Gas hydrate formation and its accumulation potential in Mohe permafrost, China

Xingmin Zhao*, Jian Deng, Jinping Li, Cheng Lu, Jian Song

Institute of Mineral Resources, CAGS, 26 Baiwanzhuang, Beijing 100037, China

ABSTRACT

The Mohe area is an area of continuous permafrost in northernmost China with strong similarities to other known gas-hydrate-bearing regions. Permafrost thickness is typically 20–80 m; average surface temperature ranges from −0.5 °C to −3.0 °C, and the geothermal gradient is roughly 1.6 °C/100 m. We estimate that 204.66 × 10¹² m³ of hydrocarbon gases have been generated in the Mohe basin from nearly 1000 m middle Jurassic dark mudstones, providing ample gas source for gas hydrate formation. Numerous folds in the shallow section provide opportunities to trap gas within sandstones and siltstones reservoirs bounded by competent mudstone seals. Gas migration to the shallow section is enabled via fault fracture zones and fracture systems. Based on core description and observations of gas releases from drilled wells, we infer that the Mohe region could hold large quantities of natural gas in the form of gas hydrate.

1. Introduction

Gas hydrate, also known as methane hydrate for its methane-dominated composition, is an ice-like crystallloid solid compound that forms mainly from water and methane molecules under low temperature and high pressure. Actually, gas hydrate is a kind of special-form (solid) or special-type (unconventional) natural gas (Pan, 1986; Dai et al., 1989; Zhang and Zhang, 1989). In nature, gas hydrate frequently occurs either in submarine sediments on continental shelves or in association with permafrost (Sloan, 1998; Majorowicz and Hannigan, 2000; Makogon et al., 2007; Makogon, 2010). Gas hydrate has significant implications for energy resources, geohazards, and climate change (Kvenvolden, 1988a, b; Macdonald, 1990; Nisbet, 1990; Paull et al., 1991; Maslin et al., 1998; Bouria et al., 2000; Milkov et al., 2000; Kennedy et al., 2001; Collett, 2002, Collett et al., 2009) and has attracted great interest from the scientists from many disciplines.

Although marine settings house the majority of global gas hydrate resources, permafrost is an important area for the formation and occurrence of gas hydrate, particularly those occurrences within sand reservoirs that have the greatest current potential for energy production. An example from the Yamal Peninsula in west Siberia indicates that the relic of gas hydrate probably occur 60–80 m below permafrost for its self-preservation effect (Chuvilin et al., 1998; Yakushev and Chuvilin, 2000), suggesting that gas hydrate may have an even more widespread distribution in permafrost than commonly thought. Recently, gas hydrate was found in Qilian mountains permafrost in Qinghai Province, China (Zhu et al., 2010), in a similar to that of the Mohe area.

The Mohe area, situated in the northernmost portion of China (Fig. 1), has the lowest average surface temperature in China and widespread development of permafrost. In the past few years, a range of geochemical, geological, and geophysical investigations have provided confirmation of the existence of the necessary elements for a well-developed gas hydrate petroleum system (after Collett et al., 2009) in the basin.

2. Regional geological setting and its control of gas hydrate formation

The Mohe basin occupies roughly 21,300 km² of China north of N 52° 20′. The region is among the least explored for hydrocarbons in China. Paleogeographically, the Mohe basin is attributed to Mongolia-Okhotsk ocean (Zhang et al., 2003; Wu et al., 2006) and is currently tectonically situated on the Eerguna micro-plate within the Okhotsk folded belt (Zhang et al., 2003) on the sutured boundary between the Siberia plate and the Northeast China put-together plate. The southern margin of the basin is marked by Proterozoic granite (Fig. 1). Tectonic processes, including Mongolia-Okhotsk ocean crust subduction, interaction between the Siberia plate and China plate, and subsequent underthrusting of Pacific plate etc., have significantly influenced both the depositional
(including source rocks, reservoirs, and seals) and structural (including the development of trapping geometries and fault/fracture related migration pathways).

