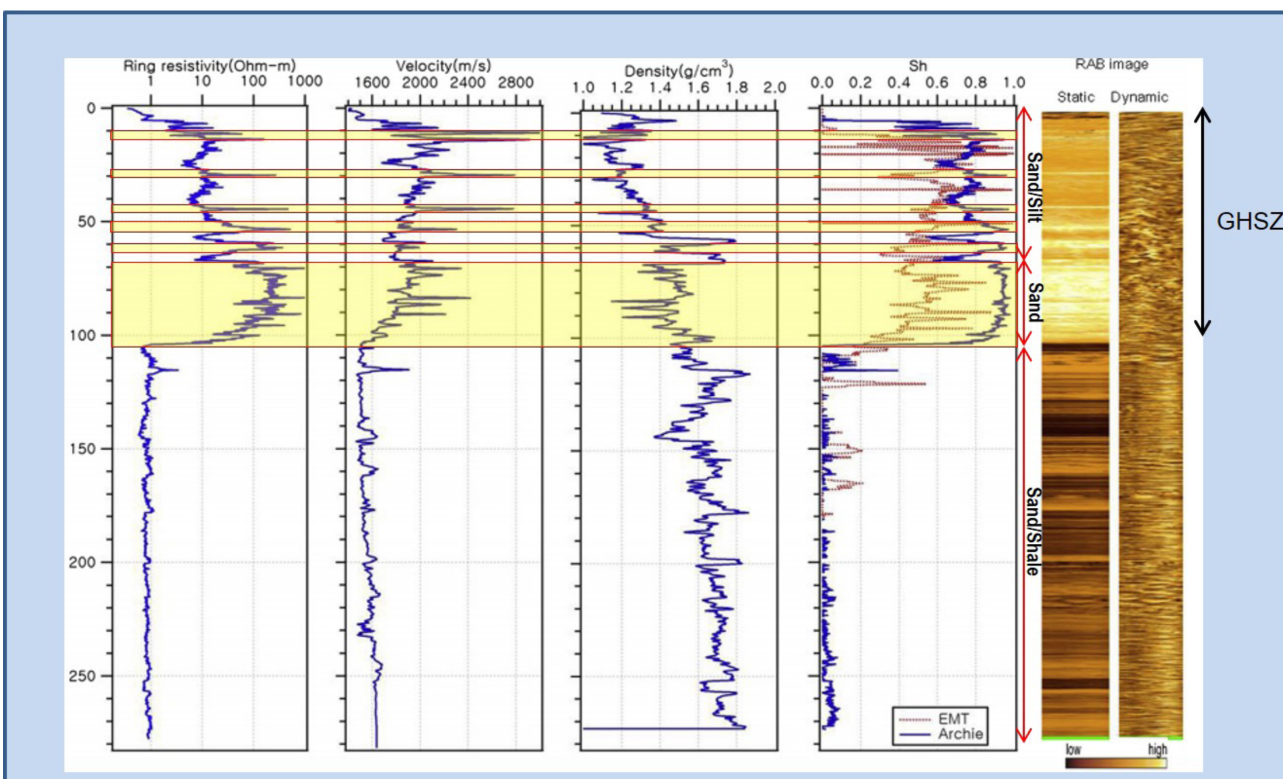

Figure 11: Higher resistivity, P-wave velocity and gas saturation readings are noted throughout the GHSZ, while the density readings remain lower (adapted from Ryu *et al.*, 2013).

presence in sediment cores during ODP Leg 164 at the Blake Ridge (Paull *et al.,* 1996), and has since served as the basis for the development of a technology involving the automated infrared imaging of the recovered core immediately after it arrives on deck (Long *et al.,* 2010). The development of pressure coring, a technique that recovered sediment in devices that maintain pressures near *in situ* conditions, has greatly increased the ability to characterize and image NGH-bearing formations. Pressure coring is thus ideally suited to the problem of NGH sampling, providing means to determine NGH concentrations and showing remarkable detail of the morphology of NGH occurrences (Holland *et al.,* 2008).

NATURAL GAS HYDRATES – THE CAUSE AND MITIGATION OF DRILLING GEOHAZARDS

As hydrocarbon exploration and production activities move from shallow shelf to deepwater environments, the chance of penetrating NGH accumulations is increased (Goh *et al.,* 2017). The drilling of NGH may expose geohazards such as slope instability, activation of shallow faulting, and the expulsion of seafloor/shallow gas or water flows (Maslin *et al.,* 2010; Liu *et al.,* 2019). The presence of NGH may affect wellbore stability and lead to casing collapse as a result of gas dissociation. Many of these geohazards can be forecast based upon their individual seismic characteristics within a recognizable depositional system (Shipp, 2006).