Mohe basin is a continental basin formed through the Mesozoic. The approximately 6000 m or more of strata fill consists of clastic and volcanic rocks of the middle and upper Jurassic (with minor Cenozoic sediments) which lies upon Devonian basement. The middle Jurassic, which is the majority of the basin fill, is mostly made up of fluvial and lacustrine terrigenous clastics of the Xiufeng, Ershierzhan, Mohe, and Kaikukang Formations (Table 1). The Ershierzhan and Mohe Formations occur widely throughout the basin and include the majority of source rocks and reservoir rocks for potential gas hydrate formation. The Xiufeng Fm, also widely distributed in the region, primarily embraces reservoir rocks. The Kaikukang Fm is restricted to the northeast part of the basin. The upper Jurassic occurs only locally and primarily consists of volcanic and pyroclastic rocks interbedded with fluvial and lacustrine terrigenous clastic formations. During the late stage of basin filling, the interaction among Siberia plate, Northeast China put-together plate and Pacific plate resulted in the development of many northeast-to-east northeast striking overthrust faults and associated faults, alternating depressions and uplifts, as well as large-scale volcanic eruption in the region (Zhang et al., 2003). These faults make up the primary conduits for continuous hydrocarbon-supply to the shallow section. The uplifts or salients act as the traps for gas hydrate accumulation.

3. Gas hydrate petroleum system

3.1. Thickness of permafrost and geothermal gradients

Permafrost is continuously spread throughout Mohe region (Zhou et al., 2000; Jin et al., 2009) and thickens to the northwest. Thickness of permafrost ranges has been alternatively reported as ranging from 50 to 100 m (Zhou et al., 2000) and from 0 to 60 m (Jin et al., 2009). Our geophysical surveying from 2003 to 2004 indicates that the thickness of permafrost to the west of the jingou Forest Farm is about 20–80 m with thickness up to 140 m or so locally. These thicknesses are comparable to those reported in other gas-hydrate-bearing regions including Qilian mountains region in China (Zhu et al., 2010) and Yamal Peninsula in Siberia where is speculated on gas hydrate occurring (Chuvilin et al., 1998; Yakushev and Chuvilin, 2000).

Geotemperature, which is usually characterized by ground surface temperature, geothermal heat flow and gradient, has a profound impact on occurrence of gas hydrate. Prior data (Wang and Huang, 1988a, b) indicate that the surface temperature of the permafrost in northeastern China is between 0.5 and −2.5 °C; geothermal flux is from 30 to 71 mW/m²; and geothermal gradient is from 1.0 to 4.54 °C/100 m. As far as it is further concerned, Mohe region has the lowest surface temperature of −1.0 to −2.5 °C, the northeast part of Inner Mongolia shows the lowest geothermal heat flow of 40 mW/m², and the north area of Heilongjiang Province has the lowest geothermal gradient of 1.2 °C/100 m. Our data reveal, however, that the surface temperature and geothermal gradient in Mohe region is from −0.5 to −3.0 °C and around 1.6 °C/100 m respectively, which is similar to those of Messoyakha in Siberia (−8 to −12 °C (Romanovsky et al., 2007) and 1.0–3.0 °C/100 m (Makogon, 2010)), Prudhoe Bay on Alaska North Slope (−4.6 °C to −12.2 °C (Kamath et al., 1987) and 1.5 °C–5.2 °C/100 m (Collett et al., 2011), and Qilian Mountains area in China (−1.5 °C to −2.4 °C and 2.2 °C/100 m; Zhu, personal correspondence). Consequently, Mohe permafrost has a favorable geothermal condition of gas hydrate formation.

3.2. Temperature-pressure condition of gas hydrate formation

Temperature and pressure requisite for gas hydrate formation (Sloan and Koh, 2008) have a decisive effect on the phase balance of gas hydrate petroleum system. In the subsurface, temperature and pore pressure are dominant controls on the stability of gas hydrate. In general, the thickness of the gas hydrate stability zone can be
No matter how the gases were generated, the source material is from gas hydrate can be either biogenic and thermogenic in origin. 3.3.1. Source material for hydrocarbon gases

3.3. Source and quantity of hydrocarbon gases

According to our present knowledge, the hydrocarbon gases from gas hydrate can be either biogenic and thermogenic in origin. No matter how the gases were generated, the source material is organic matter within sedimentary rocks or sediments. Therefore, the type, origin and quantity of organic matter from gas source rocks are very important for gas hydrate formation.

As discussed above, 6000 m thickness of the basin fill is mostly terrigenous clastic sedimentary formations, which consist dominantly of sandstones and mudstones originated from shallow lake, braided river delta and braided river environments. In the light of the data acquired from regional surveying and drilled cores,
mudstones, mainly including dark gray or black mudstone and silty mudstone, are the dominant gas source rocks (greater than 85%) in the Mohe basin. Based on the measured results of 144 samples from Mohe basin, the argillaceous rock (including carbonaceous shale) greater than 0.75% of total organic carbon content is defined as gas source rock in this paper (Chen et al., 1997). According to this definition, total estimated thickness of gas source rocks in the Mohe basin is 1000 m or more (Table 2), of which there is 142–477 m in Xiufeng Fm, 120–660 m occurs in Ersheirzhan Fm, 797–1631 m in Mohe Fm, and none in Kaikukang Fm.

3.3.2. Generation and quantity of hydrocarbon gases

Gas source rocks are certainly of great importance to the formation of gas hydrate. More important, however, is the abundance of organic matter in gas source rocks. The analysis of 125 mudstone samples show that samples of higher than 0.75% of total organic carbon (TOC) exceed 80% with more than 65% in Xiufeng Fm, around 73% and 89% in Ersheirzhan Fm and Mohe Fm respectively. The measured data of 22 mudstone samples also reveals that the samples higher than 0.0015% of chloroformal bituminous A is about 50%, of which there is little in Xiufeng Fm, there is about 55% in Ersheirzhan Fm, and there is more than 65% in Mohe Fm. Rock pyrolysis data from 62 samples shows that over 70% of samples have more than 0.5 mg/g of hydrocarbon potential ($S_1 + S_2$). Taking into account the fact that due to these samples being taken from the ground surface in the field, weathering may make such a significant loss of organic matter in rock that the abundance of organic matter in gas source rocks decrease greatly (Chen, personal correspondence), the abundance of organic matter from mudstone in Mohe region may be much higher than that described here. Therefore, in the light of the abundance of organic matter, the study area has great richness of hydrocarbon-generating materials.

The microscopic analysis of kerogen from 65 mudstone samples and vitrinite reflectance of 55 mudstone samples indicate that the organic matter from the Middle Jurassic in Mohe basin is dominated by type III kerogen with vitrinite reflectance (Ro) usually between 0.90% and 1.35%. According to the modern theory of petroleum geology, these organic matters are the parent materials of thermogenic hydrocarbon gases. On the other hand, the modern oil and gas geochemical studies have shown that some of organic matter (especially type II kerogen of lacustrine origin) from the mudstones may be the major sources of biogenic hydrocarbon gases (Liu et al., 2009). Furthermore, some recent research also indicates that biogenic hydrocarbon gases from organic matter in the mudstones of permafrost (Ward et al., 2004) and non-permafrost (Rice, 1993; Scott et al., 1994. DATE; Smith and Pallasser, 1996; Luo et al., 2003; Zhu et al., 2006; Manzur and Smith, 2001) are also common.

The hydrocarbon gases generated in Mohe basin include both thermogenic and biogenic gases, the amount of which were calculated according to thermogenic (Schmoker, 1994) and biogenic models (Wang et al., 1996) respectively. It was calculated that the hydrocarbon gases generated in Mohe basin amounts to $204.66 \times 10^{12}$ m$^3$ or so, of which thermogenic gases is about $52.9 \times 10^{12}$ m$^3$, and biogenic gases is up to around $151.76 \times 10^{12}$ m$^3$. Obviously, such a great volume of hydrocarbon gases may be gas source for potential gas hydrate formation in Mohe basin. What is more, the biogenic gases almost three times as much as the thermogenic is roughly consistent with the permafrost of Mohe region in the formation time (late Pleistocene, Zhou et al., 2000). Consequently, biogenic gases are more favorable to gas hydrate formation and accumulation in Mohe region.