There are two key concerns associated with NGH dissociation that could result in wellbore instability:

a) If the equilibrium temperature and pressure condition is disturbed, it could trigger the dissociation of NGH into gas and water. The affected drilling fluid would become gasified, resulting in gas-cut mud. NGHs adjacent to the wellbore would continue to dissociate and gasify the drilling fluid until the temperature and pressure reach a new equilibrium. This could lead to a decrease in the drilling fluid density and changes to drilling fluid rheology (Tan *et al.,* 2005; Amodu, 2010).

b) If dissociation of NGH occurs, the physical and mechanical properties of the NGH-bearing sediment

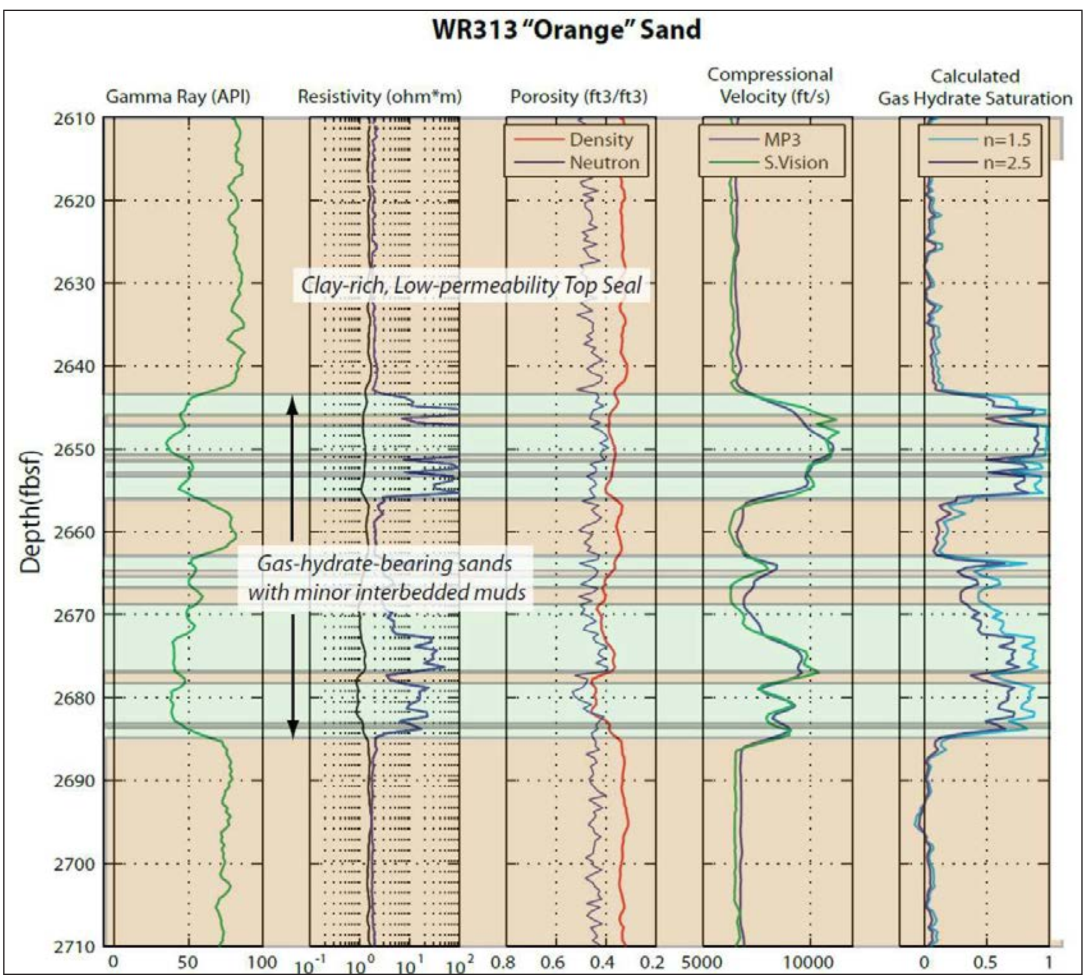

Figure 12: Well data from a NGH exploration well drilled in the northern Gulf of Mexico in 2009. These data obtained from the Walker Ridge 313 "H" well show two sand-rich reservoirs enclosed in clay-rich sediments that are fully saturated with NGH (right panel). (from UNEP, 2014 and adapted from Boswell, 2011).

would alter, causing in a reduction in rock strength (Young's modulus), increased permeability, and wellbore instability (Tan *et al.,* 2005; Amodu, 2010).

Casing collapse is a major hazard associated with drilling NGHs. When the temperature increases and pressure decreases, NGH dissociation will occur. Injection of drilling chemicals into the NGH-bearing sediments may influence their stability (Neshat, 2016). In the scenario illustrated in Figure 13, dissociation has caused the hydrate pressure to exceed the differential collapse pressure of the casing. Gas dissociated from the hydrates may diminish cement integrity, potentially resulting in upward migration of free gas to the seafloor, which could result in the weakening of the drilling rig sub-structure (Neshat, 2016).