3.3.3. Composition and origin of hydrocarbon gases

Taking the absorbed gases from 59 drilled cores collected from well Mk-1 in the Mohe basin as examples, the origin of hydrocarbon gases in this area is discussed. Gas chromatograph analyses of the absorbed gas from the drilled core show that it is mainly comprised of methane($C_1$) with some wider range of heavier hydrocarbon($C_2$), that is about 51.53%–93.65% of methane($C_1$), 1.31%–29.6% of ethane($C_2$), 0.05%–4.73% of ethylene($C_2H_4$), 0.81%–16.5% of propane($C_3$), 0.06%–3.82% of propylene($C_3H_6$), 0.45%–30.6% of normal butane($nC_4$), 0.08%–8.75% of isobutane($iC_4$), 0.01%–3.8% of normal pentane($nC_5$), 0.01%–3.07% of isopentane($iC_5$) (Table 3). Compared with some permafrost areas where gas hydrate were found, the methane out of the absorbed gas in Mohe basin has also a wider range of abundance, which is less than both the Alaska North Slope and Messoyakha in West Siberia and roughly equivalent to or a bit higher than Qilian Mountains region in China (Table 4). In addition, Gas chromatograph analysis of dissolved gas from 42 spring water samples in Mohe area also shows that dissolved gas is dominated by methane (about 78%–99%) with a little of ethane and none of other heavier hydrocarbon gases. The methane of water-dissolved gas in Mohe basin is a little higher than the Canadian Shield permafrost (64%–87% of methane) where gas hydrate may occur (Scotet et al., 2010). Therefore, as far as gas composition is concerned, the hydrocarbon gases in the Mohe basin is fully able to meet the basic requirements for gas hydrate formation.

The fact of enhanced ethane and other heavier hydrocarbon of hydrocarbon gases in Mohe basin disclose non-biogenic origin of them (Liu et al., 2009). However, to further explore the origin of these hydrocarbon gases, we analyzed the $\delta^{13}CCH_4$ of the absorbed gases from the drilled cores and dissolved gases in the spring water. The results show that the $\delta^{13}CCH_4$ of the absorbed gases typically range from -47.7$\permil$ to -22.7$\permil$, with sometimes less than -55$\permil$, which indicate that thermogenic and biogenic gases coexist. The $\delta^{13}CCH_4$ of the dissolved gas are generally between -78.9$\permil$ and -64$\permil$, which apparently suggest biogenic gases. Moreover, C1 to C2 + C3 ratios of absorbed gases is typically less than 100 and that $\delta^{13}CCH_4$ of those gases are larger than -50$\permil$, further indicating thermogenic origin (Fig. 3). The C1 to C2 + C3 ratios of dissolved gases with $\delta^{13}CCH_4$ usually less than -65$\permil$ are frequently lower than 300, which indicate mixed origin of the gas (Fig. 3). All the mentioned above reveal that both thermogenic and biogenic gases

<table>
<thead>
<tr>
<th>Lithostratigraphic Unit</th>
<th>Thickness in measured strata (m)</th>
<th>Thickness in measured gas source rocks (m)</th>
<th>Ratio of source rocks to stratigraphy</th>
<th>Source rocks (%) with TOC &gt; 0.75%</th>
<th>Thickness in gas source rocks (m)</th>
<th>Speculated thickness in gas source rocks (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaikukang Fm.</td>
<td>254.6</td>
<td>0.6</td>
<td>0.002</td>
<td>0.1</td>
<td>12–2734</td>
<td>1–3</td>
</tr>
<tr>
<td>Mohe Fm.</td>
<td>2284.27</td>
<td>946.89</td>
<td>0.41</td>
<td>90.4</td>
<td>1945–3979</td>
<td>797–1631</td>
</tr>
<tr>
<td>Ersheirzhan Fm.</td>
<td>3079.16</td>
<td>466.06</td>
<td>0.15</td>
<td>77.1</td>
<td>799–4400</td>
<td>120–660</td>
</tr>
<tr>
<td>Xiufeng Fm.</td>
<td>977.3</td>
<td>163.8</td>
<td>0.17</td>
<td>64.3</td>
<td>836–2806</td>
<td>142–477</td>
</tr>
<tr>
<td>Total</td>
<td>6595.33</td>
<td>1577.35</td>
<td>0.24 (mean)</td>
<td>84.6 (mean)</td>
<td>3580–13,919</td>
<td>1060–2773</td>
</tr>
</tbody>
</table>
contribute to gas hydrate formation and are practically gas source for potential gas hydrate formation.