There are a number of approaches to mitigate NGHs as a drilling geohazard, which are briefly summarised below:

a) Operators may mitigate risk by avoiding potential pockets of shallow gas trapped below NGH deposits (Nimblett *et al.,* 2005). Shallow hazard desktop analysis of seismic profiles, as performed for Block X deepwater drilling operations, should be conducted during the pre-drill operation phase, and the well path positioned to minimise the identified geohazards (Hadley *et al*., 2008). The risk of encountering NGHs can be assessed by evaluating the high resolution shallow seismic data to identify the occurrence of BSR and the potential thickness of NGH accumulations. The risk of encountering NGHs also can be evaluated by conducting amplitude analysis to identify the potential risk of shallow gas accumulations. Evidence of rapid variation in NGH thicknesses may be used to identify migrating fluid plumes and anomalies in the geothermal gradient.

b) As drilling progresses, the well is periodically lined with steel casing. This helps to segregate and maintain the well from the NGHs that are located in the shallow sedimentary zones when drilling took place, as well as to minimize the risk of well damage (Folger, 2008).

c) The risk of NGHs as a drilling geohazard also can be mitigated by monitoring the temperature above and pressure below NGH zone in order to prevent the dissociation of NGHs. To minimize the risk, cool drilling fluid mixed with chemical inhibitors may be used in order to mitigate NGH dissociation and to diminish the hydrate destabilization in the NGH formation (Ghajari *et al.,* 2013).

Fortunately, during the deepwater drilling operations conducted for Block X, no significant concern associated with NGH as a drilling geohazard was experienced when the NGH zones were penetrated.

NATURAL GAS HYDRATE EXTRACTION

Although NGHs can contribute to drilling geohazards, they are also a potential energy resource. According to Kvenvolden (1998), one cubic metre of dissociated NGH is equivalent to 164 m^3 of gas released, representing a significant potential energy resource; based on the study by the US Geological Survey (2001), the carbon volume in methane hydrates is twice the amount of Earth's recoverable and non-recoverable fossil fuel.

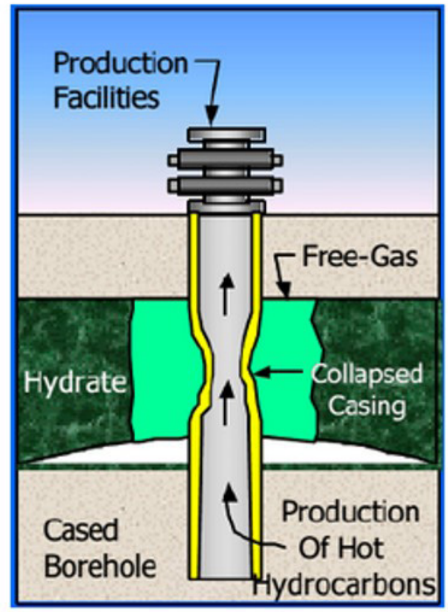

Figure 13: Casing collapse due to NGH dissociation and hydrate pressure exceeding the differential collapse pressure (from Neshat, 2016).

A few countries have conducted NGH pilot production, such as Japan and China, which extract marine NGHs by depressurization (Chen & Zhu, 2017; Wan *et al.,* 2018). In March 2013, the world's first field trial of gas production from marine methane hydrate deposits was conducted in the Eastern Nankai Trough, off the Pacific coast of Japan as a process to bring NGHs under the seafloor to valuable energy resource (Yamamato *et al.,* 2013, Yamamato, 2015), where useful formation temperatures and fluid data were obtained to verify applicability of the depressurization technique as a methane hydrate production technology. More recently, extended production test performed from a floating platform in Shenhu area of the South China Sea provides positive encouragement to overcome technical obstacles for a future sustainable commercial production, with a maximum daily gas output of 35,000m^3 was recorded during the operations (Wan *et al.,* 2018).

NGH extraction is not the scope of this study. Nonetheless, the three common extraction methods are summarised below for general reference:

Depressurization

Depressurization is one of the methods to extract methane from NGHs. Pressure is decreased below hydrate equilibrium to induce NGH dissociation (Demirbas, 2010; Arora & Cameotra, 2015; Jani, 2017). Potentially, geothermal energy could be used to drive this process (Kvenvolden, 1998). Reduction in the formation pressure would cause methane hydrate to become unstable and decompose into free gas and water. Subsequently, the free gas would migrate into the well bore (Figure 14).

Injection of inhibitor

The presence of the chemical inhibitor causes the temperature and pressure equilibrium to shift away from the NGH stability zone resulting in NGH dissociation and consequent release of methane gas (Figure 14). Inhibitor injection involves injecting a chemical such as methanol into the NGH-bearing sediments to promote dissociation. Other than methanol, salt can also be used to promote NGH dissociation (Demirbas, 2010; Arora & Cameotra, 2015; Jani, 2017).

Thermal stimulation

Thermal stimulation is a technique that increases the temperature in order to accomplish NGH dissociation (Demirbas, 2010; Arora *et al.,* 2015; Jani, 2017). Heat is applied to the NGH-bearing sediment by injection of steam or hot water, or indirectly through electric or sonic means. This triggers methane hydrate to dissociate and release methane gas (Figure 14). Steam or hot water injections are technically challenging, albeit it may be possible to source geothermal energy from a deeper wellbore requiring more gas and water separation at the surface (Distanislao, 2015).

According to Demirbas (2010), the cost of thermal stimulation and inhibitor injection would be more expensive than the depressurization method, which is likely the most effective in producing methane from NGHs. As such, this method is recommended for NGH extraction in polar regions from below permafrost (Arora & Cameotra, 2015). However, no commercial-scale technologies to exploit NGHs have been demonstrated so far with many complex problems for efficient and sustainable production currently under research.

In addition, to determine the gas producibility from NGHs, some of the geological and geophysical factors need to be considered. These include, among others, seal availability, porosity and permeability of the reservoir, NGH concentration, temperature, pressure, pore water salinity, gas composition, free fluid phase thickness, thickness of the NGH reservoir interval volume, sediment lithology and fluid types in contact with NGH (Grace *et al.,* 2008). Moreover, with abundant availability of natural gas from conventional and shale resources, there is currently little economic incentive to develop NGH resources.

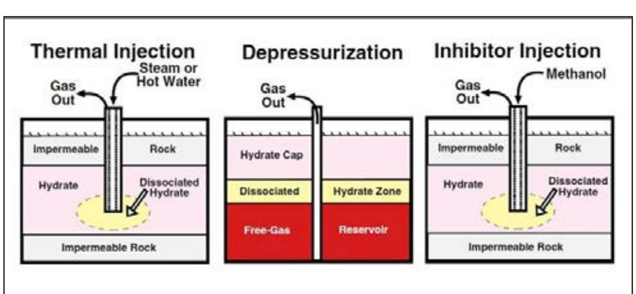

Figure 14: Extraction of methane from the methane hydrate deposits by using thermal stimulation, depressurization and inhibitor injection methods (from Jani, 2017).

RISKS ASSOCIATED WITH NATURAL GAS HYDRATE EXTRACTION

A key issue for the extraction of NGH is its potential contribution to global warming (e.g., Liu *et al.,* 2019). Methane is a greenhouse gas and is 20 times more damaging than carbon dioxide, taking up to 10 years to oxidize (Ruppel, 2007). This is because methane will react with other compounds in the air to produce carbon dioxide and gas (Ruppel & Noserale, 2012). The estimation of methane hydrates outgassing is about one or two percent of present-day atmospheric methane (Ruppel, 2007). Global warming contributes to higher average ocean and air temperature and plays a key role in raising sea level by melting of the polar ice caps (Ruppel & Kessler, 2016). Rising sea level would cause a slight increase in hydrostatic pressure in the sediments (Distanislao, 2015). Higher pressure tends to stabilize the methane hydrates; however, this would be more than offset by the increased temperature that destabilizes the methane hydrates. This can result in the release of methane to the seafloor (Kvenvolden, 1998), causing shallow water flows (e.g., McGiveron & Jong, 2018b).

Submarine slope failure is an additional risk associated with extraction of NGHs (Maslin *et al.,* 2010). With constant sedimentation, water depth would decrease, causing an increase in seabed temperature which could promote NGH dissociation (Figure 15). Nevertheless, the *in situ* temperature and pressure regime, changed by the sedimentation process

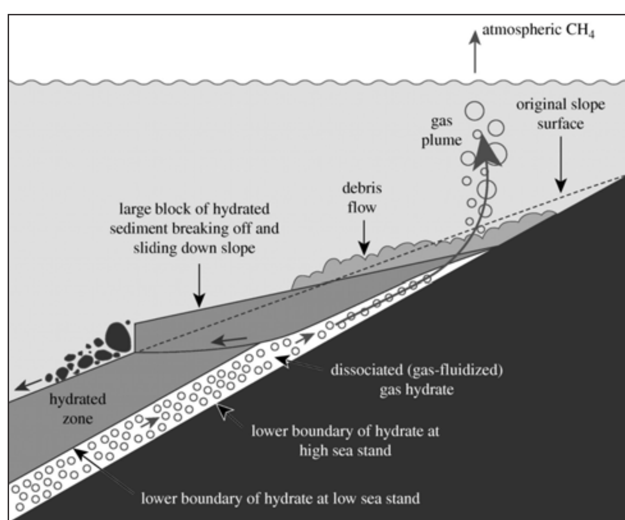

Figure 15: Submarine slope failure caused by NGH dissociation (from Maslin *et al*., 2010 and adapted from Kvenvolden, 1998).

can also induce NGH dissociation (Kvenvolden, 1998). From when the temperature and pressure are initially disturbed, until a new temperature and pressure equilibrium is reached, the NGHs will dissociate (Dillon *et al.,* 1998; SAARC Energy Centre, 2010), reducing seafloor shear strength and inducing submarine slope failures (Maslin *et al.,* 2010).