3.4. Trap condition

Trap is a concept of petroleum geology and the requisite for oil and gas accumulation. In the past ten years, great importance has been attached to it in the activity of gas hydrate exploration and research (Bunz et al., 2003; Collett et al., 2008, 2011; Boswell et al., 2011; Makogon, 2010; Scotter et al., 2010; Winters et al., 2011). This is because, whether on the Alaska North Slope in Prudhoe Bay where gas hydrate was detected by drilling, or in the Beaufort-Mackenzie area of north Canada where gas hydrate production test was conducted, gas hydrate deposits are gathered in a large anticline, or uplift site (Majorowicz and Hannigan, 2000; Saffron et al., 2010).

Trap condition of Mohe basin has been unclear due to its lower explored, but the preliminary investigation reveals that “a depression between two uplifts” structural framework (i.e. the Heilongjiang Coast Uplift to the north, the Gulian River Uplift to the south) was gathered in the test was conducted, gas hydrate deposits are gathered in a large anticline, or uplift site (Majorowicz and Hannigan, 2000; Saffron et al., 2010).
south and the Central Depression) and patterns of alternating sags and salients on this framework likely occur. Such structures are fairly favorable to migration of hydrocarbons generated in low-lying area to the structural highs, that is, migration of hydrocarbon generated in the depressions or sags to their adjacent uplifts or salients of the basin and promotes formation of gas hydrate by transferring of the hydrocarbon gases in the region to the near-surface permafrost.

The reservoir, an important component of traps, plays a significant role in gas hydrate accumulation, which was recognized by most of the explorer and researchers in gas hydrate area. This is because both gas hydrate accumulation theory and its successful practice of exploration have demonstrate that gas hydrate can accumulate to high concentrations in the sandy sediments, sandstones (Makogon, 2010; Safronov et al., 2010), such reservoirs won’t prevent gas and groundwater from migrating and accumulating. Furthermore, these units (such as sandstones, conglomerate and mudstones etc.) are extensively fractured, adding significant additional permeability and bulk porosity to the units. Therefore, in terms of gas hydrate formation, a great number of reservoirs occur throughout the Mohe region.

Analysis of 131 sandstone samples show that porosity and permeability of the sandstones from Mohe region range from 0.5% to 9.1% and from 0.03 md to 2.11 md respectively. Although they are inferior to reservoir of gas hydrate deposits in the other permafrost (Makogon, 2010; Safronov et al., 2010), such reservoirs won’t prevent gas and groundwater from migrating and accumulating. Furthermore, these units (such as sandstones, conglomerates and mudstones etc.) are extensively fractured, adding significant additional porosity and permeability to the units. Therefore, in terms of gas hydrate formation, a great number of reservoirs occur throughout the Mohe region.

The seal, another important part of traps, also plays an important role in gas hydrate formation. Whether it is the Beaufort-Mackenzie Basin in northern Canada (Majorowicz and Hannigan, 2000), or Prudhoe Bay on the Alaska North Slope (Boswell et al., 2011), or the Qilian Mountains in China, all of the large-scale, high saturation gas hydrate deposits are sealed by thicker mudstones (>10 m). As mentioned above, Mohe Fm, usually distributed on the upper section in Mohe Basin (therefore close to the permafrost), has a great amount of mudstone (>40%) that may act as a cap rock for formation and accumulation of gas hydrates in Mohe region.

In addition, the Mohe Fm includes thick section of interbeded sandstone and mudstones. The upper part of the Mohe Fm, often in the upper section of stratigraphy fill of Mohe basin, is usually spread in permafrost. Therefore, Mohe Fm is the best stratigraphic unit of source rocks, reservoirs and seals for gas hydrate formation and accumulation.