Solid methane hydrates contribute to geotechnical stability. However, if the solid methane hydrates undergo dissociation, liquid hydrates are formed. Due to the NGH dissociation, the area around the formation can become destabilised and large amount of methane is released to the seafloor. The shift in the seafloor could damage the wellbore and result in additional cost for drillers and operators (Garratt, 2012).

Last but not least, another risk associated with extraction of NGHs is the physio-biological impact on the microbial communities associated with methane hydrate ecosystem. Large microbial communities thrive in the areas surrounding NGH deposits and are influenced by changes in the rate of gas release. During NGH exploitation, as methane gas is released to the seafloor the increase in methane concentration could result in the decrease of microbial communities. Conversely, a depletion of NGH resources can also adversely impact the ecosystem of microbial communities (Tinivella, 2016).

RESOURCE ESTIMATION OF A NATURAL GAS HYDRATE DEPOSIT IN DEEPWATER SABAH

The areal distribution of NGHs within the “B” development area located in “Block X”, previously operated by JX Nippon in deepwater Sabah was undertaken as a case study for resource estimation (Figure 16). The combination of seismic and limited available well log data were used to estimate the shallow NGH volume in the study area. A pre-drill desktop shallow geohazard study was used to evaluate the presence of NGHs at the “B-1” and “B-2” well locations. The B-2 well encountered 33.7m of NGH (from 1226.3 m to 1260.0 m MD) whereas the B-1 well (drilled in a “low probability” area) encountered none.

The estimation of the potential resource volume was conducted, which required well derived input parameters in the detailed volumetric calculations. These essential input parameters for resource estimation are:

a) GRV = Gross rock volume in MMm^3
b) N/G = Net to gross ratio
c) ρ = Porosity
d) S_h = NGH saturation in pore volume
e) VR = Volume ratio
f) Co = Cage occupancy

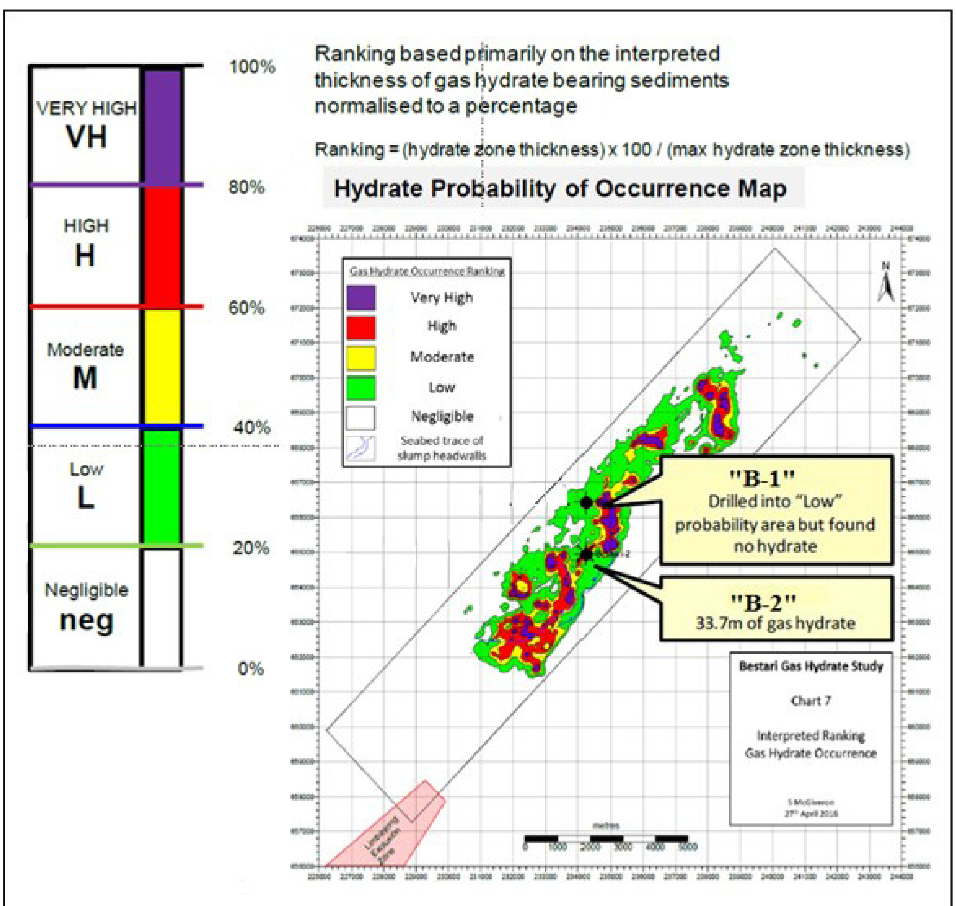

Figure 16: Occurrence areas of NGH in the “B” development area located in “Block X”, with “B-1” the initial exploration well and “B-2” the follow-up appraisal well (from JX Nippon, 2016).