3.5. Migration conditions

Similar to conventional oil and gas accumulations, fluid migration has an active influence on the gas hydrate formation and accumulation. For a large-scale commercial gas hydrate deposits, fluid migration is certainly essential as the gas occurring in thick gas hydrate deposits typically exceeds what could be produced locally (Collett et al., 2009). As result, it is essential for the formation of large-scale gas hydrate deposits that external hydrocarbon gases be supplied continuously by faults, fractures and permeable strata etc. (Safronov et al., 2010; Boswell et al., 2011).

The role of non-local gas sourcing along pathways such as faults in gas hydrate formation is demonstrated in the Gulf of Mexico, the sea to the north California, the Cascadia edge of the northern Oregon (Brooks et al., 1986, 1991; Kastner et al., 1993), northern Siberia (Yakushev and Chuvilin, 2000; Safronov et al., 2010), Prudhoe Bay on the Alaska North Slope (Collett et al., 2011; Dai and Lee, 2010; Lorenson et al., 2010) and the Muli region of the Qilian Mountains in China.

In the Mohe area, the fractures acting as potential migration system is not known well, but preliminary investigation and exploration shows that both northeast and nearly east-west trending faults and fractures are well-developed. These faults and fractures are interconnected in space and provide connected pathways for fluid migration in this area, which is confirmed by frequent and great loss of drilling mud fluid during drilling in this area.

3.6. Groundwater salinity

An effect of salinity on the formation and accumulation of gas hydrate is well established, however, recent studies have shown that, when the salinity is less than $4 \times 10^{-2}$, it has little effect on the formation and stability of gas hydrate (Husebø et al., 2009). Our data show that the salinity of groundwater in northern Heilongjiang Province is generally less than $1 \times 10^{-3}$. In addition, analyses of three spring water samples from Mohe region show groundwater salinity (Cl-ion concentration) of $\sim 2.94 - 17.6 \times 10^{-6}$.
and higher than the North Slope’s Prudhoe Bay, Alaska ($<1.0 \times 10^{-12}$) (Collett et al., 2011), but lower than Messoyaka, Siberia ($\leq 1.5 \times 10^{-2}$) (Makogon, 2010). Salinity throughout Mohe area therefore has little effect on gas hydrate formation and can be ignored.

4. Indications of gas hydrate occurrence

4.1. Authigenic calcite and pyrite

Examination of cores recovered from the Mohe region reveal large numbers of calcite veins and epigenetic pyrite that occurs within fissures (Fig. 5), in intergranular and intragranular pores in sandstones, and within fractures in individual clastic grains (Fig. 6). These features are indicative of the strong underground fluxes of hydrocarbon activity that, in the presence of anaerobic bacteria, can lead to the following chemical reactions:

$$\text{CH}_4 + \text{SO}_4^{2-} \rightarrow \text{HS}^- + \text{HCO}_3^- + \text{H}_2\text{O}$$

HCO$_3^-$ anion reacts with Ca$^{2+}$ anion as follows:

$$\text{HCO}_3^- + \text{Ca}^2+ \rightarrow \text{Ca(HCO}_3)^2$$

$$\text{Ca(HCO}_3)^2 \rightarrow \text{CaCO}_3 \downarrow + \text{CO}_2 \uparrow + \text{H}_2\text{O}$$

Here, CaCO$_3$ precipitate is the calcite filled the fractures in the rocks. Meantime, in the reduction circumstances caused by oxidation of hydrocarbons, sulfur and iron ions react to product pyrite as follows:

$$\text{HS}^- + \text{Fe}^{2+} \rightarrow \text{FeS}_2 \text{ (pyrite)} \downarrow + \text{H}^+$$

We infer that epigenetic calcite and its associated pyrite, which is characteristic of common secondary alteration above oil and gas accumulations, indicate the intense activity of the underground hydrocarbon fluid. Authigenic pyrite and calcite have been reported in association with gas-hydrate–bearing sediments both in seafloor or permafrost settings (Mazzini et al., 2004; Sassen et al., 2004; Rose et al., 2011). Combined with gas hydrate formation condition discussed above, these authigenic minerals can be indicative of the formation of potential gas hydrate.