Based on this volumetric assessment method, the potential resource volume of the investigated NGH deposit is calculated from the equation below:

Gas Hydrate GIIP (gas in place, BCF) =
GRV × N/G ×ρ × S_h ×VR × CO/28.3

a) Gross rock volume (GRV)

Based on the NGH map, the GRV is estimated. From the 3D full stack seismic volume, a thickness map was produced. The thickness map is generated based on ranking system as shown in Figure 16. As investigated by JX Nippon (2016), the result of gross rock volume shows that there is an absence of NGHs in the "B-1" well, as there is a low probabilty of NGH occurence. As such, on the probability occurrence map, the area that is most probable manipulated for the estimation of hydrate GIIP is the area with high NGH occurrence. As mentioned earlier, the "B-2" well shows there is presence of NGHs of about 33.7 m (Figure 16).

b) Net to gross ratio (N/G)

The volume of shale (V_{sh}) obtained from the gamma ray log was used to estimate the thickness of net reservoir. However, the high viscosity mud used caused a lower gamma ray reading making it difficult to predict the net reservoir thickness from gamma ray alone. To estimate the volume of shale a combination of the gamma ray log, the neutron porosity log and the bulk density log can be used to estimate the shale volume t, however these logs were not acquired in the NGH concentrated zone. Instead, the resistivity log was used to estimate shale volume.

$$Z = R_{shale} / R_t \text{ x } (R_{clean}\text{-}R_t) / (R_{clean}\text{-}R_{shale})$$

When the R_t is more than 2 × R_{shale}, the V_{sh} can be calculated using this equation:

$$V_{sh} = 0.5 \text{ x } (2\text{x}Z)^{0.67\text{x}(Z=1)}$$

where:
R_{shale}: shale resistivity
R_{clean}: clean reservoir resistivity
R_t : true resistivity

Based on the N/G ratio calculation, the calculated ratio is 0.97, while the net thickness of estimated reservoir is 32.6 m. To capture the uncertainty of N/G ratio, a range from 0.5-1.0 was used for estimation of resource to account for lateral changes in lithology.

c) Porosity

In "B-2", the porosity is hard to calculate from the well data due to the deficiency of porosity logs and samples of rock in the shallow section. Based on the regional well data, the mean porosity in offshore NW Sabah sediments within the NGH stability zone is around 55%. For resource assessment, the porosity ranges commonly applied is 45-55-65% in order to capture the uncertainty of porosity (Behain, 2005).

d) Gas hydrate saturation

According to Collett & Ladd (2000), there are two forms of Archie relation that were used to estimate the saturation of water from the resistivity log. The equation of NGH saturation is:

$$S_h = 1\text{-}S_w$$

Where:
S_h: NGH saturation
S_w: water saturation

Two different porosity datasets were used to estimate two comparable water saturations by using standard Archie equation:

$$S_w = (aR_w / Ø^m R_t)^{1/n}$$

Where:
S_w: water saturation
R_t: true resistivity
n: empirically derived constant
Ø: porosity
R_w: formation water resistivity
a: coefficient of tortuosity
m: coefficient of cementation

The resistivity of the 100% water saturated sedimentary section was measured by the deep-reading resistivity tool when the sediment pore space is 100% saturated with water. The hydrocarbon saturation can be identified within the neighbouring hydrocarbon-bearing intervals. The hydrocarbon saturation from the relative baseline is represented as value of measured R_o (Collett & Ladd, 2000). Based on the study by Pearson *et al.* (1983), to estimate the NGH saturation, the n value usually used is 1.94. In the concentrated zone of NGHs, the baseline of R_o is represented as R_o=1.3 ohm.m.

Using the "quick-look" Archie method, water saturation can be calculated using the formula below:

$$S_w = (R_o / R_t)^{1/n}$$

Where:
S_w: water saturation
R_o: sedimentary section's resistivity that contain water (S_w = 1.0)
R_t: true resistivity
n: a constant that is empirically derived

From the empirical formula of Arp (1953), the formation water resistivity that exists in the NGH concentrated zone was calculated by deducing that the trend of water salinity formation is constant with depth:

$$R_{w2} = R_{w1} (T_1+21.5) / (T_2+21.5)$$

Where:
R_{w1}: formation water resistivity at temperature T_1 in degree Celcius (°C)
R_{w2}: formation water resistivity at temperature T_2 in degree Celcius (°C)

At temperature T_1, the known resistivity is R_{w1}. The seawater resistivity and temperature of seabed were utilized as R_{w1} and T_1 in this research study. The geothermal gradient and temperature of seabed are used to calculate T_2, which is temperature of NGH concentrated zone. At the "B-2" well location, the geothermal gradient is 5.7°C/100 m and temperature of seabed is 3°C (JX Nippon, 2016).

Salinity in sea water is used to identify seawater resistivity and resistivity of sea water was calculated by using the equation (Bigelow, 1992; JX Nippon, 2016):

$R_w = (0.0123+3647.5 / C_{NaCl}^{\ 0.955}) \times (81.77 / T+6.77)$

Where:

R_w: formation water's resistivity

C_{NaCl}: concentration of NaCl in ppm

T: temperature in °F

Based on the study by Behain (2005), the parameters of Archie (a, m, n and R_w) are commonly used to estimate the NGH saturation by using Archie's equation with an average 55% porosity. From the logging while drilling attenuation and phase shift log data in the net reservoir interval, the values of P_{mean} resistivity is used to estimate NGH saturation. The values for calculated NGH saturation range from 62.5 % to 83.5% as shown in Table 1. NGH saturation was calculated by using the "quick-look" Archie method and standard Archie equation. Based on these two methods, the average of NGH saturation was calculated, which is 73.7% and the NGH saturation value was most probably represented by the average value as shown in the Table 1.

e) Volume ratio

The standard condition of the volume ratio was 0 °C and 1atm was used (Fujii *et al.,* 2008; JX Nippon, 2016).

f) Cage occupancy

Based on the findings by Lu *et al.* (2005), the cage occupancy value of 0.96 was used and it was estimated from core samples.

Table 2 summarises the input parameters and uncertainty distributions of gas initially in place (GIIP) of the assessed gas hydrate deposit.

NATURAL GAS HYDRATE GIIP RESOURCE ASSESSMENT

The total calculated gas volume in the NGH concentrated zone in the "B" development area is 1003.4 BCF in place (P50) and ranging from 565.6 BCF (P90) to 1469.2 BCF (P10). The GIIP P10-P90 distribution of the studied NGH deposit is shown in Figure 17. From the variance diagram of NGH in place calculated, the gross rock volume and gas saturation play the most crucial role for resource estimation in this case study (Figure 18). While this study is predominantly based on well derived parameters, it is also noted that an alternative approach for the assessment of potential resource volume of NGH deposits in the Ulleung Basin, East Sea has been documented by Lee *et al.* (2013), using seismic inversion and multi-attribute transform techniques.

DISCUSSION

As well cost comprises the bulk of deepwater drilling operation expenses, careful investigation and mitigation of NGH as a drilling geohazard is paramount during planning and drilling phase. A number of recent technology developments may be applied to mitigate geohazard issues associated with NGHs that maybe encountered while drilling, these include:

- Drilling with Casing (DWC) is a one-trip casing drilling technology that helps to prevent pulsating the frozen wellbore. A rugged and hard casing can be cemented to greater depth to reduce the likelihood of substrate collapse induced by gas released from NGH dissociation which arises from the temperature and pressure changes over time. Cool drilling mud circulation can also aid in absorbing the heat released by the setting of cement (Amodu, 2010).
- Geotechnical tools such as cone penetrometers and thermal conductivity probes along with downhole scientific instruments like formation temperature probes, pressure measurement systems can be further developed to identify NGH problems. Downhole measurement tools are usually used for the industrial site surveys for analysing and determining of methane hydrate related geohazards (Collett *et al.,* 2013).
- High resolution multibeam bathymetry and side scan sonar surveys can be used to determine the ground characterization such as pock marks as gas escape features and rock mass structure in subsurface. This digital survey method allows us to obtain data from remote and inaccessible areas to help with unconventional mapping (Eberhardt & Stead, 2011). To determine surface features that might be associated with migrated methane gas along faults, high resolution shallow 3D seismic together with site survey and field-based observations can be used in the mapping of NGH distributions.
- Managed Pressure Drilling (MPD) is a drilling process that is used to regulate the annular pressure profile across the wellbore accurately (Frink, 2006). The MPD provides a closed-loop circulation system in which pore pressure, formation fracture pressure, and bottomhole pressure are balanced and managed at surface to maintain hydrate stability (Schlumberger, 2017).
- A complementary technique, controlled-source electromagnetic imaging (CSEM; Edwards, 1997), attempts to exploit the increased electrical resistivity of shallow NGH-bearing sediments. However, initial results were not promising as the physical nature of electromagnetic wave propagation through marine sediments results in a reduced lateral and vertical resolution, compared to seismic imaging. Hence,

Table 1: Calculation of NGH saturation by using the "quick-look" Archie method and standard Archie equation (from JX Nippon, 2016).

		"Quick-look" Archie	Standard Archie
LWD attenuation resistivity log	Sw	27.3%	16.5%
	Sh	72.7%	83.5%
LWD phase shift resistivity log	Sw	37.5%	23.9%
	Sh	62.5%	76.1%
Average	Sw	32.4%	20.2%
	Sh	67.6%	79.8%
Most likely	Sw	26.3%	
	Sh	73.7%	

Table 2: Input parameters and uncertainty distributions of GIIP of the assessed NGH deposit (from JX Nippon, 2016).