4.2. Dissolved methane

The dissolved methane from some spring water in Mohe area is as high as 14,000 ppm or more. During hydrogeological drilling within the Mohe basin in the winter of 2010, a continuous flame was unexpectedly produced when the wellhead was heated with a torch in order to thaw the frozen drill stem, then the flame caused the surface of mud pools to catch fire though the mud flute and keep on burning while mud liquid from the well was supplied continuously. We have determined that the fuel for this fire was mainly composed of methane (>90%) and suspect that a source of this methane may have been dissociation of gas hydrate.

5. Discussion

In Mohe area, there are the development of the petroleum systems elements that are consistent with gas hydrate formation, including thick permafrost, necessary temperature-pressure conditions and geothermal gradient, abundant gas sources, migration conduits in the form of faults and fractures, and gas hydrate-hosted traps composed of reservoirs and seals. The conditions in the Mohe area are noted to be very similar to other areas where permafrost-associated gas hydrate has been confirmed by drilling and observation.

Thousands meters of dark mudstone from the Middle Jurassic in Mohe basin provides the significant parent materials for hydrocarbon gases (including both thermogenic and biogenic gases) required for the formation of gas hydrate. A great amount
of dark mudstone in this region, of which total organic carbon is more than 0.75%, kerogen is dominantly type III, and vitrinite reflectance is frequently more than 0.90%, can yield large volumes of thermogenic gases requisite for gas hydrate formation. The type II lacustrine organic matter in dark mudstone is the better parent materials of biogenic gases and can produce quite a little of biogenic gases for hydrate formation. The huge amount of hydrocarbon gases generated from the Middle Jurassic in Mohe basin can form a great deal of gas hydrate. According to preliminary calculations, the middle Jurassic in Mohe basin can generate about $204.66 \times 10^{12} \text{ m}^3$ hydrocarbon gases for gas hydrate formation, of which thermogenic gases amounts to about $52.9 \times 10^{12} \text{ m}^3$, biogenic gases is $151.76 \times 10^{12} \text{ m}^3$ or so. Especially, biogenic gases of up to three quarters of hydrocarbon gases may roughly be in accordance with the permafrost of Mohe region in the formation time (late Pleistocene (Zhou et al., 2000)) so that they are quite conducive to the formation and accumulation of gas hydrate.
The tectonic history of the region is helpful to make the traps requisite for gas hydrate formation. The uplifts to south and north respectively and the secondary salients within them in Mohe basin create the traps for gas hydrate formation. Within the traps, the widely-spreading sandstones, sandy conglomerates and fractured rocks from all the section of strata, especially fined-grained sandstones, siltstones in Mohe Fm, are the common reservoirs for gas hydrate formation, interbedded mudstones in Mohe Fm acts as the seals for gas hydrate accumulation.

The great amount of hydrocarbon gases, the richer heavy hydrocarbon gases and the lower groundwater salinity in Mohe region are favorable to the formation of gas hydrates. The fire at the wellhead of drilled wells, the adequacy of hydrocarbon gases in the region, the richness of heavy hydrocarbon gases in hydrocarbon gases, and groundwater salinity as low as about 10 ppm are conducive to the formation of gas hydrates.

Some signs show the occurrence of gas hydrate in Mohe region. The epigenetic calcite and pyrite in drilled cores which are similar to gas hydrate-discovered region such as the Gulf of Mexico, the Lake Baikal and Alaskan North Slope, and burning on the surface of mud pool suggest the occurrence of gas hydrate.

Overall, the temperature and pressure conditions, the richness of hydrocarbon gases and its parent materials, the gas composition and the groundwater salinity, the traps required for the formation and accumulation of gas hydrate, the presence of reservoirs and seal, the huge thickness of dark mudstone, the richness of organic matter, suggest that the northwest Mohe basin is extremely favorable for the accumulation of gas hydrate.