Parameters	Unit	Distribution	Input Parameter			
			Min	ML	Max	Remarks
Gross Rock Volume (GRV)	km^2*m	Stretched Beta	165	603	851	GRV calculated from: Min: Very high gas hydrate occurrence area ML: High gas hydrate occurrence area Max: Moderate gas hydrate occurrence area
Net-to-Gross (N/G)	fraction	Stretched Beta	0.50	0.97	1.00	Min: Half of Max MK: N/G after applying 50% cut off for Vsh derived from resistivity logs (attenuation and phase shift resistivity) Max: 1.0
Porosity	%	Stretched Beta	45.0	55.0	65.0	Min: ML-10% ML: Mean porosity of sediments within gas hydrate stability zone offshore NW Sabah (Behain, 2005) Max: ML+10%
Gas Hydrate Pore Saturation	%	Stretched Beta	15.0	73.7	80.0	Min: Based on reference well data in deepwater Sabah (Hadley *et al*., 2008) ML: Average of gas hydrate pore saturation from Archie's sand and "quick-look" Archie equations for LWD resistivity logs (attenuation and phase shift) Max: Based on reference well data in deepwater Sabah (Hadley *et al*., 2008)
Volume Ratio	fraction	Constant	172			Volume ratio for standard condition (0 deg C, 1 atm was used (Fujii *et al*., 2008).
Cage Occupancy	fraction	Stretched Beta	0.90	0.96	1.00	Considering recent observation of cage occupancy from natural core samples (Lu *et al*., 2005).

CSEM was deemed more suitable for imaging chimney structures and other fracture dominated systems for indication of active hydrocarbon migration (Schwalenberg *et al.,* 2005). Nonetheless, recent improvement in 3D CSEM data acquisition, new generation of receivers and advancement in processing technology help to deliver encouraging outcomes. In the case study presented by Tharimela *et al*. (2019), a 3D CSEM survey was acquired in 2014 in the Pelotas Basin offshore Brazil, with NGH resistivity mapping as the main objective to investigate the origin and distribution of NGH deposits in the basin. The acquired data was inverted using a proprietary 3D CSEM anisotropic inversion algorithm. Prior to CSEM, interpretation of near-surface geophysical data including 2D seismic, sub-bottom profiler, and multibeam bathymetry data indicated possible presence of NGHs within features identified such as faults, chimneys, and seeps leading to pockmarks, along the BSR and within the GHSZ. Upon integration of the same with CSEM-derived resistivity volume, the interpretation revealed excellent spatial correlation with many of these features, and the resistivity volume was also inverted to derive the NGH saturation volume using Archie's equation. Another case study conducted by Tharimela & Filipov (2019) also demonstrates that CSEM-derived resistivity can provide a better guidance to mapping saturated hydrates and free gas at a regional scale in the Rakhine Basin, offshore Myanmar.

CONCLUSIONS

NGHs are potentially both a cause for drilling geohazards and a future energy resource. Their presence and extent can potentially be estimated from seismic profiles based upon the identification of a phase boundary BSR and with cored sections, wireline logs and downhole imaging data. Wellbore instability and casing collapse can be caused by the dissociation of NGHs encountered while drilling, and the risk can be minimized by careful pre-drill well path planning.

In production phase, engineers can extract gas from the methane hydrate deposits by reducing pressure inside the wellbore, by reducing temperature of hydrate formation with inhibitors or by thermal stimulation method to disturb the stability of NGHs. However, significant risks are associated with gas extraction from NGHs as they can impact global warming, seafloor destabilisation and submarine slope failure, and have a physio-biological impact on microbial communities associated within the methane hydrate ecosystem.

Recently, approaches to exploring for NGH deposits have shifted towards from evidence from seismic surveys and other remote sensing data to a more integrated evaluation of the full petroleum system (Collett *et al.,* 2009). This approach incorporates geologic information (such as the availability of gas sources, fluid migration pathways, and suitable reservoirs) with direct geophysical indicators (such as anomalous strong reflectors or high calculated velocities) in a way regularly applied in the oil and gas industry (Saeki *et al.,* 2008; Boswell & Saeki, 2010). The approach acknowledges that all exploration has great uncertainty, and that no single tool or piece of evidence will be definitive and reliable such as BSR alone for identification of gas hydrates. Instead, exploration uncertainty is best managed by a comprehensive evaluation of all relevant data to provide confidence in the occurrence of each necessary part of the system (UNEP, 2014).

With increasing economic value, some eighty-two countries have conducted scientific research activities related to NGHs (Chong *et al.,* 2015; Wei *et al.,* 2016). At some point in the future (pending improved gas price and extraction technology), methane hydrates could be a vast source of natural gas. The US Energy Department has estimated that the total amount of energy associated with NGHs could exceed the combined energy content of other fossil fuels. Based on extensive research on assessment data and drilling programs, Boswell & Collett (2011) suggest there is $3x10^{15}m^3$ of methane gas in worldwide NGH deposits. This is equivalent to 1500 Gt of carbon or 2.0 million Tg CH_4 (Liu *et al.,* 2019). However, significant additional research and technological improvements are needed before safe commercial productions can be achieved. Carefully planned production monitoring is also an essential support for harvesting this potential alternative energy in ways that are safer, more economical, and more environmentally friendly (e.g., Liu *et al,* 2019).

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